Frontal Midline Theta Reveals Temporal Dynamics of Target Amplification and Distracter Inhibition During Mental Set-Shifting

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Abstract

When humans shift between tasks, they initially show slower responses in the new task than in the previous one. Persisting attentional settings are increasingly recognized as a source for these shifting costs. However, the extent to which specific mechanisms underlying information selection and interference control contribute to this phenomenon remains less clear. Here, we use time-frequency analyses of human electroencephalogram (EEG) data to explore the aftereffects of two such mechanisms: target amplification and distracter inhibition. Participants completed a set-shifting task in which interference during switch trials could either result from the persisting amplification of previous target colors or the persisting inhibition of previous distracter colors. In a first set of analyses, we focused on frontal midline theta (FMT) as a time-continuous marker of overall interference. Compared to a control condition, we found transient peaks of FMT in both experimental conditions that matched the effects of persisting target amplification and distracter inhibition predicted by a computational model of the task. In a second set of analyses we used steady-state visually evoked potentials (SSVEPs) as a direct measure of the attentional resources allocated to target and distracter colors. However, SSVEP amplitudes did not differ reliably between stimulation frequencies during switch trials, preventing us from drawing further conclusions on the origins of the interference processes reflected in FMT dynamics. Implications for theories of selective attention and potential limitations of frequency tagging in the context of mental set-shifting research are discussed.

Keywords: frontal midline theta; attentional inertia; frequency tagging; set-shifting;

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The world that we live in is inherently volatile. Therefore, adaptive behavior requires the capability to quickly disengage from an ongoing task and reorient perception and action selection towards an alternative goal. This ability is commonly referred to as mental set-shifting and it is considered one of the building blocks of cognitive control and executive functions (Diamond, 2013; Goschke & Bolte, 2014; Miyake et al., 2000). Shifting comes at a cost, however: Responses are slower and often less accurate when tasks change as compared to when they remain constant (see e.g. Kiesel et al., 2010; Monsell, 2017; Vandierendonck, Liefoghe, & Verbruggen, 2010 for overviews). A growing body of evidence links these shifting costs to the persisting impact of previous attentional parameters on current information processing (e.g. Awh, Belopolsky, & Theeuwes, 2012; Elchlepp, Best, Lavric, & Monsell, 2017; Hutchinson & Turk-Browne, 2012). In the work presented here, we aim to elucidate the mechanisms underlying such attentional inertia by investigating the temporal dynamics of two sub-processes of attentional selection: the amplification of task-relevant and the inhibition of task-irrelevant information. To this end, we apply time-frequency analyses to human electroencephalogram (EEG) data and explore how persisting target amplification and distracter suppression impact the recalibration of action selection and attention.

In the following, we will first review the literature on attentional inertia as a source for switch costs and outline the debate on the contribution of persisting amplificatory and inhibitory attentional biases to this phenomenon. Then, we will demonstrate how a dynamic approach can provide new insights into this issue by making specific predictions how persisting target amplification and distracter inhibition manifest in the continuous evolution of cognitive conflict

and attentional selection in a set-shifting paradigm (Dreisbach & Goschke, 2004; Frisch, Dshemuchadse, Görner, Goschke, & Scherbaum, 2015; Owen, Roberts, Hodges, & Robbins, 1993). Finally, we will discuss how these hypotheses can be tested by means of two time-frequency measures of cognitive control and attention allocation in the electroencephalogram (EEG): frontal midline theta (FMT, see Cavanagh & Frank, 2014; Cavanagh & Shackman, 2015 for recent overviews) and steady-state visually evoked potentials (SSVEPs, e.g. Müller et al., 2006; Scherbaum, Fischer, Dshemuchadse, & Goschke, 2011).

Attentional Inertia as a Source for Shifting Costs

Every goal and task we pursue affords an appropriate set of cognitive parameters, processes, and resources to be fulfilled successfully. Adapting these parameters to a new goal or task is associated with substantial performance costs and many studies have been conducted with the aim to understand why these costs arise (Kiesel et al., 2010; Monsell, 2017; Vandierendonck et al., 2010). Apart from a time-consuming reconfiguration process that is deemed necessary to activate or implement new task parameters (e.g. Logan & Gordon, 2001; Meiran, Chorev, & Sapir, 2000; Rogers & Monsell, 1995), *task-set inertia* has been identified as a major contributor to shifting costs. Task-set inertia describes the transient persistence of task-set components from trial to trial (e.g. Allport, Styles, & Hsieh, 1994; Gilbert & Shallice, 2002; Goschke, 2000; Yeung & Monsell, 2003). Essentially, this means that task parameters are not reset or “switched off” instantaneously when becoming obsolete. Instead, they linger in the cognitive system, continuing to affect information processing and performance. While such lingering task-set activation is beneficial when task demands repeat, it can interfere with information processing when task demands change from trial to trial.

Theoretical accounts of task-set regulation hold that the updating of a task-set comprises multiple elements including the re-orientation of attention towards different task-relevant stimulus features, the recall and implementation of new stimulus-response mappings from memory, the preparation of different effectors for responding, or the adjustment of response thresholds for the decision process (e.g. Goschke, 2000; Logan & Gordon, 2001; Monsell, 2017). While each of these elements could contribute to the costs of shifting mental sets, research in the field focused primarily on interference at the level of response selection as the primary source for costs during mental set-switching (e.g. Allport et al., 1994; Mayr & Kliegl, 2000; Waszak, Hommel, & Allport, 2003; Wylie & Allport, 2000; Yeung & Monsell, 2003). A task-set component that has been subject to less scientific inquiry is attentional selection (Elchlepp, Lavric, & Monsell, 2015; Longman, Lavric, & Monsell, 2013). Even though computational accounts of task-set control (Altmann & Gray, 2008; Logan & Gordon, 2001; Meiran et al., 2000) attribute the re-orientation of attention towards new sources of information a central role in causing shifting costs, the contribution of lingering attentional processes has been acknowledged only recently in empirical investigations of the matter (see e.g. Longman et al., 2013).

Persisting Amplification and Inhibition as Sources for Shifting Costs

A common perspective on selective attention is that it is best described as a top-down bias that increases the impact of task-relevant relative to task-irrelevant information on information processing (e.g. Gazzaley & Nobre, 2012; Miller, 2000; Wolfe, 1994; Wolfe, Cave, & Franzel, 1989). On a process-level, the resulting distinction between target and distracter information can be achieved in two ways: First, by increasing the level of activation of target information or, second, by decreasing the level of activation of distracting information.

Accordingly, some authors have argued for a major role of the amplification of task-relevant information for attentional selection (e.g. J. D. Cohen, Dunbar, & McClelland, 1990; Pashler, 1998; Wolfe, 1994; Wolfe et al., 1989) whereas others have stressed that selective attention must incorporate additional inhibitory processes that actively suppress distracting stimuli to render attentional selection sufficiently stable (Allport et al., 1994; Houghton & Tipper, 1994; Treisman & Sato, 1990; see Noonan, Crittenden, Jensen, & Stokes, 2017, for a recent overview).

There is suggestive evidence that both amplificatory and inhibitory sub-processes of selective attention may contribute to the costs of shifting mental sets. On the one hand, several findings support the idea of an amplificatory attentional mechanism that persists in time: Performance has been shown to suffer when changes in task demands afford to abruptly ignore previously task-relevant stimulus features. Despite being instructed otherwise, participants' responses continue to be biased towards previously attended colors (Dreisbach & Goschke, 2004; Frisch et al., 2015; Kikumoto, Hubbard, & Mayr, 2016; Lamy, Antebi, Aviani, & Carmel, 2008), orientations and shapes (Kikumoto et al., 2016), and locations (Longman et al., 2013; Longman, Lavric, & Monsell, 2016; Longman, Lavric, Munteanu, & Monsell, 2014). On the other hand, a substantial body of evidence supports an inhibitory mechanism of attentional control. Especially research on negative priming has shown numerous times that attending to information that has been previously ignored incurs a cost (see D'Angelo, Thomson, Tipper, & Milliken, 2016; Frings, Schneider, & Fox, 2015 for recent overviews). While this has traditionally been interpreted in terms of an inhibitory attentional mechanism that hampers with the reallocation of attention (Houghton & Tipper, 1994), a number of alternative, non-inhibitory explanations for the negative priming effect have been introduced (e.g. MacDonald, Joordens, & Seergobin, 1999; Milliken, Joordens, Merikle, & Seiffert, 1998; Neill & Valdes, 1992), causing

some authors to reject the idea of selective distracter inhibition (e.g. MacLeod, Dodd, Sheard, Wilson, & Bibi, 2003).

