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Throwing out the rules: anticipatory alpha-band oscillatory attention mechanisms during task-set reconfigurations

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Abstract

We assessed the role of alpha-band oscillatory activity during a task-switching design that required participants to switch between an auditory and a visual task, while task-relevant audio-visual inputs were simultaneously presented. Instructional cues informed participants which task to perform on a given trial and we assessed alpha-band power in the short 1.35-second period intervening between the cue and the task-imperative stimuli, on the premise that attentional biasing mechanisms would be deployed to resolve competition between the auditory and visual inputs. Prior work had shown that alpha-band activity was differentially deployed depending on the modality of the cued task. Here, we asked whether this activity would, in turn, be differentially deployed depending on whether participants had just made a switch of task, or were being asked to simply repeat the task. It is well-established that performance speed and accuracy are poorer on switch than on repeat trials. Here, however, the use of instructional cues completely mitigated these classic switch-costs. Measures of alpha-band synchronization/desynchronization showed that there was indeed greater and earlier differential deployment of alpha-band activity on switch versus repeat trials. Contrary to our hypothesis, this differential effect was entirely due to changes in the amount of desynchronization observed during switch and repeat trials of the visual task, with more desynchronization over both posterior and frontal scalp regions during switch-visual trials. These data imply that particularly vigorous, and essentially fully effective, anticipatory biasing mechanisms resolved the competition between competing auditory and visual inputs when a rapid switch of task was required.

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Keywords

Biasing; Cueing; Suppression; Attention; Task-Switching; EEG; switch-cost

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INTRODUCTION

When individuals are required to switch rapidly from execution of one task to another, goal-related task networks and attentional mechanisms are engaged to reconfigure task-specific networks, suppressing activity within circuits responsible for performance of the old task and amplifying preparatory neural processes for the anticipated novel task (Fuxe & Simpson, 2005; Fuxe *et al.*, 2005). That is, competition between two potential task-set configurations must be resolved so that an effective strategy shift can be enacted. Often there is a significant performance cost in terms of both speed and accuracy upon the first instance of a new task that is taken to reflect these reconfiguration processes (Jersild, 1927; Wylie & Allport, 2000; Wylie *et al.*, 2004b; Wylie *et al.*, 2009). Under many such task-switching scenarios, switch costs dissipate rapidly, with near ceiling levels of performance achieved on just the second instance of the new task (De Sanctis *et al.*, 2009). The implication is that the anticipatory neural reconfigurations necessary for optimal performance of a new task are not always achieved in one step; rather it often takes performance of at least one instance of the new task to reach optimal performance (Wylie *et al.*, 2003a). Alternatively, if an informational cue informs participants of an upcoming task switch, and sufficient time is then allowed to elapse between the cue and the stimulus to be acted upon, individuals can accomplish an entirely effective task-set reconfiguration in that little or no switch cost is then observed (Wylie *et al.*, 2009).

It has been long posited that a large contribution to these initial switch costs is mediated through so-called *task-set inertia* effects; that is, optimal performance of the new task is hindered by ongoing competition from sustained activity within the neural circuitry responsible for performing the previous, but now irrelevant, task (Allport *et al.*, 1994; Wylie *et al.*, 2003b; Waszak *et al.*, 2005; Wylie *et al.*, 2006). Functional imaging studies have shown precisely this pattern of effects. In one such study, we asked participants to perform both a color task and a face identification task during a switching paradigm, while imaging activation patterns within the relevant cortical regions for analyzing these respective features. We found that activity within the circuitry responsible for color processing (e.g. V4) continued to show enhanced processing while participants performed the face task (and vice versa), despite the fact that the color task was, and would continue to be, completely irrelevant to them (Wylie *et al.*, 2004a).

Thus, in order to perform a new task under such task-switching scenarios, it seems a reasonable supposition that there are two somewhat separable mechanisms that must be engaged in parallel. The task-set configuration (goals) of the new task must be deployed effectively, while simultaneously, some form of suppression of the former task-set must also be engaged (Fuxe & Snyder, 2011). Here, we were specifically interested in how this suppression was achieved. One obvious candidate mechanism for suppressing or disengaging ongoing activity within previous task-relevant circuitry is deployment of

anticipatory alpha-band oscillatory activity. Oscillations in this band (8–14 Hz) have been convincingly associated with attentional suppression across the visual (Fuxe *et al.*, 1998; Worden *et al.*, 2000; Fu *et al.*, 2001; Kelly *et al.*, 2005; 2006; Rihs *et al.*, 2007; Romei *et al.*, 2008; Kelly *et al.*, 2009; Snyder & Fuxe, 2010), auditory (Kerlin *et al.*, 2010; Banerjee *et al.*, 2011; Gomez-Ramirez *et al.*, 2011) and somatosensory (Jones *et al.*, 2010; Haegens *et al.*, 2011) systems. Here, we asked whether alpha-band oscillatory suppression mechanisms might not also be deployed to suppress “old” task-set configurations.

We employed a well-established intersensory selective attention task where participants were cued on a trial-by-trial basis to attend to either the visual or auditory components of an upcoming compound audio-visual target event (Fuxe *et al.*, 1998). In turn, high-density electrical mapping was employed to assay anticipatory alpha-band activity during a fixed 1.35 second cue-to-target attentional deployment period. Comparisons were specifically made between switch trials (where the modality of the upcoming task had just changed) and repeat trials (where the cued modality was the same as in the previous trial). We reasoned that there would be considerably earlier and amplified deployments of alpha-band mechanisms in anticipation of a task-switch than in anticipation of a task-repeat trial. We also anticipated a considerably more extensive topographic distribution of this anticipatory alpha, reflecting increased engagement of a distributed task network that would likely also include executive control regions of the well-known fronto-parietal attention network (Corbetta, 1998; Fuxe *et al.*, 2003). In the case of task-repeats, our expectation was that alpha-suppression mechanisms would be deployed with a more focused topography, and with a more punctate time course, specifically titrated to the expected arrival of the imperative stimulus.

METHODS

Participants

Sixteen (8 females) healthy volunteers participated in this experiment (mean age = 23.5 years, SD = ± 3.6 , range = 18–32 years). All participants provided written informed consent and the procedures were approved by the Institutional Review Board of the Albert Einstein College of Medicine where the experiments were conducted. All procedures conformed to the tenets of the Declaration of Helsinki. All participants reported normal or corrected-to-normal vision and normal hearing. Participants received a modest fee (\$12/hour) for their efforts.

