The neural representation of intrusive thoughts

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Based on the philosophical notion that language embodies thought we investigated whether a habitual tendency for intrusive thought that younger and older participants report over a period of 100 sessions, spread out over about 6 months, is associated with brain regions related to language production. In favour of this hypothesis, we found that individual differences in habitual intrusive thoughts are correlated with activity in the left inferior frontal gyrus (IFG, Broca's area) as well as the cingulate cortex (CC) during a two-choice reaction-time task in fMRI. Participants who habitually tended to experience intrusive thoughts showed greater activity during task-free (baseline) compared to task periods in brain regions involved in language production. Task performance was unrelated to individual differences in intrusive thoughts. We conclude that intrusive thoughts may be represented in a language-like format and that individuals reporting a habitually higher tendency for intrusive thoughts may have stronger and more habitual inner speech processes.

Humans spend a good deal of their waking time engaged in so-called inner speech with natural language sentences occupying the stream of their conscious mentality (Sokolov, 1972). In philosophy, the question of how thought and language are related has long been debated (Carruthers, 2002). The assumption that language plays a direct role in normal human cognition has been put forward and implies that thought requires language (Wittgenstein 1953; Davidson 1975; McDowell 1994). Another view suggests that language is an input–output system for central cognition and is therefore only a channel to transfer thoughts out of or into the mind (Cummins, 1996). A third view would argue that language is one among several - possible formats in which thoughts can be processed (Kosslyn et al., 2003). In this study, we focus on a particular kind of thought, namely intrusive thoughts. Intrusive thoughts have been defined as unwelcome repetitive thoughts, images or impulses (Rachman, 1981). In the last decades, clinical psychologists have empirically investigated the role of unwanted, intrusive thoughts in pathologies, such as obsessive compulsive disorders (Julien et al., 2007), depression (Wenzlaff et al., 1988, Cooney et al., 2010), post-traumatic stress disorder (Sprung, 2008) and generalized anxiety disorder (Ruscio and Borkovec, 2004). But also healthy individuals experience intrusive thoughts that are comparable to clinical obsessions in form and content (Rachman and de Silva, 1978; Purdon and Clark, 1993; Langlois et al., 2002).

Here, we assessed the habitual tendency for intrusive thoughts by means of three items ('Today, I cannot get certain thoughts out of my mind'; 'Today, I keep thinking about something over and over again'; 'Today, I have difficulties suppressing thoughts about myself') experienced by younger and older healthy participants over about 100 days during which participants took part in a micro-longitudinal study of day-to-day variability in cognitive performance. Given that these items were assessed a 100 times over a period of about 6 months, intrusive

thoughts, as assessed in the present study, may qualify as indicating the habit to ruminate. We performed a functional magnetic resonance imaging (fMRI) session with a two-choice reaction time (RT) task before and after the 100 days of intrusive thought assessment. Based on previous neuroimaging studies on mind wandering (Mason et al., 2007; Wang et al., 2009) we reasoned that a stronger tendency for intrusive thought would manifest in more presence of these thoughts during task-free periods. We focused on the two-choice RT data instead of data from memory tasks (working and episodic memory), which were also administered within the scope of the present study, because the memory tasks are known to involve articulatory rehearsal processes (Logie et al., 2003; Nixon et al., 2004). We reasoned that strong involvement of inner speech during task performance might preclude or confound the detection of hypothesized inner speech processes during task-free baseline activity.

Based on the notion that intrusive thoughts are represented in a language format, we investigated whether the reported habit for intrusive thoughts is associated with activity in brain regions related to language production, particularly the left inferior frontal gyrus (IFG, Broca's area), which has been associated with verbalizing and inner speech processes in previous neuroimaging studies (McGuire et al., 1996a, b; Morin and Michaud, 2007). Based on the notion that participants who show a stronger habitual tendency for intrusive thoughts also ruminate more in the task free periods, we predicted to find a positive correlation between the tendency for intrusive thoughts and brain activity in language related regions during task-free baseline periods. This question was addressed by correlating self-reported habitual tendency for intrusive thoughts with the contrast of brain activity in the task-free baseline > task performance. In addition, we examined the generality of our findings by testing whether they hold before and after the 100 days of assessment and cognitive practice.