Recently, however, the debate on selective distracter inhibition has been rekindled by several studies providing compelling evidence that task-irrelevant information is actively suppressed online, that is, while it is present in a stimulus display (Frings, Wentura, & Wühr, 2012; Frings & Wühr, 2014; Scherbaum et al., 2011; Wühr & Frings, 2008). For example, Wühr & Frings (2008) had participants name the color of one of two overlapping shapes while congruent or incongruent color words were presented either inside the target shape, inside the distracter shape, or in the background. The authors found that the Stroop-effect induced by incongruent color words was significantly smaller when the color words appeared inside the distracter shape than when they appeared inside the target shape or in the background (Wühr & Frings, 2008). This suggests that distracter shapes (and stimuli presented in their vicinity) are suppressed below baseline during information processing. What is less clear, however, is whether such an inhibitory attentional bias also persists in time, thus, contributing to the costs of shifting mental sets.

Taken together, there is initial evidence that aftereffects of attentional selection may contribute to the costs of shifting mental sets. While there is little doubt that amplificatory attentional biases persist in time and affect information processing, it is less clear to what extent inhibitory mechanisms of attentional selection continue to impact performance after becoming obsolete.

A Dynamic Perspective

In the present study, we explore the after-effects of persisting amplificatory and inhibitory attentional sub-processes to the costs of mental set-shifting from a dynamic

perspective (see Frisch et al., 2015; Scherbaum, Dshemuchadse, & Kalis, 2008; Spivey & Dale, 2004). At the heart of this approach lies the idea that a deeper understanding of cognition can be reached by tracing how the underlying processes unfold over time. For example, in a recent study, Frisch et al. (2015) traced the process dynamics of attentional selection in an established set-shifting paradigm that taps both amplificatory and inhibitory mechanism of selective attention (Dreisbach & Goschke, 2004; Owen et al., 1993). In each trial of this paradigm, participants are presented with two digits. Their task is to judge the magnitude of the digit appearing in a previously cued target color (e.g. red) while ignoring the digit appearing in a different, uncued distracter color (e.g. green). After several repeat trials in which target and distracter colors remain constant (e.g. always attend to red and ignore green), colors switch. In the *Perseveration* (PS) condition, the target appears in a new color that was not part of the previous display (e.g. blue) while the distracter appears in the previous target color (e.g. red). Behavior in this condition thus reflects the persisting amplificatory aftereffects of attending to a specific source of information. In the *Learned Irrelevance* (LI) condition, the target appears in the previous distracter color (e.g. green) while the distracter appears in a new color (e.g. blue). Behavior in this condition thus reflects the persisting inhibitory aftereffects of ignoring a specific source of information. To trace the unfolding of amplificatory and inhibitory processes over time, Frisch et al. (2015) measured participants' mouse movements (see Scherbaum, Dshemuchadse, Fischer, & Goschke, 2010; Spivey, Grosjean, Knoblich, & McClelland, 2005) as a continuous marker of response tendencies and compared them to the predictions of a Dynamic Neural Field model (Lins & Schöner, 2014; Sandamirskaya, Zibner, Schneegans, & Schöner, 2013; Schöner, 2008) for the same task. Simulations with this model indicated distinct patterns

of continuous performance for a model version that was based solely on amplification in contrast to a model that incorporated both, amplification and selective distracter inhibition.

The mouse trajectories showed the predicted pattern of persisting amplification in the PS condition but not the pattern of persisting inhibition in the LI condition. This was interpreted as evidence that persisting target amplification but not persisting distracter inhibition contributed to the costs of shifting mental sets in our paradigm (Frisch et al., 2015). However, these interpretations are limited since mouse-tracking only measures interference at the level of motor activation. Since inhibitory processes are often understood as a weaker supplement to more powerful excitatory mechanism of attentional selection, the relatively crude, motor-based approach might have missed the traces of this process. While it is plausible to assume that a misallocation of attention also causes interference at the level of response selection, this is an assumption that should be tested more directly.

The Present Study

In the present study, we addressed this issue by inspecting two time-frequency measures extracted from human electroencephalogram (EEG) data in our set-shifting paradigm. The investigation is divided into two sections. In a first, confirmatory section, we will re-examine the presumed effects of persisting target amplification and distracter inhibition predicted by our DNF model (Frisch et al., 2015) with frontal midline theta power (FMT) as the main dependent variable. FMT is a neural oscillatory pattern in human EEG that is recorded above medial prefrontal cortex in a range of 4 to 7 Hz which is increasingly recognized as a neurophysiological correlate of cognitive interference (Cavanagh & Frank, 2014; Cavanagh & Shackman, 2015; Cavanagh, Zambrano-Vazquez, & Allen, 2012; Nigbur, Cohen, Ridderinkhof, & Stürmer, 2011; Nigbur, Ivanova, & Stürmer, 2011; Pastötter, Dreisbach, & Bäuml, 2013). FMT originates from

midcingulate cortex (Nigbur, Ivanova, et al., 2011; Pastötter et al., 2013), a neural structure that serves as an important hub within a larger cognitive control network (Cavanagh et al., 2012; Shackman et al., 2011), and has been shown to scale with current control demands. In particular, a growing number of studies have linked phasic increases in FMT to increased levels of cognitive interference, both at the level of stimulus and response selection (Nigbur, Cohen, et al., 2011). For example, FMT has been shown to increase when habitual responses are inhibited in Go-/NoGo tasks (e.g. Funderud et al., 2012; Kamarajan et al., 2004) or when multivalent stimuli elicit conflicting responses in Stroop (e.g. Hanslmayr et al., 2007), or Flanker-tasks (M. X. Cohen & Cavanagh, 2011; Nigbur, Cohen, et al., 2011; Nigbur, Ivanova, et al., 2011). Since FMT can be traced continuously over time, it is an alternative, time-continuous marker of the occurrence and resolution of cognitive conflict that may be better-suited than mouse-movements to verify the effects of persisting target amplification and, more importantly, distracter inhibition predicted by our model. If amplificatory attentional biases persist in time and interfere with mental set-shifting, we would expect a phasic increase in FMT in switch trials of the PS condition of our set-shifting paradigm. Inversely, if inhibitory attentional biases persist in time and interfere with mental set-shifting, we would expect this to result in a phasic increase in FMT in switch trials of the LI condition. Crucially, these phasic increases in FMT resulting from interference due to persisting attentional biases should occur in addition to increases that likely occur in connection with mental set-shifting in general (e.g. Cooper, Wong, McKewen, Michie, & Karayanidis, 2017). To account for these effects, we used an additional control condition in the set-shifting paradigm utilized by Frisch et al. (2015). In switch trials of the *Target Switch* (TS) condition, the target color changed to a color that had not been part of the stimulus display before while the distracter color remained the same. Switches in the TS condition hence

represent the arguably most simple case of mental set-shifting that only affords activating a new target representation without running the risk of interference caused by persisting attentional biases. Accordingly, the specific patterns of interference predicted for the PS and LI conditions should occur relative to the overall pattern of FMT-change observed in the TS control condition.

In a second, more exploratory section, we aim to go beyond FMT as a marker of cognitive interference and measure the re-allocation of attention directly via frequency tagging (see Norcia, Appelbaum, Ales, Cottureau, & Rossion, 2015 for a recent review of the method). Frequency tagging allows measuring the attentional resources deployed to target and distracter stimuli by tagging them with different flicker frequencies, for example, by surrounding them with circles flickering at different frequencies (e.g. Scherbaum et al., 2011). The flicker induces steady-state, visually evoked potentials (SSVEPs) in primary visual cortex (Andersen & Müller, 2010; Müller et al., 2006) which oscillate at the same frequency as the driving stimulus. As SSVEP amplitudes increase with attention (Andersen, Hillyard, & Müller, 2008; Müller et al., 2006; Müller, Teder-Sälejärvi, & Hillyard, 1998; Scherbaum et al., 2011; Toffanin, de Jong, Johnson, & Martens, 2009), changes in power for the different tagging frequencies reflect the redistribution of attention in real-time. By employing different tagging frequencies, we can hence extract the time-course of attentional deployment towards target and distracter frequencies simultaneously.