Stimuli and Task

We employed a classic S1–S2 cued attention task, where each trial consisted of a cue (S1), an intervening blank preparatory period, followed immediately by a task-relevant second stimulus (S2) (see Figure 1). Tasks of this type often use probabilistic cues, where participants are told to respond to all targets, even in the uncued modality or location (Posner *et al.*, 1980). Here, instructional cues were used such that participants were directed only to respond to targets within the cued modality and to suppress/ignore all stimuli in the uncued modality. This is an important design feature since stimuli in the uncued modality served as distractors, suppression of which would be expected to benefit task performance.

The first stimulus (S1), which served as the task cue, consisted of a simple light-grey line drawing depicting either a pair of headphones or a computer monitor. In mixed task blocks, these S1 stimuli instructed the participant as to which modality (auditory or visual) was to be attended when the second stimulus (S2) arrived (Fig. 1). The second stimulus (S2) was a compound bisensory auditory–visual stimulus and participants performed a go/no-go discrimination task on this S2 within the cued modality. Participants were cued randomly on a trial-by-trial basis to attend to either the visual or auditory components of the upcoming bisensory S2 event.

Local switch costs, reflecting the cost related to changing tasks, were obtained by comparing switch versus repeat trials in mixed blocks (i.e. blocks where task switches were required). The probability of a switch trial in such blocks was 50%, of a first repeat trial was 34%, and of a second repeat trial was 16%. To obtain a measure of so-called global switch costs, we also ran “pure” task blocks, where participants were instructed to perform only the visual or only the auditory task throughout a block of trials. In the visual “pure” task, the S1 was a line-drawing depicting a monitor and the S2 consisted of purely visual inputs. In the auditory “pure” task, the S1 was a line-drawing depicting headphones and the S2 consisted of purely auditory inputs. Global switch costs (also referred to as mixing costs), reflecting the cost related to performing two tasks instead of one task, were obtained by comparing repeat trials in mixed blocks versus “pure” task blocks.

The auditory part of the bisensory S2 stimulus consisted of two sequentially presented sinusoidal tones (100 ms duration, 10 ms rise/fall) with a 5 ms interval between presentations. On non-target trials, the two tones were of identical frequency (2000 Hz) and subjects were required to withhold responses when no difference between the tones was detected. On target trials, the two tones presented were of slightly different frequency. One of the two tones was 2000 Hz, whereas the frequency separation of the other tone was psychophysically titrated based on each participant’s performance (see Procedure below). When participants detected a frequency difference between the pair of tones, they were instructed to respond with a fast accurate button push.

The visual part of the bisensory S2 stimulus consisted of a pair of gabor patches (100 ms duration, 4.8° in diameter, 0.25 cycles per degree) centered 5.2° to the left and right of the fixation cross. On target and non-target trials the two patches were of different and identical orientation, respectively. As with the auditory stimuli, the orientation difference between the gabors was psychophysically titrated for each participant (see Procedure below). The timing of the visual presentation was adjusted such that the Gabors appeared coincident with the second tone of the pair rather than the first.

The likelihood of receiving a target stimulus within the cued modality was set at 50%. The stimulus onset asynchrony (SOA) between the cue and the imperative stimulus (i.e. the S1–S2 period) was 1350 ms. A black fixation cross (subtending 0.3° vertically and horizontally) was presented in the center of the monitor throughout testing. The inter-trial interval (ITI: the S2–S1 period) was randomized ranging from 2000 to 3000 ms during which the fixation cross remained on the screen.

Procedure

Participants were seated in a double-walled, darkened, sound-attenuated, electrically-shielded booth (International Acoustics Company (IAC), Bronx, New York). Visual stimuli were presented on a LCD monitor positioned 100 cm from the participant. Auditory stimuli were binaurally presented over a pair of headphones (Sennheiser, model HD 555). Stimuli were delivered using Presentation software (Neurobehavioral Systems, Albany, CA). The sound pressure level was set to a level reported as comfortable by the participant at the beginning of testing, and held constant from then onwards. All participants underwent a staircase procedure at the beginning of testing for each of the two tasks. This procedure, known as the Up-Down Transformed Rule (UDTR) was used to rapidly equate performance across the two tasks and across participants (Wetherill & Levitt, 1965). UDTR employs different rules that converge on specific levels of accuracy. We used a 3-up, 1-down rule, meaning that, for three consecutive hits we adjusted the stimulus one step harder and for any miss, we adjusted the stimulus one step easier. This rule necessarily converges on an accuracy level of 79.4%.

During the experimental session, participants were instructed to respond as quickly and accurately as possible to the detection of targets within the cued modality and to withhold responses otherwise. Participants were further instructed to refrain from eyeblinks during each trial as much as possible. Each participant completed one visual and one auditory pure-task block of 100 trials, followed by approximately 20 mixed-task blocks of 30 trials each, resulting in the collection of ~300 trials per cue condition.

EEG Acquisition and Preprocessing

Continuous EEG was recorded, with a band-pass of DC to 134 Hz, from 168 scalp electrodes (Biosemi ActiveTwo System: Amsterdam, Netherlands) at an analog-to-digital sampling rate of 512 Hz. Biosemi replaces the ground electrodes that are used in conventional systems with two separate electrodes that: Common Mode Sense (CMS) and Driven Right Leg (DRL) passive electrode. These two electrodes create a feedback loop, thus rendering them as references. With the Biosemi system, every electrode or combination of electrodes can be assigned as a reference, which is done purely in software after acquisition. EEG data were processed using the FieldTrip toolbox (Donders Institute for Brain, Cognition and Behaviour, Radboud University Nijmegen, The Netherlands). This MATLAB (The MathWorks Inc., Natick, Massachusetts) toolbox and supporting materials can be accessed at <http://www.ru.nl/neuroimaging/fieldtrip>. The continuous EEG data were stored and then re-referenced to the average reference and low-pass filtered with a cut-off frequency of 40Hz. Trials with blinks and excessive eye movements were rejected based on the horizontal and vertical electro-oculogram. Over all other electrodes, a trial rejection threshold of ± 100 microvolts was used. Trials were then epoched from -200 to 1805 ms around the onset of the S1 cue-stimulus. The period of -100 to 0 ms was defined as baseline.

Behavioral Measures

To obtain so-called global switching costs, we quantified the difference in reaction times (RT) and accuracy (d-prime) between mixed and “pure” task blocks. To obtain local switching costs, we analyzed differences in RT and d-prime between switch and repeat trials

within the mixed blocks. The RT was measured from all correct 'go' trials (i.e., trials with a target in the cued modality). Responses were only considered valid if they occurred in the window of 200 to 1500 ms following the onset of the gabor in attend-visual conditions and the second tone stimulus in the attend-auditory conditions. The signal detection measure *d-prime* was used to assess response accuracy. This measure is widely used to assess the detectability of an imperative stimulus in a manner independent of a given individual's response criteria, or fluctuations therein. *d-prime* is computed by taking into account the probability of correctly responding to targets when a target is present and the probability of incorrectly initiating a response in the absence of a target (Green & Swets, 1966).