METHODS

Participants

The parent sample of this study consisted of 101 adults aged 20–32 years and 103 adults aged 65–80 years who participated in

over 100 days of daily assessments of cognitive performance over a period of 6 months. Participants of this parent sample were asked to take part in imaging, and those volunteering were screened for eligibility. As a result, the effective samples consisted of 24 younger adults ($M_{age} = 25.2$; s.d.$_{age} = 3.2$, range$_{age} = 20.5–31.1$) and 15 older adults ($M_{age} = 70.2$; s.d.$_{age} = 4.0$, range$_{age} = 65.0–80.4$). Participants were right-handed, had normal or corrected-to-normal vision and reported no history of cardiovascular disease (except treated hypertension), diabetes, neurological or psychiatric conditions, or drug/alcohol abuse and no use of anti-seizure or antidepressant drugs. Participants in the effective sample completed pre-test imaging, about 100 days assessment of primarily cognitive performance, and post-test imaging and showed no imaging artefacts or brain abnormalities. In terms of global cognitive performance measures [Digit-Symbol Substitution (DS) and Vocabulary], selectivity [for a given age group, $(M_{Imaging\ Sample} - M_{Total\ Sample})/s.d._{Total\ Sample}$] was negligible for younger adults (DS: s.d. $= 0.05$; vocabulary: s.d. $= 0.00$). As expected from the contraindications for MRI, the older MRI sample was positively selected (DS: s.d. $= 1.01$; vocabulary: s.d. $= 0.73$).

Incentives for participants varied between 1450 and 1950 €, depending on the number of completed sessions and their pace of completing them. All participants gave written informed consent. The ethical review board of the Otto-von-Guericke University of Magdeburg approved the imaging study and the review board of the Max Planck Institute for Human Development, Berlin, approved the behavioural parent study.

Materials and procedure

Daily longitudinal assessment

Participants practiced computerized tasks individually during an average of 101 ($M_{young} = 102$, s.d.$_{young} = 3.1$; $M_{old} = 99$, s.d.$_{old} = 3.7$) sessions. Working memory tasks included three-back, numerical updating and alpha-span. Episodic memory tasks included word list recall, object–location memory and number–noun pairs. Speed tasks were three comparison and three two-choice RT tasks. Each ability domain contained tasks with numerical, verbal and figural–spatial content. F. Schmiedek et al. (2010) describe these tasks in detail. Here we describe the two-choice RT tasks in more detail.

The two-choice RT tasks were based on the same stimulus layout: the seven lines of the number '8' as displayed on pocket calculators (Kühn et al., 2011) (Figure 1). Stimuli were masked with a stimulus that combined this 'calculator 8' with extending lines in all 10 possible directions. Possible masking times were 12, 24, 47 or 94 ms. Depending on pre-test performance, two of these masking times (one fast and one slow condition) were chosen for each participant to work on during the longitudinal phase. The two-choice RT task block consisted of 40 stimuli (20 fast and 20 slow), with randomly chosen stimuli out of the two response categories. Participants decided whether the displayed number was odd or even (odd: '3', '5', '7'; even: '2', '4', '6'). In the verbal task, participants decided whether letters were either consonants or vowels (consonants: 'F', 'H', 'P'; vowel: 'A', 'E', 'U'). No performance feedback was provided during the task.