Based on this rationale, we would expect the time-courses of SSVEP amplitudes to reflect the amplificatory and inhibitory aftereffects of attentional selection (see *Figure 1* for a schematic representation of our hypotheses). More specifically, during switches in the PS condition, we would expect task-irrelevant information (which was attended to before the switch) to have higher levels of activation than task-relevant information (which was not part of

the previous stimulus display). This would indicate cognitive interference at the beginning of PS switches that is primarily driven by the persisting aftereffects of amplificatory sub-processes of attention. Over the course of the trial, this interference must be resolved for subjects to give a correct response by a decrease of the activation of task-irrelevant information and an increase of activity of task-relevant information. In contrast, at the beginning of switch trials in the LI condition, we would expect task-relevant information (which was ignored before the switch) to have lower levels of activation than task-irrelevant information (which was not part of the previous stimulus display). This would indicate cognitive interference at the beginning of LI switches that results from a persisting inhibitory sub-process of attention. Over the course of the trial, this interference should be resolved by a decrease of activation of task-relevant information and a decrease of activation of task-irrelevant information. Finally, in switch trials of the TS condition, we would expect task-relevant information (which was not part of the previous stimulus display) to have higher levels of activation than task-irrelevant information (which was already ignored prior to the switch). This contrast between task-relevant and irrelevant information should increase further over the course of the trial.

Figure 1. Hypotheses for frequency tagging.

Methods

Participants

34 students of Technische Universität Dresden (68 % female, $M_{\text{Age}} = 23.18$ years, $SD_{\text{Age}} = 2.88$ years) took part in the experiment. All participants had normal or corrected-to-normal vision and were screened for color-blindness and epilepsy. Datasets of 2 participants had to be discarded due to technical problems during data acquisition. The final sample size of $N = 32$ allowed us to detect a medium-sized effect ($\eta_p^2 \geq 0.3$) with a power of 0.97 (Faul, Erdfelder, Lang, & Buchner, 2007). Participants gave informed consent in line with the Declaration of Helsinki and received course credits or 5€ per hour of participation. The experiment was approved by the ethics committee of Technische Universität Dresden (application number EK 485112015).

Apparatus and Stimuli

Participants were placed in a dark and electrically shielded EEG recording cabin, their heads resting on a chin rest in front of a 17-inch CRT screen running at a resolution of 1024 x 768 pixels. The experiment was controlled by Psychophysics Toolbox 3 (Brainard, 1997; Pelli, 1997) in MATLAB 2010 (The Mathworks, Inc.) running on a Windows XP SP2 personal computer.

The German words for red, green, and blue served as cues and were presented in white ink on a black background in the centre of the screen. The digits 1, 2, 3, 4, 6, 7, 8, and 9 served as target and distracter stimuli. They were presented in red, green, or blue ink 0.8° above and below the cue and had a width of 0.6° at a seating distance of 1.5 m. Upper and lower stimulus locations were underlaid with white circles with a diameter of 0.7° which flickered with a frequency of 9 or 12 Hz to induce SSVEPs (Scherbaum et al., 2011).

Procedure

Each trial started with the presentation of a fixation cross at the centre of the screen. After a random inter-trial-interval (ITI) of 600, 800, or 1000 ms, the fixation cross was replaced by the cue, indicating the target color for the upcoming trial. Target and distracter digits appeared 50 ms after cue onset. Participants were asked to respond to the magnitude of the target digit by pressing a left ('x') vs. right key ('.', ',') on a German standard computer key board when the digit was smaller vs. larger than five, respectively. Cue, target and distracter digits remained on screen until the participant gave a response or until a response deadline (1500 ms after stimulus presentation) expired. Instructions at the beginning of the experiment stressed both speed and accuracy of performance and included 45 practice trials.

Trials were grouped into runs of trials consisting of a random number of 6 to 8 trials each. Every run began with one switch trial in which target and distracter colors changed which was followed by a random number of 5 to 7 repeat trials in which target and distracter colors remained constant (e.g. always respond to the red digit and ignore green digit). Over the course of five blocks, each participant completed 240 runs of trials.

SSVEPs were elicited by white circles surrounding target and distracter locations that flickered at 9 (Scherbaum et al., 2011; Toffanin et al., 2009). Flickering was elicited by coupling the “on” vs. “off” state of each circle to cosine waves with the respective frequencies with each circle being “on” and “off” for half of the cycle of its wave. In contrast to other SSVEP studies which reset the flickering process at the beginning of each trial (e.g. Scherbaum et al., 2011), circles flickered uninterruptedly throughout each block of our experiment. This way, circles not only flickered continuously throughout the three phases of single trials (i.e. inter-trial-interval, cue presentation, and stimulus presentation) but also across trials. Doing so, we tried to

accomplish two things. First, we wanted to pare down the initial flicker phase previous studies incorporated to re-accommodate SSVEP amplitudes to the flickering stimuli after they break between two trials (e.g. Scherbaum et al., 2011). And second, we hoped to capture the reallocation of attention both within and across trial borders – the latter of which being of particular interest in shifting paradigms like the one we used. **Design**

The experiment contained two experimental factors that were varied within-person. The first experimental factor *Repetition* varied whether the task-relevant and task-irrelevant colors in a given trial remained constant (repeat trial, e.g. always attend to the red digit and ignore the green digit) or changed (switch trial) relative to the target and distracter colors in the previous trial. Accordingly, each run of trials contained one switch trial (in which target and/or distracter colors changed) and a variable number of repeat trials (in which target and distracter colors remained the same). To keep the number of switch and repeat trials equivalent, only the trials immediately preceding the next switch trial were included in the analyses. Because these “pre-switch trials” are the last trials of each run, they represent the cognitive system’s maximum level of adaptation to the attentional settings specified during the switch trial at the start of the run. The second experimental factor *Switch Type* then varied precisely how target and distracter colors changed at the beginning of a run. It had three levels: In switches in the perseveration (PS) condition, the target appeared in a new color (e.g. blue) while the distracter appeared in the previous target color (e.g. red). Hence, PS switches afforded participants to ignore a source of information that had been task-relevant shortly before. In contrast, in switch trials in the learned irrelevance (LI) condition, the target appeared in the previous distracter color (e.g. green) while the distracter appeared in a new color (e.g. blue). Hence, switches in the LI condition afforded participants to attend to a source of information that had been task-irrelevant before. Finally, in

switch trials of the target switch (TS) condition, the target appeared in a new color (e.g. blue) while the distracter color remained constant (e.g. green). Hence, switches in the TS condition afforded participants to respond to a new source of information without having to ignore a previously task-relevant source of information or attending a previously task-irrelevant source of information. As this arguably represents the simplest type of goal switching, the TS condition served as a baseline for the other two levels of the factor *Switch Type*. To complete the factorial design, repeat trials following a PS-, LI, or TS-switch were classified as PS-, LI-, and TS-repeat trials, accordingly. Because only the last repeat trial of each run (i.e. the pre-switch trial) was included in the analyses (see above), differences in performance in repeat trials would indicate that the effects of the three *Switch Types* persisted through the entire run of trials. The order of switch types was randomized across participants.

In summary, our experimental design followed a 2 (*Repetition*: repeat vs. switch trials) x 3 (*Switch Type*: PS vs. LI vs. TS) design. Additionally, the design was balanced regarding repetitions (vs. switches) of the location of the target stimulus (upper vs. lower location) as well as regarding repetitions (vs. switches) of the demanded response (left hand response vs. right hand response) before vs. after the switch. Moreover, we varied whether target and distracter stimuli afforded the same (congruent) vs. different (incongruent) responses. Trials immediately preceding a switch (pre-switch trials) were always incongruent because incompatible response options are known to increase goal activation (e.g. Goschke, 2000) which should maximize the persisting effects of previous goals on behavior in switch trials. Switch trials were held incongruent as well because assigning target and distracter information to opposing (instead of the same) response options ensures that conflict at the level of information selection also manifests in conflict at the level of response selection and thus in performance. For all remaining

trials, response compatibility was balanced such that congruent and incongruent trials were equally likely. Finally, the tagging of upper vs. lower stimulus locations (i.e. above vs. below the cue) with 9 Hz vs. 12 Hz flicker frequencies remained constant within a given block, it was reversed between blocks (i.e. from 9 Hz above 12 Hz to 12 Hz above 9 Hz and vice versa). The assignment of frequency to location in the first experimental block was balanced between participants.