Temporal Spectral Evolution technique

To assess the time-course of oscillatory power changes in the alpha band during our cued-attention task, Temporal Spectral Evolution (TSE) waveforms were computed (Foxy *et al.*, 1998). TSE waveforms provide a robust measure of induced oscillatory power changes (i.e., changes in amplitude of rhythmic activity in which phase varies randomly from trial to trial). The computation of the TSE waveforms in the present study took the following course: 1) Individual trials were bandpass filtered from 8 to 14 Hz (4th order digital Butterworth, zero-phase); 2) The analytic representation of the bandpass-filtered trials were acquired by applying the Hilbert transform; 3) The absolute value of the analytic representation of each trial was taken as a measure of the instantaneous amplitude in the alpha band across the trial; 4) trials in each condition were averaged.

Statistical Analysis Strategy

RT and *d-prime* accuracy were analyzed using a repeated measures analysis of variance (ANOVA) with Trial (switch versus repeat) and Task Modality (visual versus auditory) as within-subject factors. TSE measures were analyzed using the mean amplitude across nine electrode sites over fronto-polar (D4/D5/D6/D11/D12/D13/C28/C29/C30 in the Biosemi labeling convention) and parieto-occipital (A15/A16/A17/A21/A22/A23/A28/A29/A30) scalp regions during an early (700–900ms) and late (1100–1300ms) phase of anticipatory preparatory activity.

As a first step, our analyses detailed the time-course and topographic distribution of oscillatory power changes in the alpha band associated with task-set reconfiguration. This was accomplished by a repeated measures ANOVA with factors Modality (visual versus auditory), Trial (switch versus repeat), Time (early versus late) and Scalp Region (fronto-polar versus parieto-occipital). If a significant Modality $\times$ Trial interaction was found, our second step was to run two protected ANOVAs, one testing task-set reconfiguration between and one within modalities in order to unpack the interaction. For the between modality ANOVA, we tested the time-course and strength of alpha power deployment contrasting switch auditory against switch visual trials and repeat auditory against repeat visual trials. The between modality ANOVA considers alpha power deployment associated with task-set reconfiguration and differences therein between "SWITCH" and "REPEAT" trials. For the within modality ANOVA, we tested time-course and strength of alpha power deployment contrasting switch auditory against repeat auditory trials as well as switch visual against repeat visual trials. The within modality ANOVA considers alpha power deployment

associated with task-set reconfiguration and differences therein between "AUDITORY" and "VISUAL" modalities.

Topographical statistics

Since we initially hypothesized that switch trials would engage distributed networks of task-set reconfiguration and top-down attention to a greater extent than repeat trials, we sought to test for topographic differences among conditions that would suggest the differential engagement of a subset of cortical generators. To test for periods of topographic modulation irrespective of changes in oscillatory amplitude, we calculated the global dissimilarity (GD) (Lehmann & Skrandies, 1980) between differential alpha-band activity (8–14 HZ) across the anticipatory period preceding "SWITCH" trials and "REPEAT" trials. Differential activity is derived by subtracting cue-visual trials from cue-auditory trials. GD is a method to assess configuration differences between two scalp distributions, independent of their strength, as the data are normalized using the global field power. The GD is calculated as the square root of the mean of the squared differences between the potentials measured at each of the 168-scalp electrodes. For each subject and time point, the GD indexes a single value, which varies between 0 and 2 (0 = homogeneity, 2 = inversion of topography). To create an empirical probability distribution against which the GD can be tested for statistical significance, the Monte Carlo MANOVA was applied. This is a nonparametric bootstrapping procedure, wherein each subject's data from each time point are permuted such that they can "belong" to either condition. For each time point, the dissimilarity was then calculated for each of 5000 such permutations (Manly, 1997).

Statistical Cluster Plot

To provide a more general description of the spatio-temporal properties of differential alpha-band activity as a function of task-set reconfiguration, we computed separate statistical cluster plots (SCP) for trials preceding a "SWITCH" and "REPEAT" of task. This procedure has been used effectively in *post hoc* analyses as a means to more fully explore complex datasets and generate pointed follow-up hypotheses (Molholm *et al.*, 2002; Murray *et al.*, 2002). Point-wise two-tailed t-tests between attend-visual and attend-auditory trials were calculated at each time-point for all electrodes. The results of the point-wise t-tests from 168 electrodes are displayed as an intensity plot to efficiently summarize and facilitate the identification of the onset and general topographic distribution of differential alpha-band activity preceding a "SWITCH" and "REPEAT" of task. The x-, y-, and z-axes, respectively, represent time, electrode location, and the t-test result (indicated by a color value) at each data point. For each scalp electrode, only the first time point where the t-test exceeded the 0.05 p-value criterion for at least 11 consecutive data points (>20 ms at a 512 Hz digitization rate) is considered significant (Guthrie & Buchwald, 1991; Foxe & Simpson, 2002).

RESULTS

Behavioral Data

Figure 2 shows reaction time (RT) and accuracy (*d-prime*) data for the mixed-task blocks, where participants switched between visual and auditory tasks within a block, and for the

pure-task blocks, where participants performed either the visual or auditory task alone throughout a block of trials. As previously defined, local costs were obtained by comparing performance between switch and repeat trials during mixed-task blocks. Global mixing costs were obtained by comparing performance between mixed and pure task blocks.

Tests for Local Switch Costs (Reaction Times)—Analysis of variance with Trial (switch versus repeat) and Modality (visual versus auditory) as independent factors revealed a Trial $\times$ Modality interaction ($F_{1,15}=8.69$, $p=.01$). The interaction of Trial $\times$ Modality was driven by the fact that reaction times on Auditory Switch trials ($A_{\text{switch}}=621\text{ms}$) were marginally slower than those on repeat trials ($A_{\text{repeat}}=605\text{ms}$) – a switch cost of 16ms – whereas RTs for visual switch trials ($V_{\text{switch}}=638\text{ms}$) were actually marginally faster than those seen on repeat trials ($V_{\text{repeat}}=657\text{ms}$) – an ostensible 19ms switch benefit. While the interaction term of the ANOVA was significant, follow-up t-tests within modality (i.e. switch versus repeat RTs) showed that neither the auditory switch cost nor the visual switch benefit reached conventional levels of statistical significance ($p>0.06$). As such, there was no evidence here of classic switch costs in terms of response speed.