Intrusive thoughts. Intrusive thoughts were conceptualized as repeatedly occurring thoughts that might be unwanted or negative. They were measured daily with three items of which two were adapted from the *Stress Coping Inventory* (Janke and Erdmann, 2002). Participants were asked to rate how much the statements 'Today, I cannot get certain thoughts out of my mind' and 'Today, I keep thinking about something over and over again' matches their thoughts and feelings during that day. A third item was developed to capture self-related intrusive thoughts, 'Today, I have difficulties suppressing
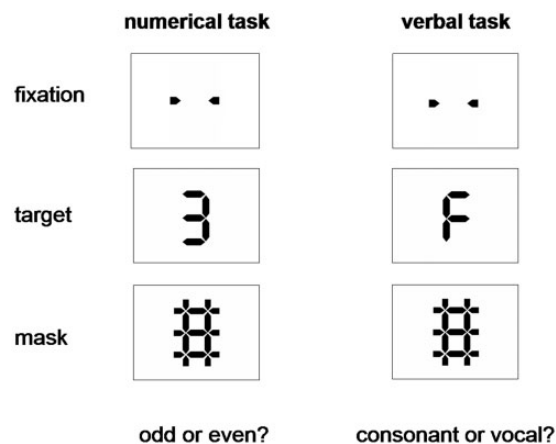

Fig. 1 Schematic drawing of the experimental two-choice RT task.

thoughts about myself'. An 8-point answering scale was used, ranging from 0 (does not apply at all) to 7 (does apply very well). Average Cronbach's α reliability for this scale was 0.89 (ranging from 0.82 to 0.92 across occasions) and has been reported previously (Brose et al., 2011).

The average score across all three items and across 100 days was used for analysis, indicating the average amount or intensity of intrusive thoughts across study time. We consider this as a measure of the habit or trait to ruminate.

Behavioural Task in MRI scanner. The task consisted of 53 s task blocks of the numerical or verbal task intermixed with 16 s fixation blocks. Each task block included 16 trials (16 odd/even; 16 consonant/vowels) presented with jittered inter-stimulus intervals between 2000 and 8000 ms. In total, eight blocks per task were presented, distributed over four runs. Thus, in total 128 trials per task were presented, with randomly chosen stimuli out of the response categories. Masking times were 50 ms for all participants and time points.

MRI procedures. Images were collected with a 3T Magnetom Trio MRI scanner (Siemens, Erlangen, Germany) using an eight-channel radiofrequency head coil. Functional images were collected using a T2*-weighted EPI sequence (TR = 2000 ms, TE = 30 ms, image matrix = 64 × 64, FOV = 224 mm, flip angle = 80°, slice thickness = 3.5 mm, distance factor = 0%, voxel size = 3.5 × 3.5 × 3.5 mm³, 32 axial slices). One hundred and forty-seven image volumes were acquired per run all aligned to AC-PC. Anatomical images were acquired using a T1-weighted sagittal 3D spoiled gradient echo (SPGR) image (TR = 24 ms, TE = 8 ms, acquisition matrix = 256 × 256 × 124, FOV = 250 × 250 mm², flip angle = 30°, slice thickness = 1.5 mm) on a GE scanner (General Electric, Milwaukee, WI).

fMRI data analysis

The fMRI data were analysed using SPM5 (Wellcome Department of Cognitive Neurology, London, UK). The first three functional volumes were excluded to allow the magnetisation to approach a dynamic equilibrium. Data processing started with slice time correction and realignment of the EPI data sets. A mean image was created to which individual volumes were spatially realigned (rigid body transformations). The structural image was co-registered with the mean image. Then the structural image was normalized to the Montreal Neurological Institute template, and the normalization parameters were applied to the EPI images. A commonly applied filter of 8-mm

full-width at half-maximum was used. Low-frequency drifts in time were removed by modelling the time series for each voxel by a set of discrete cosine functions (cut-off: 224 s). Single subject-level statistical analyses were performed with general linear model. Vectors containing the event onsets entered as a stick function were convolved with the canonical haemodynamic response function to form the main regressors. The vectors were also convolved with the temporal derivatives. The design matrix further included six realignment parameters.