Overall, subjects completed 80 trials for each cell of the *Repetition x Switch Type* design matrix. On average, participants completed 67.06 trials per cell ($SD = 6.38$) correctly.

Preprocessing and Analyses of Behavioral Data

Behavioral analyses focused on trials immediately preceding (repeat trials) and following a task switch (switch trials). For ease of interpretation, response time and error data were integrated into a single index of performance by calculating the inverse efficiency score RT^* (Townsend & Ashby, 1983; cf. Hughes, Linck, Bowles, Koeth, & Bunting, 2014; Vandierendonck, 2016) as the quotient of response times and accuracy for each participant and each cell of the design matrix (Frisch et al., 2015, but see the supplemental material for parallel analyses of response time and error data). Trials with missed response deadlines or response times with z-values larger than 2.5 were excluded from behavioral analyses. Behavioral data were analysed using Matlab, R2010b (the Mathworks, Inc., 2010) and IBM SPSS Statistics for Windows, Version 23 (IBM Corp., 2015).

Recording and Preprocessing of EEG Data

EEG data was recorded with a modified 10-20 setup consisting of 61 Ag/AgCl electrodes mounted in an elastic electrode cap. To monitor for eye blinks and vertical eye movements, vertical electrooculograms were recorded below the right and left eye. During recording, all

electrodes were referenced to the left mastoid. Impedances were kept under 5 $k\Omega$ and electrical activity was recorded with a sampling rate of 500 Hz across all electrodes.

Preprocessing and analyses of EEG data were conducted using EEGLab (Delorme & Makeig, 2004) and custom-written code in Matlab 2015a (The Mathworks). After recording, data were bandpass-filtered (1 Hz to 70 Hz using a Hamming windowed FIR filter) as well as Notch-filtered (50 Hz) to remove line noise. Data was then down-sampled to 125 Hz and re-referenced to linked mastoids. To include as much valid information as possible from all participants in the subsequent analyses, data was then epoched to time periods of -500 ms to 1368 ms relative to stimulus onset with the upper limit of this interval representing the smallest maximum response time across all participants. Epoches data was baseline-normalized with the period of -400 ms to -100 ms relative to stimulus onset serving as baseline-window. To minimize the loss of trials due to non-brain electrical activity, muscle artefacts, eye blink artefacts, and eye movement artefacts were removed by independent component analysis (Delorme, Sejnowski, & Makeig, 2007; Jung et al., 2000) and independent component clustering (Scherbaum, 2006). Trials in which participants responded incorrectly, exceeded the response deadline or produced a response time considered an outlier ($z_{RT} > 2.5$) were excluded from EEG analyses ($M = 16.07\%$, $SD = 6.26\%$). Analogous to the analyses of behavioral data, EEG analyses focused on trials immediately preceding (repeat trials) and following a switch (switch trials).

Extraction of frontal midline theta (FMT) and SSVEPs

All time-frequency calculations were computed using custom-written routines in Matlab (M. X. Cohen, 2014). As FMT is known to be maximal over fronto-central electrode sites (e.g. Hsieh & Ranganath, 2014), power in the theta range (4 – 7 Hz) was extracted at electrode Fz by means of wavelet analyses using complex Morlet's wavelets (see Scherbaum et al., 2011 for a

detailed description of the wavelets used). To compensate for trial-to-trial fluctuations in overall power levels, raw power signals were converted to the percentage of signal change relative to baseline. To this end, the mean power in a range between 400 ms and 100 ms before stimulus onset was subtracted from each data point during stimulus presentation and divided by the standard deviation of power in the same time window and normalized to 100 equal time slices (Scherbaum et al., 2010).

Extraction of SSVEPs

Extraction of SSVEPs followed similar steps as the extraction of FMT. However, the electrodes that were included in the analyses were chosen via a “best electrode” approach as it is often used in the field to improve the signal-to-noise-ratio of the data (e.g. Fuchs, Andersen, Gruber, & Müller, 2008; Scherbaum et al., 2011). The identification of best electrodes followed the following rationale. The purpose of our SSVEP analyses was to explore the reallocation of attentional resources during a goal shifting. This reallocation is most readily observable when target and distracter information is clearly separated prior to a goal shift. The trial type in which this separation should be most pronounced is a response incongruent repeat trial in which the target stimulus appears at the same location as in the previous trial. In this condition, responding correctly affords to separate target from distracter information but it does not require a re-allocation of feature- or location-based attention. Thus, attentional resources should be optimally distributed over the entire course of such trials. We identified the electrodes for our SSVEP analyses by exploiting this optimal distribution of attention. In particular, we identified those electrodes at which the mean difference between the raw SSVEP stream representing attention towards the target stimulus and the raw SSVEP stream representing attention towards the distracter stimulus during these trials was maximal for both frequencies used. Electrode selection

relied on raw power signals because performing a baseline normalization prior to this step would have run the risk of eliminating the desired contrast between target and distracter activation by subtraction. To prevent results being unduly biased by outliers in electrode selection, we also identified the neighboring electrode with the second-largest contrast between target and distracter streams during the said set of trials (Scherbaum et al., 2011). Instantaneous energy for 9 and 12 Hz was extracted at both electrode sites with the procedure described above, averaged within and across their frequency bands, and time-normalized to 100 equal time slices.

Results

Behavioral Data

A two-factorial repeated measures analysis of variance (RM-ANOVA) with *Repetition* (repeat vs. switch trials) and *Switch Type* (PS vs. LI vs. TS) as independent variables and RT* as dependent variable yielded a significant main effect of *Repetition*, $F(1, 31) = 100.79, p < .001$, $\eta_p^2 = 0.77$, and *Switch Type*, $F(2, 62) = 85.85, p < .001$, $\eta_p^2 = 0.74$, as well as a significant interaction of the two, $F(2, 62) = 74.83, p < .001$, $\eta_p^2 = 0.71$. The latter indicated that goal switches resulted in significant switching costs the size of which varied between the different levels of the *Switch Type* manipulation (see Figure 2). To follow up on this effect, we conducted separate RM-ANOVAs for each level of the factor *Repetition*. For repeat trials, this analysis yielded a non-significant main effect of *Switch Type*, $F(2, 62) = 0.38, p > .60$, $\eta_p^2 = 0.01$, suggesting that performance during repeat trials did not differ between the different *Switch Type* conditions. In contrast, a parallel analysis of switch trials yielded a significant main effect of *Switch Type*, $F(1.17, 36.18) = 90.14, p < .001$, $\eta_p^2 = 0.74$, indicating that performance varied with the control demands posed in a given condition. Bonferroni-corrected pairwise comparisons showed that ignoring previously relevant information in the PS condition was accompanied by significantly worse performance than attending to previously ignored information in the LI condition (PS vs. LI: $p < .001$) or attending to new information in the TS condition (PS vs. TS: $p < .001$) during a goal switch. In contrast, whether the to-be-attended target information had been ignored beforehand or not did not have a significant impact on behavioral performance (TS vs. LI: $p = .08$).

Figure 2. *Inverse efficiency score* RT* during repeat and switch trials for the three different *Switch Types*. Error bars represent standard errors.

Theta Power

In line with a large body of literature (Cavanagh & Frank, 2014; Cavanagh et al., 2012), theta power was maximal at fronto-central electrodes, particularly at electrode Fz (*Figure 3A*). Therefore, all subsequent analyses focused on theta at this site.