Tests for Global Mixing Costs (Reaction Times)—Two participants did not complete the pure task blocks, and were thus excluded from this analysis. An analysis of variance with factors of Block (mixed versus pure) and Modality (visual versus auditory) was conducted. While both the auditory ($A_{\text{pure}}=582\text{ms}$, $A_{\text{mixed}}=605\text{ms}$) and visual tasks ($V_{\text{pure}}=587\text{ms}$, $V_{\text{mixed}}=657\text{ms}$) suggested a marginal mixing cost - a mixing cost of 17ms and 70ms for the auditory and visual tasks, respectively - no main effects or interactions reached significance (all $ps>0.1$). As such, there was no strong evidence here of mixing costs in terms of response speed.

Tests for Local Switch Costs (Response Accuracy)—For the *d-prime* measurement of discrimination accuracy, we observed highly similar measurements of discrimination between switch and repeat trials ($A_{\text{switch}}=2.93$ versus $A_{\text{repeat}}=2.82$ and $V_{\text{switch}}=2.81$ versus $V_{\text{repeat}}=2.85$), and an analysis of variance with factors of Trial (switch versus repeat) and Modality (visual versus auditory) unsurprisingly revealed no significant main effects or interactions. As such, there was no evidence of switch costs in terms of task accuracy.

Tests for Global Mixing Costs (Response Accuracy)—Again, two participants did not complete the pure task blocks, and were thus excluded from this analysis. Analysis of variance with Block (mixed versus pure) and Modality (visual versus auditory) as factors revealed a main effect of Block ($F_{1,13}=11.74$, $p=.005$), which was driven by a mixing cost in both the auditory ($A_{\text{pure}}=3.7$ versus $A_{\text{mixed}}=2.86$; $A_{\text{mixcost}}=0.84$) and visual tasks ($V_{\text{pure}}=3.5$ versus $V_{\text{mixed}}=2.84$; $V_{\text{mixcost}}=0.76$). No other main effects or interactions reached statistical significance. In sum, there was clear evidence for mixing costs, such that the need to switch between the auditory and visual tasks, rather than perform each task alone in a sequence, resulted in a robust decrease in target discrimination accuracy for both the auditory and visual tasks.

TSE analysis

Panel A of Figure 3 shows the topography of the differential alpha-band (8–14Hz) oscillatory activity between all attend-auditory and all attend-visual trials (auditory *minus* visual) at 1000ms (i.e. where switch and repeat trials are collapsed together). The parieto-occipital focus of differential alpha power is highly consistent with our previous findings (Fuxe *et al.*, 1998; Fu *et al.*, 2001; Gomez-Ramirez *et al.*, 2007). Panel B of Figure 3 depicts the alpha-band (8–14 Hz) TSE waveforms derived from the three highlighted parieto-occipital electrode sites (central head - panel A). A sustained divergence in TSE amplitude is seen starting at ~600ms post-cue, some 750ms before the onset of the S2 task stimulus, which occurs at 1350ms. Alpha-band activity is greater when subjects have been cued to attend selectively to impending auditory stimulation (i.e. to ignore or suppress concurrent visual inputs). In panel C of Figure 3, the TSE waveforms for attend-auditory (red traces) and attend-visual (black traces) are further distinguished according to trial type (i.e. switch trials (dotted traces) versus repeat trials (solid traces)). If participants are required to reconfigure the task-set on switch trials, the divergence in TSE waveforms is seen to start ~200ms earlier at about 400ms post-cue and reaches a maximum just before the S2 stimulus onset.

Figure 4 depicts the TSE waveforms for attend-auditory and attend-visual trials at six representative electrodes over fronto-polar, and parieto-occipital scalp regions, broken out for switch trials (panel A) and repeat trials (panel B). The extended electrode representation reveals that the modulation of alpha-band activity shows a considerably broader topographic distribution from the more typical focus over the parieto-occipital region, with clear divergence seen over frontal/fronto-polar scalp regions when participants are preparing for a switch of task (panel A). Early and wide-spread TSE modulation for switch compared to repeat trials is also depicted in the statistical cluster plot (SCP - far right column). For repeat trials, there is one main cluster of activation starting at ~1100 ms post-cue, which is distributed over both frontal and parieto-occipital scalp regions. For switch trials, two main clusters of differential activation are evident, an early one starting at ~600 ms and a later one starting at ~1100 ms. Both the early and late clusters show widespread scalp distributions over parieto-occipital, central, and fronto-polar scalp regions. Topographical mapping shows maximal distributions over the parieto-occipital region starting at ~700 ms and over more frontal regions starting at ~1000ms - both are enhanced on switch trials (panel C). Tests for periods of topographic differences between switch and repeat trials revealed significant differences between 900 and 1150 ms, likely indicating greater extent of differential alpha activity over more frontal scalp regions for switch trials.

Figure 5 depicts comparisons of the TSE waveforms between switch and repeat trials as a function of sensory modality, with the auditory modality depicted in panel A and visual modality in panel B. Almost completely overlapping TSE waveforms are observed for switch and repeat trials in the auditory modality and the corresponding SCP map (right column) shows no evidence for any major periods of differential alpha-band activity as a function of this switch versus repeat comparison. Simply put, when it comes to anticipatory deployment of alpha-band activity in advance of performance of an auditory task, there is no evidence for differential deployment as a function of whether individuals are in the process

of switching tasks versus simply repeating the same auditory task. In contrast, robust differential TSE modulations are evident for the comparison of switch and repeat trials when the brain is being prepared to perform the impending visual task. An early difference (~200–350ms) focused over frontal scalp regions is evident in the SCP, as is a more broadly distributed difference over both frontal and posterior scalp in the period between approximately 600ms and 1100ms.

Topographical mapping of differential alpha-band activity during auditory anticipation (panel C) revealed little evidence for robust differential alpha-band activity, although from approximately 700–1200 ms, a modest focus of differential activity can be seen over parieto-occipital scalp. However, as above, this differential activity did not reach conventional levels of significance. For the visual modality, on the other hand, there are two clearly defined foci of differential activity, the most prominent of which is evident over parieto-occipital scalp, with a second clear focus evident over midline fronto-polar scalp (panel D).