To investigate the neural correlates of intrusive thoughts we computed the contrast (t) baseline > numerical and verbal task averaged over pre- and post-test scan and regressed the resulting map on the z-standardized variable reflecting reported mean habitual tendency for intrusive thoughts for each individual. The resulting statistical values were thresholded with a level of significance of $P < 0.001$ $(z > 3.09$, uncorrected). A significant effect was reported when the volume of the cluster was greater than the Monte Carlo simulation determined minimum cluster size (>38 voxels) above which the probability of type I error was <0.001 (AlphaSim, Ward et al., 2000).

We used Marsbar (http://marsbar.sourceforge.net/, Brett et al., 2002) to plot percent signal changes (time window of 4–6 s after stimulus onset) of significant regions derived from the whole-brain correlation of intrusive thoughts over 100 days and brain activity in the contrast task free vs task for each subject, region and condition separately. This was to ensure that correlations were not driven by outliers. Those regions were defined as spheres of 10 mm radius around the peak voxel of clusters derived from the group-level correlation analysis. In addition, we used this data to examine the correlations separately for the age groups.

RESULTS

Behavioural data

The participants reported on average 2.44 (s.d. = 1.52) intrusive thoughts averaged over the 100 days of assessment. We found no significant correlations between the habitual tendency for intrusive thought measure and task performance in the scanner, as indexed by the drift rate parameter derived by means of the diffusion model (Kühn et al., (2011) for more details) $[r(39) = 0.15, P = 0.35]$.

fMRI data

We examined the correlation between the habitual tendency for intrusive thoughts over 100 days and the whole-brain activation maps of baseline vs verbal and numerical task in a multiple regression model also including the factor age. As hypothesized based on the notion that intrusive thoughts should be more prominent during task-free periods (baseline), we found a positive correlation with intrusive thoughts in left IFG (BA 44/45, −42 18 0) and in cingulate cortex (CC, BA 24/32, −9 6 42) $(P < 0.001$, multiple comparison corrected). For individuals reporting more habitual tendency for intrusive thoughts, these brain areas were either more active during fixation intervals between task performance, relatively more suppressed during task performance or both (Figure 2). The associations were of similar magnitude for younger [left IFG: $r(24) = 0.70$, $P < 0.001$; CC: $r(24) = 0.62$, $P < 0.001$] and older [left IFG: $r(15) = 0.62$, $P < 0.05$; CC: $r(15) = 0.57$, $P < 0.05$] participants.

In order to probe the generality and reliability of our finding, we performed the analysis separately for task (numerical and verbal) and time point (pre-test and post-test). We found activation in left IFG in all four analyses using an uncorrected threshold $(P < 0.005$, clusters >10 voxels, uncorrected; Figure 3). Activation in CC was less consistent (only verbal task during pre-test and numerical task during post-test). When comparing the brain correlates of habitual tendency for intrusive thoughts on odd vs even sessions the resulting brain regions were

highly overlapping and showed left IFG and CC $(P < 0.001$, multiple comparison corrected; Figure 4A). Additionally, we correlated the reported habitual tendency for intrusive thoughts during the first and the last half of the 100 sessions with brain activation at pre- and post-test during task-free baseline > task. Pre- and post-test brain activity in left IFG during baseline correlated positively with the tendency for intrusive thoughts in the first as well as the last 50 sessions with a more lenient threshold $(P < 0.001$, cluster >10 voxels, uncorrected) (Figure 4B).

DISCUSSION

Between-person differences in habitual tendency for intrusive thoughts reported over a period of about 100 days were associated with brain activity in the left IFG (Broca's area) and the CC, in both younger and older adults. These results were corroborated by a split of reported intrusive thoughts into a measure on even and odd days, which revealed largely overlapping brain activity in left IFG and the CC. The reliability of the association with left IFG was further demonstrated when analyzing the tasks (numerical and verbal) and time points (pre- and post-test) separately, while the reliability of the association with activity in the CC was less convincing.