As expected, frontal midline theta power (FMT) was affected by attentional set-shifting. As can be seen in *Figure 3B*, the spectral composition of electro-cortical activity during switch and repeat trials differed markedly. Overall, switch trials were characterized by a stronger increase in power in the theta band than repeat trials and this difference started to occur early in the trial. Importantly, the relative increase in FMT activity during switch trials was modulated further by the precise type of attentional shift that had to be performed. As *Figure 3C* illustrates, average FMT was numerically larger during switches in the PS condition than during switches in the LI or TS conditions. To test for the effects of the factors *Repetition* (repeat vs. switch trials) and *Switch Type* (PS vs. LI vs. TS) on average FMT levels statistically, we ran a RM-ANOVA with both experimental factors as independent variables and mean FMT at Fz as independent

variable. The results corroborate the visual impression: apart from a significant main effect of the factor *Repetition*, $F(1, 31) = 15.45$, $p < .001$, $\eta_p^2 = 0.33$, and a non-significant main effect of the factor *Switch Type*, $F(2, 62) = 5.41$, $p < .01$, $\eta_p^2 = 0.06$, the analysis yielded the predicted interaction of *Repetition* x *Switch Type*, $F(2, 62) = 5.41$, $p < .01$, $\eta_p^2 = 0.15$., indicating that FMT increased during goal switches but that the size of this increase varied with the control demands the cognitive system is confronted with during set shifting.

Figure 3. Results of analyses of frontal midline theta power (FMT). **A:** Topography of FMT collapsed across all valid trials. **B:** Difference plots of time-normalized event-related spectral perturbations (ERSPs) during switch trials relative to repeat trials at Fz. **C:** Mean FMT at Fz as a function of *Repetition* and *Switch Type*. **D:** Time-course of FMT during switch trials of the three different *Switch Types*. **E:** Difference in the time-course of FMT at Fz when previously relevant information must be ignored (PS switches) or previously irrelevant information must be attended to (LI switches) as compared to when new information must be attended to (TS switches). Lines in the upper part of the figure indicate sequences of 8 or more consecutive time slices with mean difference values significantly different from zero (t-test, two-tailed, $p = .05$). Shaded areas and error bars indicate standard errors of the mean.

We conducted two sets of additional analyses to further pin down the potential aftereffects of persisting target amplification and distracter inhibition on FMT. First, at the *aggregate level*, we ran two one-way RM-ANOVAs to test for the effect of *Switch Type* on mean FMT for repeat and switch trials separately (see *Figure 3C*). Mirroring the results of our analyses

of behavioral performance, repeat trials showed no effect of *Switch Type* on FMT, $F(2, 62) = 0.57, p = .57, \eta_p^2 = 0.02$, in contrast to switch trials which showed an effect on FMT, $F(1.65, 50.99) = 5.92, p < .01, \eta_p^2 = 0.16$. Follow-up Bonferroni-corrected pairwise comparisons revealed that FMT was significantly larger during switches in the PS condition than in the TS condition ($p = .02$). Thus, as expected, ignoring previously task-relevant information while shifting attention towards a new goal resulted in higher FMT levels than shifting attention alone. In contrast, average FMT levels did not differ significantly ($p = .80$) between switches where attention was shifted to a previously ignored source of information (in the LI condition) and switches where attention was shifted to a new source of information (in the TS condition).

In the second set of analyses, we compared the *time-course* of theta activity across the switch trials of the three switching conditions. As can be seen in *Figure 3D*, shifting goal-directed attention towards a new task-relevant source of information in the TS condition resulted in an increase in FMT at stimulus onset which reached a plateau at about half of the trial until response. When shifting the focus of attention additionally involved ignoring previously task-relevant information, FMT followed a different pattern: in the PS condition, FMT rose more steeply at the beginning of the trial, peaked about mid-trial and then fell again slightly until a response. Finally, shifting goal-directed attention towards a previously ignored source of information resulted in yet another pattern of FMT over time: whereas FMT in the LI condition increased similarly to the TS condition throughout the first half of the trial, it exhibited a marked peak prior to response which was not observed for switches in the TS condition.

To test the reliability of these differences in FMT, we subtracted time-continuous theta activity in the PS and LI conditions from time-continuous theta activity in the TS condition. For each time-slice, running t-tests were computed to test whether the resulting difference was larger

than zero (see *Figure 3E*). The results confirmed our observations: relative to merely reorienting attention towards a new task goal in the TS condition, ignoring previously task-relevant information in the PS condition resulted in higher levels of FMT throughout the trial whereas attending to previously ignored information in the LI condition resulted in a relative increase in FMT only prior to response execution. Importantly, a more conservative statistical analysis in which we compared the evolution of theta in PS and LI switches with the evolution of FMT in TS switches over time in two separate RM-ANOVAs also confirmed this pattern of results. To this end, time-continuous FMT data was divided into three time-windows, each averaging across 33 time slices, to reduce the levels of the *Time* factor of the subsequent analysis from 100 to three (see Scherbaum et al., 2011). The RM-ANOVA representing the contrast between FMT in PS and TS switches revealed significant main effects for both *Switch Type*, $F(1, 31) = 8.86$, $p < .01$, $\eta_p^2 = 0.22$, and *Time*, $F(2, 62) = 34.70$, $p < .001$, $\eta_p^2 = 0.53$, but no significant interaction of the two, $F(1.57, 48.77) = 2.26$, $p = .13$, $\eta_p^2 = 0.07$. This indicated that FMT in the PS condition was significantly larger than in the TS condition and that this difference was comparable in size across all three time-windows. In contrast, the RM-ANOVA representing the contrast between LI and TS yielded a non-significant main effect for *Switch Type*, $F(1, 31) = 1.28$, $p = .27$, $\eta_p^2 = 0.04$, a significant main-effect for *Time*, $F(1.58, 48.99) = 41.05$, $p < .001$, $\eta_p^2 = 0.57$, and, most importantly, a significant interaction of the two, $F(2, 62) = 3.34$, $p < .04$, $\eta_p^2 = 0.10$. The latter indicated that the marked increase in FMT in the last third of the trial that was not present in the TS condition is indeed statistically reliable. This indicated that FMT differed between TS and LI conditions, yet only in the last third of the switch trial (see *Figure 3E*).

SSVEP Amplitudes

We conducted two control analyses to check whether the induction of SSVEPs had been successful and whether SSVEP amplitudes reliably reflected the redistribution of attention across task-relevant and -irrelevant stimuli in our setup (see Scherbaum et al., 2011; Toffanin et al., 2009). To check whether rhythmic brain activity had been induced at the two stimulating frequencies, we examined the distribution of raw signal power for the 9 Hz and 12 Hz collapsed across all valid trials of all participants. As is apparent from *Figure 4A*, power for both stimulation frequencies was clearly localized to and maximal over occipital electrodes. Such topographies are typical for SSVEP signals which arise from oscillatory neural activity in visual areas of the human cortex (e.g. Andersen & Müller, 2010; Müller et al., 2006; Scherbaum et al., 2011). To check whether changes in SSVEP amplitudes reliably reflected the redistribution of goal-directed attention across the stimulus display, we compared SSVEP signals during incongruent repeat trials of our paradigm that involved a switch in target locations. As this also involves a switch in target frequencies, we would expect SSVEP amplitudes to reflect a gradually increasing contrast between task-relevant and -irrelevant information (e.g. Scherbaum et al., 2011). As a first approximation to this question, we collapsed baseline-normalized power of the SSVEP streams representing task-relevant and -irrelevant sources of information (irrespective of whether this was the 9 Hz or the 12 Hz stream) for each trial of each participant and calculated the contrast between target- and distracter-related activity at each electrode. *Figure 4B* depicts this contrast and reveals a cluster of occipital electrodes at which the overall activity of the target SSVEP stream is larger than the overall activity in the distracter SSVEP stream. This overlaps in large parts with the topographies of raw 9 Hz and 12 Hz oscillatory activity depicted in *Figure 4A*. To add the temporal dimension to this, we compared the time-

course of target- and distracter SSVEP amplitudes at those electrodes which had been selected for further analyses. The average time-course of target and distracter activation during repeat trials at these electrodes is depicted on the left side of *Figure 4C*. For each participant, we calculated the difference score between the time-course of target and distracter activation averaged across the two stimulation frequencies. Running t-tests were used to identify segments in which mean target activation was significantly larger than mean distracter information. They revealed a significant segment in the second half of the trial, supporting the expected contrast enhancement between target and distracter information over time (see right side of *Figure 4C*, cf. Scherbaum et al., 2011). To put this observation to a more conservative test, we ran a RM-ANOVA that compared the time-course of target- and distracter-activation (factor *Source*) over three equal-sized time-windows (factor *Time*). Both main effects of *Source*, $F(1, 31) = 4.80$, $p = .04$, $\eta_p^2 = 0.13$, and *Time*, $F(1.52, 47.14) = 3.70$, $p = .04$, $\eta_p^2 = 0.11$ proved statistically reliable, but the interaction of the two was not significant, $F(2, 62) = 1.00$, $p = .37$, $\eta_p^2 = 0.03$. Accordingly, SSVEP amplitudes for flicker streams tagging target stimuli were larger than SSVEP amplitudes for flicker streams tagging distracter stimuli and this did not change throughout the trial. Taken together, the SSVEP control analyses provided promising results. Our experimental setup successfully induced localized, rhythmic activity at electrode sites typically involved in SSVEP generation whose amplitudes differed as a function of attentional deployment between task-relevant and distracting sources of information during repeat trials. Surprisingly, however, the resulting target-distracter contrast did not increase over the course of the trial (Scherbaum et al., 2011).