Formal statistical analysis of these apparent differences using repeated measures analysis of variance revealed main effects of Modality ($F_{1,15}=9.38$, $p=.008$), Time ($F_{1,15}=9.33$, $p=.008$), Scalp Region ($F_{1,15}=9.21$, $p=.008$), as well as significant interactions of Trial $\times$ Modality ($F_{1,15}=5.55$, $p=.032$). Given the significant Trial $\times$ Modality interaction, we followed up with two protected ANOVAs, testing differential alpha band activity associated with task-set reconfiguration processes between and within modalities (see methods section for rationale). The between modality ANOVA tests differences in anticipatory alpha power between visual and auditory modality considering Trial (switch versus repeat), Time (early versus late), and Region (frontal versus parietal) as factors. The within modality ANOVA tests differences in anticipatory alpha power between switch and repeat trials considering Modality (visuals versus auditory), Time (early versus late), and Region (frontal versus parietal) as factors. The between modality ANOVA revealed main effects of Trial ($F_{1,15}=5.55$, $p=.032$), Time ($F_{1,15}=5.26$, $p=.037$), Region ($F_{1,15}=6.45$, $p=.023$), and a Trial $\times$ Time $\times$ Region ($F_{1,15}=8.23$, $p=.012$) interaction. Region-specific tests confirmed that a trend towards a Trial $\times$ Time interaction was only evident over the parietal-occipital scalp region ($F_{1,15}=3.97$, $p=.06$). The within modality ANOVA revealed a main effect of Trial ($F_{1,15}=5.55$, $p=.032$), and a Trial $\times$ Time $\times$ Region ($F_{1,15}=8.23$, $p=.012$) interaction. Region-specific tests confirmed that a trend towards a Trial $\times$ Time interaction was only evident over parietal-occipital scalp region ($F_{1,15}=3.98$, $p=.06$).

Further investigation of the behavioral indices of task-set reconfigurations

The behavioral data did not exhibit any overt indication of a classical local switch cost. Yet, in light of the current findings regarding alpha oscillatory processes and as suggested by a reviewer, we sought to probe deeper into the behavioral data in order to explore the relationship of the relative behavioral success of a given task-set reconfiguration to the current findings in the oscillatory domain. Certainly prior work has shown links between the effectiveness of alpha-band deployment mechanisms and subsequent task success (Thut *et al.*, 2006; Kelly *et al.*, 2009)

To do this, we undertook a *post-hoc* analysis in which we sorted individual trials based on RT. On an individual participant basis, we split experimental trials based upon the median RT within a given condition (i.e., Repeat Auditory, Switch Auditory, Repeat Visual, and Switch Visual). Dividing each of these original four conditions by the median of the RT distribution yielded what we will refer to as "Fast" and "Slow" conditions for each participant and for each of the original conditions.

The reasoning behind this approach is that a Fast Switch trial reflects a more successful task-set reconfiguration than a Slow Switch trial. This comes with the necessary caveat that a raw RT value on any given trial is by no means a direct index of successful task-set reconfiguration. That is, a relatively fast response on a switch trial is not a pure index of a successful switch but necessarily indexes the multiple underlying neural events that give rise to the stochastic nature of reaction time. Thus, in an attempt to bolster the relevance of "Fast" and "Slow" trials to the successful instantiation of a new task set, we performed the following additional analysis. First, both hit trials (a correct response on a go trial) and false alarm (FA) trials (a mistaken response on a no-go trial) were included in the RT distributions of each of the experimental conditions. Next, after performing the median splits of these distributions, the proportion of hits relative to false alarms was calculated (i.e., hits/hits+FAs) yielding what we will refer to as the success rate. Behavioral success rates were then submitted to a $2 \times 2 \times 2$ repeated measures ANOVA with factors of Modality (visual versus auditory), Trial (switch versus repeat), and Speed (fast RTs versus slow RTs). The ANOVA revealed a main effect of Speed ($F_{1,15} = 4.72, p = 0.046$) and an interaction of Speed $\times$ Trial ($F_{1,15} = 4.55, p = 0.05$). To disentangle this interaction, the data were collapsed across Modality, and two repeated measures t-tests were conducted, one comparing the Switch Fast condition to the Switch Slow condition, and one comparing the Repeat Fast to the Repeat Slow condition. The comparison of Switch Fast versus Switch Slow indicated a significant difference between these two conditions ($t_{15} = 2.57, p = 0.021$), reflecting the fact that the success rate was greater on Switch Fast (0.93(0.06)) versus Switch Slow (0.88(0.08)) conditions. The comparison of Repeat Fast versus Repeat Slow did not cross the significance threshold ($t_{15} = 1.48, p = 0.158$). The results of this analysis indicate that Fast Switch trials were accompanied by a greater proportion of hits to FAs compared to Slow Switch trials, suggesting that RT latency does at least partially reflect the completeness of a given task-set reconfiguration. That this relationship was specific to Switch trials and did not extend to repeat trials adds further weight to this contention.

With this established, we next sought to investigate alpha oscillatory deployment on Fast and Slow trials. From Figure 6 it is evident that on Auditory-Switch-Fast relative to Auditory-Switch-Slow trials a punctate increase in alpha power is evident in the last ~150ms prior to S2 onset over frontal and parietal regions. This effect is wholly absent in the SCPs comparing Auditory Repeat Fast to Auditory Repeat Slow. In the Cue Visual conditions, both Switch and Repeat comparisons exhibit greater alpha desynchronizations on Fast trials relative to Slow trials. However, on observation of the SCPs, Repeat trials show a more focal effect over parietal-occipital areas, while this effect on Switch trials is present over frontal regions as well.

DISCUSSION

We set out to assess the role of anticipatory alpha-band mechanisms during preparation for the first instance of a new task relative to a repeated instance of that same task, on the premise that a key component of initial task-set reconfigurations would involve a vigorous and selective suppression of processing within circuits responsible for the “old” task. And indeed, when we compared the differential deployment of anticipatory alpha-band activity on switch versus repeat trials, by contrasting anticipatory alpha-band power between sensory modalities (i.e. preparing for an auditory versus preparing for a visual task), we found considerably greater differential activity between modalities during switch trials. Further, this differential modulation onset earlier and had a considerably more extensive topographical distribution across the scalp, with clear additional foci evident over more frontal cortical regions. On first assessment, this pattern seems entirely in line with our original thesis that greater attentional suppression mechanisms would be deployed on switch trials relative to repeat trials as the system worked to “erase” the old task-set configuration. However, inherent in this thesis is the notion that greater differential activity should be driven by increased alpha-band suppressive mechanisms during switch trials – i.e. greater synchronization over fronto-parietal control regions. This, however, is not what was found here. Instead, when we made within-modality comparisons of switch versus repeat trials, a wholly different picture emerged. The increases in differential between-modality effects were actually driven by greater desynchronizations rather than the predicted increases in synchronization. Further, these differential effects were entirely driven by changes in alpha-band power during anticipations of the visual task rather than the auditory task. When switch and repeat trials in anticipation of the auditory task were compared, there were essentially no differences found, with late increases in synchronization of alpha-band activity found to be just as prominent during repeat trials as they were during switch trials. In contrast, desynchronizations of alpha during visual trials were found to be substantially stronger and earlier on switch trials than they were on repeat trials. These more vigorous desynchronizations also showed a more wide-spread scalp topography that included a prominent focus over fronto-central scalp in addition to the more typical parieto-occipital foci. How then do the current results accord with our original hypothesis?