Because left IFG activation has previously been found during inner speech and verbalization (McGuire et al., 1996a, b; Shergill et al., 2002; Morin and Michaud, 2007), our findings could be interpreted as being in line with the notion that intrusive thoughts are represented in a language format. The present data are silent as to whether this association holds true for intrusive thoughts only, or applies to thoughts in general as proposed by certain streams of philosophy (Wittgenstein 1953; Davidson 1975; McDowell 1994). Also, it is difficult to tease apart whether individuals reporting a stronger tendency for daily intrusive thoughts suppress left IFG activity more strongly during task performance or whether they have a more active left IFG during fixation intervals. The latter is, however, more plausible considering the absence of an association between individual differences in intrusive thoughts and performance. That is, if activity during task performance was affected by intrusive thoughts, then we would expect this to show up in worse performance. We therefore take our results to suggest that individuals reporting a stronger habitual tendency for intrusive thoughts may have stronger and more continuously active inner speech processes in the absence of external task demands. The association between the tendency for intrusive thoughts and activity in the CC further supports this interpretation. Activity in the vicinity of the present CC region has been associated with conflict resolution during cognitive tasks (Van Veen et al., 2001; Botvinick et al., 2004), and it seems unlikely that individuals reporting a higher tendency for intrusive thoughts should display lower CC activity during task performance. It is more likely that the observed association with CC activation signals increased conflict detection and cognitive control demands during fixation periods aimed towards bringing attention back to the experimental task, or possibly detection of conflict within the content of intrusive thoughts itself.