In our final set of analyses, we explored the aftereffects of attentional selection during mental set-shifting by comparing target- and distracter-related SSVEP amplitudes during switch

trials of the three different *Switch Types* of our design (see upper part of *Figure 4D*). The lower part of *Figure 4D* depicts the corresponding difference between target- and distracter-related SSVEP amplitudes. Contrary to our expectations, SSVEP activity of target and distracter streams did not differ reliably throughout switch trials in the PS and LI conditions as is indicated by the results of running t-tests plotted at the top of each graph. Only in the TS condition, a significant difference emerged at the very end of the trial that went in the inverse direction. A RM-ANOVA with the factors *Source* (target vs. distracter activation), *Time* (first vs. second vs. third third of the trial), and *Switch Type* (PS vs. LI vs. TS) confirmed the absence of the predicted effects of attentional reallocation during the different switching conditions in our SSVEP data. Apart from a significant main effect of the factor *Time*, $F(1.40, 43.44) = 8.28$, $p < .01$, $\eta_p^2 = 0.21$, indicating an overall decrease in SSVEP amplitudes over time across all three switching conditions, no other effect reached significance, all F s < 2.60 ; all p s $> .12$.

Taken together, our experimental setup reliably induced rhythmic neural activity whose topography matched typical SSVEP activation patterns and whose amplitude varied as a function of attention allocation during repeat trials of our paradigm. During switch-trials, however, we neither observed the expected differences in SSVEP amplitudes between target and distracter streams nor any differences between different switch types.

Figure 4. Results of analyses of steady-state visually evoked potentials (SSVEPs). **A:** Grand average SSVEP topographies for the two stimulation frequencies of 9 Hz and 12 Hz. **B:** Topography of the power difference between target and distracter SSVEP amplitudes, collapsed across stimulation frequencies. **C:** Time-course of mean SSVEP amplitudes representing target and distracter activation (left) and their difference (right) during repeat trials. **D:** Time-course of mean SSVEP amplitudes representing target and distracter activation (upper panel) and their difference (lower panel) for each of the three switch types. Lines in the upper parts of figures C and D indicate sequences of 8 or more consecutive time slices with mean difference values significantly different from zero (t-test, two-tailed, $p = .05$). Shaded areas and error bars indicate standard errors of the mean.

Discussion

The present investigation used time-frequency-analyses of human EEG data to investigate the contribution of amplificatory and inhibitory aftereffects of attentional selection on mental set-shifting. In an adapted version of an established set-shifting task (Dreisbach & Goschke, 2004; Frisch et al., 2015; Owen et al., 1993), participants responded to digits in a cued target color while ignoring digits in uncued distracter colors. Target and distracter colors switched repeatedly over the course of the experiment. To assess the relative impact of persisting amplificatory and inhibitory attentional biases on set-shifting, we compared behavioral performance and EEG oscillatory activity from switch trials in which previous target information had to be ignored (PS condition) and switch trials in which previously distracting information had to be attended to (LI condition) to switch trials of a control condition in which a new source of information had to be attended to (TS condition). The investigation comprised two parts. In a first, confirmatory part we used frontal midline theta activity (FMT) as a continuous marker of cognitive interference to re-assess the predictions regarding the persisting impact of amplification and inhibition on cognitive processing made by a Dynamic Neural Field (DNF) model of selective attention in the task (Frisch et al., 2015). In a second, more exploratory part, we used steady-state visually evoked potentials (SSVEPs) to trace the precise reallocation of attention to target and distracter information during set-shifting.

Persisting Amplification and Inhibition Affect Behavior and FMT

As is commonly observed in the literature (Kiesel et al., 2010; Monsell, 2017), participants' performance was worse when shifting mental sets as compared to when target and distracter colors repeated. Importantly, the size of these shifting costs depended on the control demands posed by the different shifting conditions. Particularly large behavioral costs were

observed in the PS condition in which previously task-relevant information must be ignored. This corroborates a substantial body of theoretical and empirical work that puts an amplificatory process at the centre of attentional selection (J. D. Cohen et al., 1990; Pashler, 1998; Wolfe, 1994; Wolfe et al., 1989). Moreover, this shows once again that this amplificatory attentional bias persists in time and interferes with information processing when previously important stimuli need to be ignored (e.g. Frisch et al., 2015; Longman et al., 2013, 2016, 2014).

What is more controversial is whether a similar source of interference results from inert inhibitory processes that hamper the re-allocation of attention (see e.g. D'Angelo et al., 2016; Frings et al., 2015; MacLeod et al., 2003). In the paradigm used here, this should be primarily reflected in differences between LI switches and TS switches: Whereas the former affords participants to shift the focus of attention to a different color that had to be ignored beforehand, the latter requires a shift in attention to a different color that had not been part of the previous stimulus display. Thus, if persisting distracter suppression existed, it should result in larger conflict and, in consequence, worse performance in LI switches as compared to TS switches.

The behavioral data collected in this study did not reveal a significant difference in performance between switches in the LI condition and the TS condition. This connects to a larger body of literature having difficulties to provide convincing evidence for persisting distracter inhibition when focusing on discrete data alone (D'Angelo et al., 2016; Frings et al., 2015). Some researchers have taken this as a reason to negate the concept of selective distracter suppression altogether (e.g. MacLeod et al., 2003). From a dynamic perspective (Frisch et al., 2015; Scherbaum et al., 2010; Spivey & Dale, 2004) however, discrete measures of performance such as response times or error rates may just be too crude to detect subtle and transient effects cognitive inhibition may have on overt behavior in cognitive tasks. Therefore, in the present

study, we looked at FMT as a time-continuous marker of cognitive interference (Cavanagh & Frank, 2014) to investigate aftereffects of persisting attentional amplification and inhibition.

On an aggregate level, FMT data resembled the behavioral findings: average FMT levels were higher during switch than repeat trials and the extent of this increase depended on the processing demands posed by the different switch types with FMT levels during switches in the PS condition being significantly larger than during switches in the TS and LI conditions. Time-continuous analyses revealed that the surplus in FMT during PS switches occurred from the very beginning of the switch trial, peaked halfway to response execution and fell again in the second half of the trial. This pattern closely resembles the predicted effects of persisting amplificatory attentional biases on response generation provided by the DNF model of selective attention by Frisch et al. (2015). Thus, time-continuous FMT data from our investigation provides further support for the existence of a strong, excitatory attentional bias that persists in time and interferes with ongoing information processing (e.g. Frisch et al., 2015; Goschke, 2000; Longman et al., 2013, 2016, 2014).

Regarding persisting inhibition, average theta levels did not differ significantly between switches in the LI and the TS conditions. However, when looking at the continuous unfolding of FMT over time, diverging patterns emerged. While the simple reorientation of attention during TS switches resulted in an increase in FMT that plateaued roughly in the middle of the trial, the added processing demand of attending a previously ignored source of information produced an increase in FMT at the end of LI switches that did not occur during TS switches. Again, this is consistent with the predictions of the DNF model presented by Frisch et al. (2015) which had revealed characteristic deflections of movement trajectories during LI switch trials as a marker for selective distracter inhibition. According to this model, the bump in FMT observed during LI

switch trials in the present study results from the continued suppression of the current target (previous distracter) color at the beginning of an LI switch. This creates an activation disadvantage for the current target color – which had to be ignored in the previous stimulus display –vis-à-vis the uninhibited distracter color – which had not been part of the previous stimulus display – resulting in heightened levels of cognitive conflict and, therefore, FMT (Cavanagh & Frank, 2014). By demonstrating a transient increase in an established marker of conflict during LI switches, our findings provide an important addition to Frisch et al.'s (2015) empirical work who found no such evidence using mouse movements as a dependent variable (Scherbaum et al., 2010; Spivey et al., 2005) and therefore concluded that attentional selection does not rely on inhibitory processes (c.f. MacLeod et al., 2003). The present investigation refines this conclusion. It strengthens findings that demonstrate the active inhibition of distracting information online (Frings et al., 2012; Frings & Wühr, 2014; Scherbaum et al., 2011; Wühr & Frings, 2008) and extends them in scope by showing that these inhibitory processes may persist in time after becoming obsolete (see Allport et al., 1994; Houghton & Tipper, 1994).