Performance Measures and Alpha-Band Activity

The pattern of behavioral results is instructive here. First, when one compares task performance on mixed-task blocks to that on pure-task blocks, it is clear that the need to switch between tasks had a major impact on task accuracy. Participants were considerably less able to discriminate targets (even on repeat trials) during the blocks where switching was required as opposed to blocks where only one task was performed alone over extended periods. On the other hand, the use of instructional pre-cues to indicate which task was to be engaged during mixed blocks led to the complete alleviation of the classical switch-costs that are typically seen during mixed blocks. The implication is that whatever switching processes were deployed in advance of the switch trials must have been fully effective, in that no further improvement in performance was observed on repeat trials, neither in terms of accuracy or speed. In fact, in the case of the visual task, there was a slight slowing of performance on repeat trials that suggested that anticipatory resources were not as

effectively deployed as they had been on the preceding switch trials. This latter finding is consistent with the recorded physiology in that there was clearly less alpha-desynchronization on visual repeat trials than on visual switch trials, suggesting less effective engagement of visual cortical regions.

Why would more effortful deployment on switches lead to differential alpha-involvement during visual anticipation but not auditory anticipation? One simple answer may be that anticipatory alpha-suppression mechanisms were fully and effectively deployed during auditory switch trials and no additional enhancement of this processing strategy was possible on repeat trials. On the other hand, the strong desynchronizations seen during the visual switch trial could represent the vigorous deployment of anticipatory preparatory mechanisms in visual cortices needed to effectively prepare the new visual task, whereas the ‘relaxation’ of this desynchronization during visual repeat trials may represent the withdrawal of resources once optimal task performance levels have already been achieved on the switch trial.

A more nuanced view emerged, however, when we conducted post-hoc analyses of these behavioral patterns. Based on the suggestion of a reviewer of this manuscript, we sought to establish whether more effective switches of task were associated with more vigorous deployments of alpha-band mechanisms. Prior work, for example, has shown that the strength of modulation of anticipatory alpha-band processes is related to subsequent success rates in difficult visual discrimination tasks (Thut *et al.*, 2006; Kelly *et al.*, 2009). It is not entirely straightforward, however, to derive a behavioral measure of “more successful” switches with the current design, since the perceptual discriminability of the stimuli to be acted upon was not manipulated. One possibility though, was that faster switches might represent more effective switches, and so we divided the reaction time distribution of each participant into a FAST and a SLOW half. In support of the notion that faster switches were more effective switches (i.e. trials where the switch cost was most ameliorated), we found that commission error rates were also significantly lower for fast switches than slow switches. That is, participants were much less likely to respond in error when they responded more quickly. In turn, when we examined the alpha-band processes associated with the fast vs. slow switches, we found that alpha synchronization was amplified in the late anticipatory phase in the attend-auditory condition, and that alpha desynchronization was more vigorous in the attend-visual condition. Since this pattern of results was uncovered during post-hoc analyses, it will bear replication in future work, but these data do point to the link between more effective alpha-band deployments and more effective task-set reconfigurations during switch trials.

Is Alpha-band Activity Exclusively a Visual Mechanism?

Another possibility is that alpha-band activity represents a mechanism exclusive to the visual system, and as such, all alpha-modulations should be interpreted insofar as they represent changes in visual receptiveness. A number of recent studies, however, suggest otherwise. First, that alpha-band processes over parieto-occipital scalp are also engaged during audio-spatial selective attention tasks has been shown in a pair of recent studies. Kerlin and colleagues showed distinct lateralization of alpha-band activity over posterior

(presumably visual) regions when participants were required to deploy attention to competing spoken sentences presented either to the left or right side of space (Kerlin *et al.*, 2010). Compellingly, the strength of this alpha-band lateralization was related to the amplification of speech-related activity within the attended stream, suggesting that alpha suppressive mechanisms were indeed involved in biasing audio-spatial attention. Similarly, our group examined anticipatory alpha-band activity during a purely audio-spatial task, also showing clear lateralization of oscillatory activity over parieto-occipital scalp, suggesting that even when no visual events were to be anticipated, visuo-spatial oscillatory processes were engaged (Banerjee *et al.*, 2011). In that study, we also compared anticipatory alpha-band processes between the audio-spatial and a closely matched visuo-spatial paradigm. When attentional deployments to left and right space were collapsed so that the involvement of more general anticipatory alpha-band control processes could be examined, it was clear that there was a strong focus over right parietal scalp sites for both the auditory and visual tasks. Compellingly, the topography of this activity was completely distinct between sensory modalities, such that a strong focus over medial inferior-parietal scalp was observed during visuo-spatial deployments, whereas a more lateral right parietal focus was observed for audio-spatial deployments. As such, the data pointed to the involvement of distinct anticipatory alpha-band processes in both auditory and visual spatial attention deployments, and that these were generated in sensory-specific control fields within the right parietal attention network. In agreement with these results, sensory-specific selective attentional fields within the inferior parietal sulcus (IPS) complex have also been recently shown using functional neuroimaging where auditory spatial control regions were found to be more lateral than visual control regions (Kong *et al.*, 2012). Lastly, in a study employing direct intracranial subdural recordings from the lateral surface of the temporal lobe in humans performing an intersensory selective attention task, our research group found clear evidence for locally-generated auditory-cortical alpha-band activity, and for its involvement in selectively biasing auditory cortical processing (Gomez-Ramirez *et al.*, 2011). In that study, participants were asked to sustain their attention to either the auditory or visual modality while a constant stream of competing bisensory inputs was presented. They performed a difficult perceptual task within the attended sensory stream and we asked what the role of oscillatory activity in modulating auditory cortex would be. We found that activity in the delta band (1–2 Hz) entrained to the regular presentation rates of the task stimuli, but that the phase of delta reversed depending upon which sensory modality was to be attended on a given block of trials. We also found that modulation of alpha-band power was coupled to the phase of the ongoing delta entrainment, and that this led to increases in alpha-band power over auditory cortex that were coincident with the presentation of to-be-ignored auditory stimuli when attention was specifically deployed to the difficult visual task. As such, there was clear evidence for a role for alpha-band activity in modulating the responsiveness of auditory cortex, and the pattern of results was entirely consistent with the notion that this activity served in a suppressive role. The implication of this series of studies is that alpha-band activity is very much involved in the deployment of attentional resources within auditory cortex.