This interpretation of our findings is also in line with a recent study reporting that self-reports of mind wandering during a Go/NoGo task were associated with CC and left IFG activity, as well with several regions typically associated with resting state (Christoff et al., 2008). The authors suggested that the activation in the executive network (e.g. CC and left IFG) may explain why mind wandering can undermine task performance because it may interfere with the processes in brain regions needed for task performance (Smallwood et al., 2004; Smallwood and Schooler 2004, 2006). Our findings are however different than those reported in previous neuroimaging studies on inter-individual differences in daydreaming (Mason et al., 2007,
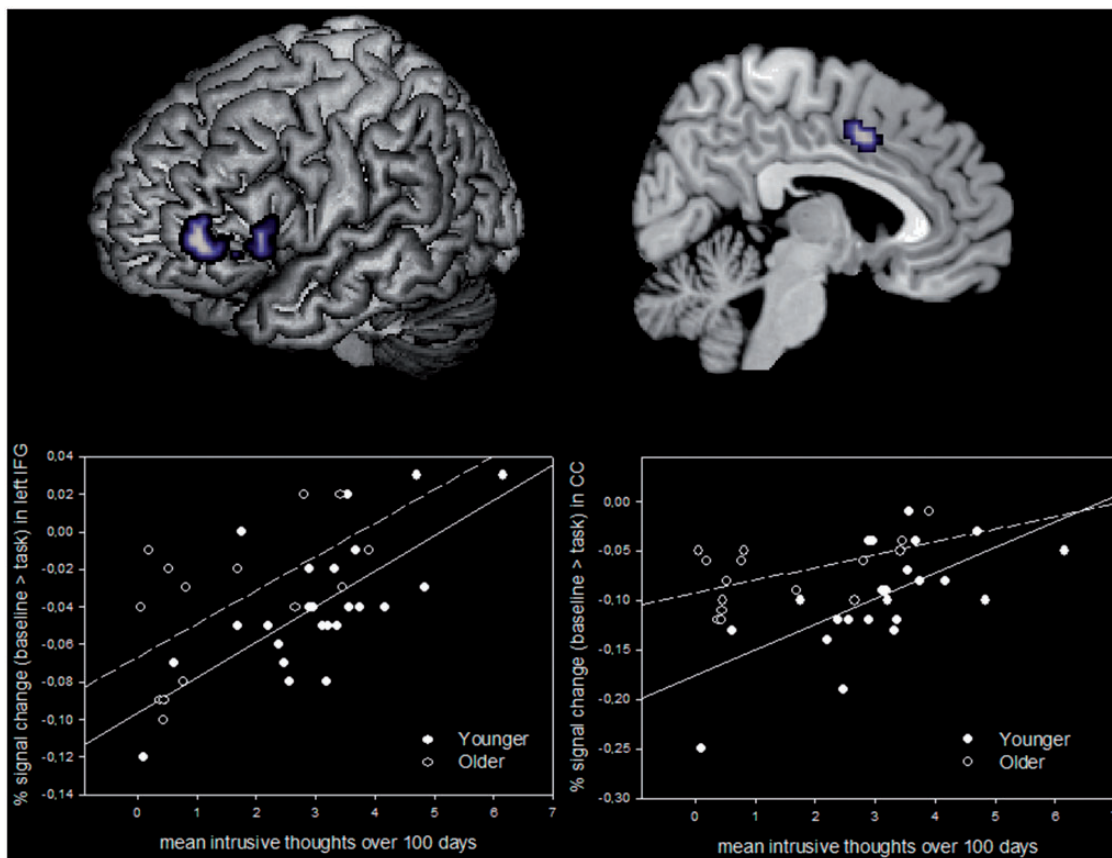
Fig. 2 Activation map averaged over 39 subjects ($P < 0.001$, cluster corrected, $k > 38$) mapped onto a template T1 image (colin27). Brain activity during baseline > task (percent signal change averaged over pre- and post-training session and over numerical and verbal task) correlated positively with the intrusive thoughts over 100 days. Left IFG and CC were defined based on a whole brain correlation between intrusive thoughts over 100 days and brain activity during baseline > task. Note that the regression lines are plotted separately for old and young participants.
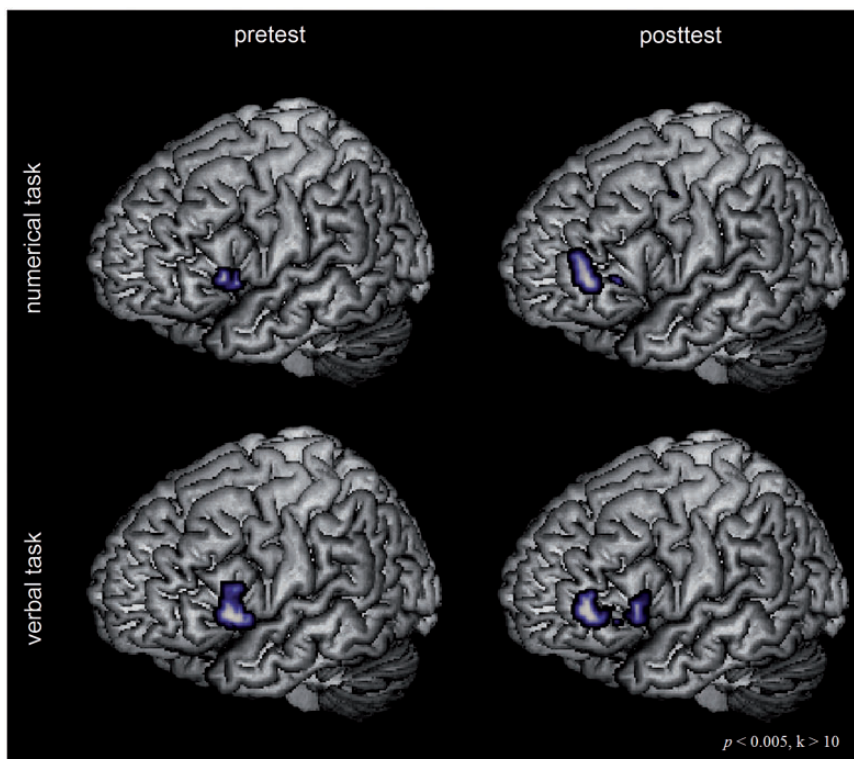