It should be noted that the interference reflected in the increase in FMT during LI switches of our paradigm could also result from a non-inhibitory mechanism. While an inhibitory account would attribute the underlying activation advantage of distracter vs. target information to a persisting inhibition of the current target color, a similar imbalance would arise if distracter colors were unduly amplified during LI switches. For instance, one might argue that distracter colors during LI switches are novel (i.e., they have not been part of the previous stimulus display) and therefore draw attention automatically (see e.g. Corbetta & Shulman, 2002; Dreisbach & Goschke, 2004). Yet, it is unlikely that such a novelty bias is responsible for the interference reflected in changes in FMT during LI switches of our paradigm. On the one hand,

the experiment involved only three colors – red, green, and blue – that were presented in pseudo-randomized order over the entire course of the experiment. Hence, after the first switch trial, participants had seen all colors in the stimulus set at least once. Moreover, colors switched every six to eight trials, so that any color that did not serve as a target or distracter during a given run was encountered again after eight trials at the latest. In consequence, it is fair to assume that participants became familiar with the colors occurring throughout the experiment rather quickly. As novelty effects are known to decrease with increasing stimulus familiarity (e.g. Debener, Kranczioch, Herrmann, & Engel, 2002; Friedman & Simpson, 1994), it appears unlikely that our experimental design that incorporated regular switches between a small set of colors induced novelty effects to a significant degree. Moreover, novelty-related processes should impact all switch conditions equally. Therefore, if novelty capture increased interference during LI switches, it should have an inverse, positive effect on performance during TS switches in our paradigm. During TS switches, a familiar target color (prior to the switch) is replaced by a novel target color (after the switch). Thus, under the assumption of a strong novelty bias, we would expect relatively high levels of performance in TS switches in comparison to both repeat trials in the TS condition and to switch trials in the LI condition where novelty capture would have adverse effects. The fact that neither is the case sheds doubt on the idea that novelty capture had a large impact on performance in the different conditions of our paradigm.

An interesting finding of this investigation is that the increase in FMT relative to baseline appeared at different points in time during PS and LI switches. This observation deviates from the predictions generated by Frisch et al.'s (2015) computational model which produced mid-trial peaks of conflict for both PS and LI switches. While this fits well with the course of FMT observed in the PS condition, the comparatively late increase in FMT observed during LI

switches may suggest that additional processes are at play in this condition that are not implemented in the model yet. Given that the increase in FMT during LI switches occurs immediately prior to response execution, it stands to reason that part of this increase may have resulted from response-associated processes. Indeed, it has been shown that cognitive conflict can arise from interference at the level of both stimulus- and response selection (Egner, 2008; Kornblum, Hasbroucq, & Osman, 1990) and that FMT is not only sensitive to interference at the level of stimulus perception but also at the level of action generation (Nigbur, Cohen, et al., 2011; Wang, Li, Zheng, Wang, & Liu, 2014; Zhao et al., 2015) and response inhibition (Harper, Malone, & Bernat, 2014; Kirmizi-Alsan et al., 2006; Yamanaka & Yamamoto, 2009). Accordingly, it is possible that the increase in FMT observed during LI switches in our design may be driven in part by response-related conflict processing.

Importantly, this does not invalidate the assumption that the peaks of FMT observed during LI switches are indicative of a lingering inhibitory bias in the attentional system. In the model by Frisch et al. (2015), the interference caused by previous goal representations initially occurs at the attentional level but is propagated through all stages of information processing, eventually resulting in conflict at the level of response selection and motor execution as well. Inversely, classic models of cognitive control (e.g. Botvinick, Braver, Barch, Carter, & Cohen, 2001) measure cognitive conflict exclusively at the level of motor execution but resolve said conflict by adjusting attentional parameters accordingly. Both examples illustrate that the occurrence and resolution of cognitive conflict manifests at different levels of the processing hierarchy and that these occurrences are inherently interconnected. Hence, even if the increase in FMT observed in switch trials of the LI condition of our study may have been driven by conflict at the response layer, this conflict may still have originated from inert inhibitory processes at the

attentional level. To provide further evidence for this assumption, we used SSVEPs as a direct measure of attentional processing in the second part of our study.

SSVEPs as a Direct Measure of Attention

In line with previous SSVEP-studies (see Norcia et al., 2015 for an overview), we found that the flickering circles surrounding target and distracter stimuli induced rhythmic neural activity at both stimulating frequencies that had clear posterior topographies. Moreover, at the end of repeat trials, oscillation amplitudes were significantly larger for frequencies tagging target stimuli than frequencies tagging distracter stimuli. Thus, when attentional demands remained constant during repeat trials, SSVEP power reflected the distribution of attention towards task-relevant and away from distracting information. However, when attention had to be re-allocated during switch trials, no meaningful variation in average SSVEP amplitudes was observed, preventing us from drawing reliable conclusions on the time-course of attention reallocation during set-shifting.

The lack of systematic variability of SSVEP amplitudes during switch trials came as a surprise in this study. In the past, SSVEPs have been used successfully to trace the dynamics of both location- (e.g. Müller et al., 1998; Scherbaum et al., 2011; Toffanin et al., 2009) and feature-based attention continuously over time (e.g. Andersen, Müller, & Hillyard, 2009; Müller et al., 2006; Müller, Trautmann, & Keitel, 2016). For example, Andersen & Müller (2010) recorded SSVEPs of participants shifting attention between clouds of differently colored dots flickering at 7 Hz or 11.7 Hz. When participants switched attention from one color to the next, the authors observed an initial amplification of the new target SSVEP followed by a suppression of the SSVEP amplitude of the distracter stimulus. We would have expected to observe similar SSVEP dynamics during the TS switches of our paradigm which closely resembles the design

employed by Andersen & Müller (2010). However, even in this simple case of re-allocating attention towards a new target color, we failed to observe the expected SSVEP dynamics. In the following, we will discuss methodological and theoretical aspects that may have contributed to this failure.

A first issue may have been the stimulation frequencies used in this study. It has been shown that different stimulation frequencies result in different characteristics of the evoked neural activation (see e.g. Srinivasan, Bibi, & Nunez, 2006; Toffanin et al., 2009). For example, Ding, Sperling, & Srinivasan (2006) demonstrated that attention can have different effects on SSVEP amplitudes depending on whether the attended frequency is in the upper vs. lower alpha band (i.e. frequencies in the range between 10 – 11 Hz vs. 8 -10 Hz): whereas the former resulted in the expected increase in SSVEP amplitudes, the latter was accompanied by a decrease in SSVEP amplitudes. In consequence, mixing a pair of frequencies from the lower (9 Hz) and the upper (12 Hz) alpha band within one study as tagging frequencies may have distorted our results. However, to the best of our knowledge, no other study has replicated the effect reported by Ding et al. (2006). If anything, more recent studies suggest that driving frequencies in the alpha range elicit particularly strong neural responses (Norcia et al., 2015; Toffanin et al., 2009). Moreover, the exact same set of stimulating frequencies used in this study reliably induced attention-sensitive SSVEPs in a previous investigation (Scherbaum et al., 2011). Given that SSVEP activity differentiated target from distracter information at the end of repeat trials, it appears unlikely that driving frequencies were the main reason for the lack of success of our SSVEP manipulation.