Consequently, a more likely explanation for the lack of obvious alpha-modulation from auditory cortical regions in many of the studies that have used non-invasive scalp recorded

EEG methods, including the current one of course, may pertain to simple issues of cortical geometry. The projection of auditory cortex to fronto-central scalp necessitates propagation of activity across a considerable distance. It seems a distinct possibility that auditory cortical generators of the relatively high-frequency oscillatory activity of the alpha-band, largely buried as they are along the supratemporal plane, may not allow for effective signal propagation to the fronto-central scalp surface.

A recent behavioral study by our group may also inform the present results in that it too points to the engagement of particularly vigorous task inhibition processes on switch trials (Weaver *et al.*, submitted). In that study, participants were free to choose which of two visual tasks to adopt on a given trial, indicating their choice with a button push. They then received a cue that typically matched their choice, but on the occasions when the cue unexpectedly contradicted their initial choice, clear costs ensued. The key observation was that costs were especially severe on trials when participants had just chosen to switch tasks but then had to unexpectedly repeat the previous task. The implication is that suppression of the old task must have been markedly stronger in response to one's choice to switch, such that the necessity to go back and engage (i.e. repeat) the old task proved particularly cumbersome. The present results accord well with this pattern in that the most vigorous preparatory neural processes are clearly evident on the switch trial, manifest as enhanced desynchronization of alpha activity for switch-visual trials. This pattern of effects is quite consistent with the tenets of a biased competition model. When two tasks must be juggled, it is a reasonable proposition that both are held in neural states of relative readiness, and both neuroimaging (Wylie *et al.*, 2004a; 2006) and ERP data (Foxe *et al.*, 2005a) clearly support this contention. Stated otherwise, it seems highly improbable that each task representation would be instantiated *de novo* whenever a switch of task is called for. The obvious next question then is what the nature of the balance between the two task representations might be and how might these differ on switch versus repeat trials? The most economical set point would likely be a situation where the balance between competing task representations is quite finely tuned, such that the currently disengaged task, while temporarily 'dormant', can be readily reinstated. It seems reasonable to suppose that the fine balance between representations would be more easily titrated during repeat trials, whereas switch trials might be characterized by more dramatic swings in this balance to ensure that the new task is properly instantiated.

In fact, it is worth considering what the nature of the cue stimulus and the temporal trajectory of cue-decoding would be in a paradigm such as the one used herein. The cue stimuli clearly serve a dual purpose. The first purpose is to act as a warning stimulus, marking the beginning of a temporally stereotyped trial, and this information is provided by the cue very early during the processing hierarchy. That is, the semantic information content of the cue (i.e. which task is to be engaged), which is encoded in the pictorial representation, will not be available until relatively later in processing (likely after 150 ms) (Thorpe *et al.*, 1996). In contrast, simple detection of the occurrence of the cue is registered some 80–100 ms earlier. This raises an interesting dichotomy and one that bears on the instantiation of preparatory processes. It is entirely likely that initial registration of the cue as a temporally predictive warning stimulus would initiate parallel preparation of both task-set

configurations before the system has any access to the semantic content of the cues, and that it is only later, as this content is decoded, that the system begins to bias preparatory processes towards the cued task. Again, the notion that the now irrelevant task preparatory processes would somehow be aborted completely is not consonant with the nature of ongoing neural processing dynamics. Rather, the probability is that preparation for the irrelevant task begins to decay, or is actively suppressed, as preparation for the relevant task begins to be actively enhanced.

Previous explorations of the role of oscillations during switches of task

Results from a recent audio-visual task-switching study are in very close agreement with those reported herein (Rapela *et al.*, 2012). In mixed blocks, a stream of interspersed auditory and visual stimuli were presented and occasional cues (the words “look” and “hear”) instructed participants to switch to the task within the cued modality. Strong desynchronization of alpha-band activity was measured when the cue counseled a switch to the visual task, a desynchronization that subsequently attenuated substantially once sustained attention had been established for the visual stream (i.e. for repeat trials). When attention was switched to the auditory modality, a clear synchronization of high alpha-band activity emerged, and as here, this synchronization did not significantly attenuate over time as attention was sustained on the auditory inputs. Unfortunately, the authors did not report performance measures on the tasks, so the modulations of oscillatory activity cannot be interpreted accordingly. Nonetheless, there is striking similarity between the physiological effects they report and those of the current study.

The modulation of alpha-band activity over parieto-occipital scalp as a function of task switches versus repeats has also been addressed in studies where both tasks were performed on visual stimuli (i.e. within-modality). In one such study, for example, participants were free to choose which of a pair of tasks to perform on a set of geometric shapes (either a location or a color task) (Poljac & Yeung, 2012). Performance measures made it clear that the location task proved easier in that participants were both faster and more accurate on this task. What these authors found was that alpha-desynchronizations were equivalent preceding switches to both tasks, whereas there was a distinct increase in synchronization preceding repeats of the easier location task, an effect not seen for repeats of the more challenging color task. Similar to the differences seen here for switch versus repeat visual trials, these data suggest that equally vigorous desynchronizations were employed to switch to each visual task, regardless of difficulty, but that once a switch had been made and the participants were ‘locked onto’ the task at hand, resources could be withdrawn from the easier location task. More vigorous alpha-desynchronizations over parieto-occipital scalp preceding switch versus repeat trials in purely within-modality visual task-switching designs have now been reported by a number of groups (Sauseng *et al.*, 2006)

This issue of differential oscillatory suppression as a function of task difficulty was also recently addressed in a study in non-human primates (Buschman *et al.*, 2012). Recording from prefrontal cortex, monkeys were required to switch between performing a color discrimination task and a line orientation discrimination task. Saccadic reaction times were significantly slowed by a switch away from the orientation task to the color task, but not

vice versa. This pattern led Buschman and colleagues to consider the orientation task as 'dominant' over the color task. Performing the 'non-dominant' color task was accompanied by an increase in alpha coherence in neuronal populations showing selectivity for the orientation task, whereas performance of the dominant orientation task did not result in increased alpha coherence in neurons selective for the color task. In line with the notion of alpha-band activity as a suppression mechanism, these authors contended that performing the non-dominant task required active suppression of the dominant ensembles through an oscillatory gating mechanism, implying that this gating mechanism may be asymmetrically deployed dependent on the predisposition of the brain towards one competing task versus another.