Fig. 3 Activation map averaged over 39 subjects ($P < 0.005$, $k > 10$) mapped onto a template T1 image (colin27). Brain activity during baseline > task correlated positively with the intrusive thoughts over 100 days separately for task (numerical or verbal) and time point (pre- or post-test).
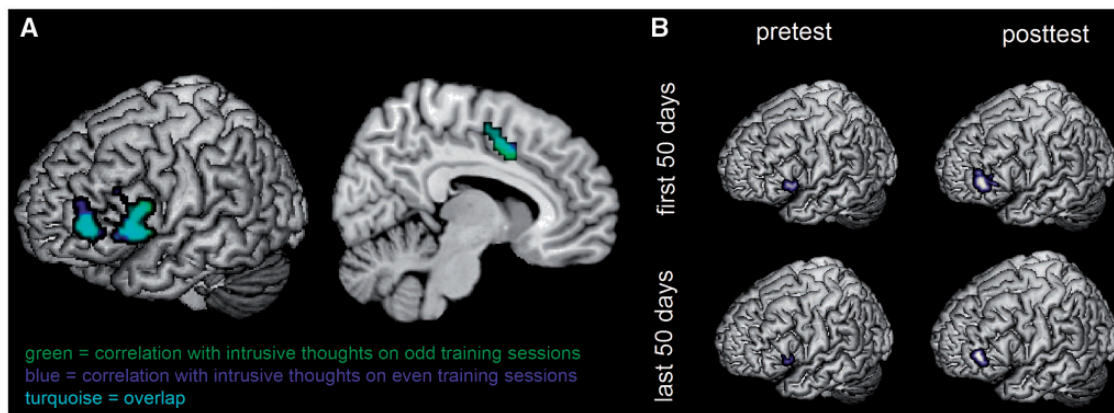
Fig. 4 (**A**) Activation map averaged over 39 subjects (*P* < 0.001, cluster corrected, *k* > 38) mapped onto a template T1 image (colin27). Brain activity during baseline > task correlated with the intrusive thoughts over 100 days comparing ratings on odd *vs* even training sessions. (**B**) Activation map averaged over 39 subjects (*P* < 0.001, *k* >10). Brain activity correlated positively with the intrusive thoughts over last and first 50 training sessions separately for time point (pre- and post-test).

2008; Wang *et al.*, 2009). This may suggest that intrusive thoughts as measured in the present study are different, and of a more verbal nature, than daydreaming. One might see a limitation of the present study in the possibility of a low occurrence rate of intrusive thoughts, since we did not explicitly attempt to evoke intrusive thoughts and tested healthy subjects. However, we conceptualized intrusiveness of thoughts as a dimensional rather than a categorical concept, by utilizing a self-report method with which we assessed intrusive thoughts on an 8-point scale.

To explore the state or trait characteristic of intrusive thoughts, we correlated the average reported intrusive thoughts during the first half and the last half of the sessions with the proximal and distal scanning session. We found a correlation within left IFG between pre-test as well as post-test brain activity and the first as well as the last fifty reports. Based on these findings, we conclude that the association between the habitual tendency for intrusive thoughts and activation in left IFG is rather stable over time. The present results contribute to our neural and psychological understanding of individual differences in the resting periods of typical fMRI experiments (Raichle *et al.*, 2001). Individuals who habitually experience intrusive thoughts may show signs of inner speech during these periods of rest. Further research is needed to explore the trait or state characteristics of intrusive thoughts.

To conclude, our findings may suggest that intrusive thoughts are represented in a language-like format and that individuals reporting a habitual tendency for intrusive thoughts may have stronger and more habitual inner speech processes. An alternative explanation could be that intrusive thoughts are represented in a non-verbal format, but that individuals have a verbal representation of a meta-cognitive acknowledgement of these intrusive thoughts. Future research should use experience sampling during task performance to allow within-subject comparisons of the occurrence of intrusive and other types of non-intrusive thoughts and to gain insights into the specific state-like content of individuals' intrusive thoughts and its relation to brain activity.

Conflict of Interest

None declared.

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