Another issue may have had graver consequences for the induction of SSVEPs. Whereas other investigations in the field typically interrupt rhythmic stimulation during the inter-trial-

interval (ITI) (e.g. Müller et al., 2006, 1998; Scherbaum et al., 2011), we induced SSVEPs continuously: Flickering started at the beginning of each block and continued within and between trials (i.e. during fixation, stimulus presentation until response, and inter-trial-interval) until the block ended. We chose this stimulation procedure because we had hoped to extend the temporal scope of our study even further. While the established method of single-trial stimulation procedures allows for the tracing of attention across the trial, it leaves aside whether the attentional adjustments occurring during a task-switch are completed with the end of the switch trial or whether they have repercussions on longer time-scales, for example during the ITI or even during subsequent repeat trials, and whether these longer-term temporal dynamics differ for persisting amplificatory and inhibitory sub-processes of selective attention.

Unfortunately, the decision to use a continuous stimulation regime that arose from this idea may have contributed to the lack of success of the SSVEP manipulation in our study. First, it is uncertain to what extent SSVEPs are stationary. The continuous induction of SSVEPs used in our study built on the assumption that the rhythmic neural activation generated through the flickering depended exclusively on the amount of attention directed at the driving frequency at a given point in time. However, recent evidence (Labecki, Nowicka, & Suffczynski, 2018) suggests that stimulation duration also affects SSVEP characteristics. In particular, subjects appear to habituate to a given set of frequencies when they are exposed to them for extended periods of time in the sense that overall signal power decreases with stimulation duration. While this is problematic for all types of SSVEP experiments, the trial-by-trial stimulation procedures implemented in previous studies in the field may have helped reduce such habituation processes. Conversely, continuous SSVEP stimulation used in our study may have produced weaker neural responses which would explain our difficulties to detect reliable differences in SSVEP signal

strength between attended and unattended flicker frequencies. Second, flickering may have interfered with the attentional dynamics we were interested in. Two recent studies suggest that switches in tagging frequencies during SSVEP experiments can interfere with the carryover of attentional sets from one trial to the next (Scherbaum et al., 2011; Scherbaum, Frisch, & Dshemuchadse, 2016). In both studies, participants completed an adapted version of the Eriksen Flanker task (Eriksen & Eriksen, 1974) in which they responded to a target digit located at the centre of a group of distracter digits that were either response congruent or incongruent to the target. Target and distracter stimuli flickered at different frequencies and the assignment of frequency to locations varied pseudo-randomly from trial to trial. The authors' primary interest was to investigate the attentional dynamics underlying the conflict adaptation effect, an increase in performance following the experience of cognitive conflict that is believed to result from attentional settings persisting from the previous trial (see e.g. Botvinick et al., 2001; Egner, 2007; Gratton, Coles, & Donchin, 1992). Surprisingly, Scherbaum and colleagues (Scherbaum et al., 2011, 2016) only observed a conflict adaptation effect in trials which repeated the target frequency from the previous trial. When target frequencies switched, the effect was reversed. The authors speculated that flicker frequencies may be processed as an integral feature of target and distracter stimuli that guide attention in addition to stimulus location, the stimulus feature that is truly task-relevant in this task. This way, when target frequencies are constant, attention is directed at the correct stimulus and control adjustments from the previous trial improve performance in the current trial. When frequencies switch, however, attention is driven towards the incorrect stimulus and the effect is reversed (Scherbaum et al., 2016).

Similar processes may have been at play in our paradigm: Flicker frequencies may have served as an extra cue for guiding attention, thus, interfering and competing with the persisting

amplificatory and inhibitory attentional biases under study here. Of course, our procedure was aimed to minimize this effect by balancing frequency switches and repetitions for the crucial trials of our design. The fact that we observed behavioral data that is consistent with previous investigations (Frisch et al., 2015) and that FMT differed meaningfully between the different conditions of our task makes us confident that the basic processes of cognitive interference – at least through amplification – have taken place. However, if flicker frequencies did serve as an additional source of information guiding attention, this would have introduced additional variability to our data that may have prevented us from observing clear results in SSVEP power.

Conclusion

The present investigation provides evidence that both excitatory and inhibitory sub-components of attentional selection persist in time and contribute to the costs of shifting mental sets. Beyond that, it showcases the opportunities and challenges of a dynamic approach to cognition and cognitive control. On the one hand, focusing on the continuous change of FMT over time revealed traces of persisting distracter inhibition which would not have been discovered had analyses been limited to discrete behavioral measures and average levels of FMT alone. However, the enriched data basis that is the strength of dynamic investigations comes at the price of more elaborate designs, stimulation procedures, and statistical analyses the interactions of which can be difficult to foresee and prevent. Therefore, future studies will have to adopt refined experimental protocols or employ measures other than SSVEPs to trace the re-allocation of attention during set-shifting directly. The present investigation prepares the ground for these endeavors, first, by demonstrating that attending to previously ignored and ignoring previously attended sources of information both produce heightened levels of interference and,

second, by providing hypotheses on the continuous dynamics of attention that may underly this interference.

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Supplement

Here, we present the statistical analyses of response times (RT), error rates (ERR) for our experiment.

Figure S1. Response times (left) and error rates (right) as a function of the experimental factors *Repetition* (repeat [R] vs. switch trials [SW]) and *Switch Type* (perseveration [PS] vs. learned irrelevance [LI] vs. target switch [TS]). Error bars represent standard errors.

Response Times

A two-factorial repeated measures analysis of variance (RM-ANOVA) with *Repetition* (repeat vs. switch trials) and *Switch Type* (PS vs. LI vs. TS) as independent variables and RT as dependent variable yielded a significant main effect of *Repetition*, $F(1, 31) = 437.27$, $p < .001$, $\eta_p^2 = 0.93$, and *Switch Type*, $F(2, 62) = 22.70$, $p < .001$, $\eta_p^2 = 0.42$, as well as a significant interaction of the two, $F(2, 62) = 16.35$, $p < .001$, $\eta_p^2 = 0.36$. The latter indicated that goal switches resulted in significant switching costs whose size varied between the different levels of the *Switch Type* manipulation (see Figure S1, left). To follow up on this effect, we conducted separate RM-ANOVAs for each level of the factor *Repetition*. For repeat trials, this analysis yielded a non-significant main effect of *Switch Type*, $F(2, 62) = 0.87$, $p > .42$, $\eta_p^2 = 0.03$, indicating that RT during repeat trials did not differ between the different *Switch Type* conditions. In contrast, a parallel analysis of switch trials yielded a significant

main effect of *Switch Type*, $F(2, 62) = 90.14$, $p < .001$, $\eta_p^2 = 0.43$, indicating that performance varied with the control demands posed in a given condition. Bonferroni-corrected pairwise comparisons indicated significant differences between all three levels of the factor switch type (all $ps < .04$). Thus, participants' responses were fastest during switches in the TS condition and slowest during switches in the PS condition with switches in the LI condition taking a middle position between the two.

Error Rates

A two-factorial repeated measures analysis of variance (RM-ANOVA) with *Repetition* (repeat vs. switch trials) and *Switch Type* (PS vs. LI vs. TS) as independent variables and ERR as dependent variable yielded a significant main effect of *Repetition*, $F(1, 31) = 99.25$, $p < .001$, $\eta_p^2 = 0.76$, and *Switch Type*, $F(1.29, 36.96) = 86.76$, $p < .001$, $\eta_p^2 = 0.74$, as well as a significant interaction of the two, $F(1.29, 39.62) = 16.35$, $p < .001$, $\eta_p^2 = 0.71$. Thus, goal switches produced a significant increase in errors the size of which varied between the different levels of the *Switch Type* manipulation (see *Figure S1*, right). To follow up on this effect, we conducted separate RM-ANOVAs for each level of the factor *Repetition*. For repeat trials, this analysis yielded a non-significant main effect of *Switch Type*, $F(2, 62) = 0.38$, $p > .68$, $\eta_p^2 = 0.01$, indicating that error rates during repeat trials did not differ between the different *Switch Type* conditions. In contrast, a parallel analysis of switch trials yielded a significant main effect of *Switch Type*, $F(1.17, 36.56) = 90.69$, $p < .001$, $\eta_p^2 = 0.75$, indicating that error rates varied as a function of the control demands of the different conditions. Bonferroni-corrected pairwise comparisons indicated that error rates during PS switches were significantly higher than error rates during LI switches ($p < .001$) or TS Switches ($p < .001$). Error rates during LI and TS switches did not differ significantly ($p = .06$).