A key distinction between these studies of within-modality switches and our between-modality study is that the two tasks are typically afforded by the same stimuli in the former, whereas in the current design, the participants switch between both the task and the stimuli affording those tasks. When one switches between auditory and visual inputs, the suppression of the potentially distracting sensory inputs can putatively be achieved by a relatively indiscriminate suppression of a large swath of cortex, likely involving early sensory regions. On the other hand, when both tasks are afforded by the same object (e.g. the printed words in a Stroop task), then the suppression mechanisms would need to target much more specific, feature-level representations. In a recent study, we assessed this issue by asking individuals to switch between a color and a motion task, where both features were afforded by the same random dot field arrays (Snyder & Fuxe, 2010). Consistent with a feature-based suppression account, we found that alpha power increased within dorsal visual regions when motion was to be suppressed (i.e., when color was the relevant feature), whereas alpha power increased in ventral visual regions when color was irrelevant. One could certainly argue that in the current experiment, the auditory and visual inputs to be acted upon had no natural relationship to each other. Thus, although they are presented simultaneously and compete for resources, they may be perceived as separable objects, and the level of competition between them would likely then be less than if the tasks were afforded by features of the same object. It may be of considerable interest in future work, to employ audio-visual stimuli where there is a clear semantic relationship between the constituent inputs (e.g. animals and their related vocalizations) (Molholm *et al.*, 2004; Molholm *et al.*, 2007; Fiebelkorn *et al.*, 2010).

Conclusions

We observed clear behavioral mixing costs in a cued audio-visual task, but no apparent switching costs, suggesting that preparatory processes during the cue-target period allowed for the entirely successful resolution of competition among the two task-sets. We argue that, within our design, the competing tasks are held in close states of readiness, and then "tipped" in favor of one or the other of the tasks by neural biasing mechanisms. Our findings support the contention that one of these mechanisms very likely involves the distribution of alpha oscillations among relevant cortical regions. Further work is required to fully tease apart the contribution of alpha synchronizations and desynchronizations to task-set reconfigurations.

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Figure 1. Stimulus configuration
The cue stimulus (S1) onsets at 0 ms, followed 1350 ms later by the compound bisensory S2, which consists of a pair of bilateral visual gabor patches and a pair of sequentially presented bilateral tone pips. Participants perform a difficult orientation task by comparing the orientations of the left and right Gabor patches when the visual task is cued (Cue = Image of computer monitor). Participants perform a difficult frequency discrimination task by comparing the pitch of the first and second tone pips when the auditory task is cued (Cue = Image of headphones). Fixation is maintained throughout each trial.

Figure 2. Performance Data

Reaction time (RT) data (top panel) and accuracy levels expressed as *d-primes* (bottom panel) are plotted for both mixed and pure task blocks for the auditory (red) and visual (black) tasks. For mixed task blocks, data are plotted for both switch and repeat trials. For the pure task blocks, there are by definition only repeat trials.

A. Topography

B. TSE by attended modality

C. TSE by attended modality and task-set (re)configuration

Figure 3. Anticipatory Alpha-Band Suppression effect

Alpha-band oscillatory activity is selectively modulated by deployment of anticipatory attention to different sensory modalities. *Panel A.* Topographic maps show the differential alpha effect over parieto-occipital scalp between attend-visual and attend-auditory trials (plotted for the 1000ms time point). *Panel B.* Corresponding alpha-band (8–14 Hz) TSE waveforms derived from the three highlighted electrode sites (central head - panel A). A sustained divergence in TSE amplitude is seen starting at ~600 ms post-cue, some 750 ms before the onset of the S2 task stimulus, which occurs at 1350 ms. Alpha-band activity is significantly greater when subjects have been cued to attend selectively to impending auditory stimulation. *Panel C.* Alpha-band TSE waveforms are ‘broken out’ as a function of

whether participants were anticipating a switch trial (dotted traces) or a repeat trial (solid traces).

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Figure 4. Between Modality Anticipatory Alpha-Band Suppression effect

Panel A. Alpha-band TSE waveforms during the anticipatory period preceding impending switch trials are displayed for a trio of representative fronto-polar electrode sites and a similar trio of parieto-occipital sites. Of note is the divergence in alpha-power between attend-auditory (red dotted traces) and attend-visual (black dotted traces) over the frontal scalp sites. The statistical cluster plot to the right shows substantial periods of both early and late alpha differentiation that encompasses both posterior scalp and frontal scalp. *Panel B.* In contrast, alpha-band TSE waveforms plotted for the same sites during anticipation of repeat

trials shows no such early modulation over frontal sites. Significant alpha-band effects are only observed robustly during the late anticipatory period (1100–1300ms). *Panel C & D*. Flattened scalp projections of differential alpha-band activity (8–14 Hz) across the anticipatory period preceding “SWITCH” trials and “REPEAT” trials. It is evident that alpha-band activity is of higher differential amplitude, begins earlier in the anticipatory period and encompasses a more extensive scalp distribution for “SWITCH” trials than for “REPEAT” trials.

A. Auditory modality **B. Visual modality** **C. Auditory modality Topography: switch auditory minus repeat auditory** **D. Visual modality Topography: switch visual minus repeat visual** **Figure 5. Within Modality Anticipatory Alpha-Band Suppression effect**

Panel A. Alpha-band TSE waveforms during the anticipatory period preceding impending switch and repeat trials within the auditory modality. No or minimal TSE modulations are seen and the related SCP map (right column) shows no robust periods of differential alpha-band activity as a function of this switch versus repeat comparison. *Panel B.* Alpha-band TSE preceding impending switch and repeat trials for the visual modality and the corresponding SCP reveal robust modulations between approximately 600ms and 1100ms. *Panel C & D.* Scalp maps of differential alpha-band activity for the auditory and visual

modality. The most prominent focus of differential activity over parieto-occipital scalp is evident for the visual modality.

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A. Auditory Switch Trials **B. Auditory Repeat Trials** **C. Visual Switch Trials** **D. Visual Repeat Trials** **Figure 6. RT-median-split Anticipatory Alpha-Band Suppression effect**

Panel A & B. Auditory alpha-band TSE waveforms and related SCP maps comparing fast and slow RT-trials for switch trials (panel A) and for repeat trials (panel B). A robust cluster of differential alpha-band activity immediately preceding the presentation of a switch trial is associated with RT. **Panel C & D.** Visual alpha-band TSE waveforms and related SCP maps comparing fast and slow RT-trials for switch trials (panel C) and for repeat trials (panel D). Robust TSE modulations immediately preceding the presentation of the target stimulus in both switch and repeat trials are associated with RT.