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The costs of crossing paths and switching tasks between audition and vision

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ABSTRACT

Switching from one functional or cognitive operation to another is thought to rely on executive/control processes. The efficacy of these processes may depend on the extent of overlap between neural circuitry mediating the different tasks; more effective task preparation (and by extension smaller switch costs) is achieved when this overlap is small. We investigated the performance costs associated with switching tasks and/or switching sensory modalities. Participants discriminated either the identity or spatial location of objects that were presented either visually or acoustically. Switch costs between tasks were significantly smaller when the sensory modality of the task switched versus when it repeated. This was the case irrespective of whether the pre-trial cue informed participants only of the upcoming task, but not sensory modality (Experiment 1) or whether the pre-trial cue was informative about both the upcoming task and sensory modality (Experiment 2). In addition, in both experiments switch costs between the senses were positively correlated when the sensory modality of the task repeated across trials and not when it switched. The collective evidence supports the independence of control processes mediating task switching and modality switching and also the hypothesis that switch costs reflect competitive interference between neural circuits.

1. Introduction

The activities of daily life require an ability to flexibly switch from one functional or cognitive operation to another. Sometimes, such switches can be triggered by environmental stimuli (e.g., a knock at the door or the ringing of a telephone) and will draw one's attention, interrupt current activities, and result in a clear set of consequent behaviors (e.g., opening the door or picking up the telephone). Other situations are more ambiguous and are thought to require the involvement of control or executive processes to guide behavior (Monsell, 1996; Norman & Shallice, 1986). For example, when arriving home after work, one must decide whether to sit and watch TV, make dinner, or tidy up the house. All of these are valid actions upon returning home, but the choice of which will depend on what one's currently relevant goals or plans are.

In an experimental setting, control processes can be investigated using task-switching paradigms. Task switching refers to the ability to perform a given task after having just performed a different task. In a cued task-switching paradigm, like the one used here, participants are presented with stimuli that afford two (or more) tasks and are instructed by cues as to which task is relevant on each trial. Sequences are arranged such that on a given trial participants are either repeating the same task that they just performed on the preceding trial or are switching to perform a different task (termed repeat and switch trials, respectively). Performance on switch and repeat trials is then compared, and participants are typically slower and more error prone on switch trials than on repeat trials—a difference in performance commonly termed 'switch cost'.

Switch costs have been thought of as an index of the operation of control processes (Jersild, 1927; Meiran, 1996; Nicholson, Karayanidis, Poboka, Heathcote, & Michie, 2005; Rogers & Monsell, 1995; Rubinstein, Meyer, & Evans, 2001; Spector & Biederman, 1976), though the precise interpretation of which neural operations are being performed remains debated. Some propose that the switch cost follows from a necessity to reconfigure brain networks, i.e.,

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to activate cognitive or attention control structures, (e.g., pre-frontal cortices, the anterior cingulate, parietal cortices, etc.) necessary for switching to the new task (Rogers & Monsell, 1995; Rubinstein et al., 2001). Some part of this reconfiguration is thought to occur during the preparation interval between presentation of the cue stimulus and imperative stimulus (e.g. Wylie, Murray, Javitt, & Foxe, 2008). Others interpret switch costs as due in part to the coding of the cue stimulus itself (Logan & Bundesen, 2003), though more recent studies would suggest that encoding of a new cue does not account for the full switch cost (Brass & von Cramon, 2004). In addition to these propositions, previous studies from Wylie and colleagues provide evidence that a substantial portion of the switch cost arises from interference (competition) with persisting, task-related activity of the previous trial, i.e. with activity in neural circuits that were associated with the no longer relevant task and/or with processing stimulus features for this task (Allport & Wylie, 1999; Allport & Wylie, 2001; Wylie & Allport, 2000; Wylie, Javitt, & Foxe, 2003a; Wylie, Javitt, & Foxe, 2003b; Wylie, Javitt, & Foxe, 2004a; Wylie, Javitt, & Foxe, 2004b; Wylie, Javitt, & Foxe, 2006).

In addition to costs associated with switching tasks, variation in the sensory modality in which a task is performed has been shown to result in modality switch effects, wherein participants are typically slower and more error prone on modality switch trials than on modality repeat trials despite the task remaining constant (e.g. Gondan, Lange, Rösler, & Röder, 2004; Spence, Nicholls, & Driver, 2001; though see also Duncan, Martens, & Ward, 1997). At present, the commonality between the mechanisms mediating the costs associated with task switching and modality switching remain understudied. To the best of our knowledge only one study has to date been conducted. Hunt and Kingstone (2004) investigated whether task switching and modality switching rely on independent control mechanisms, in which case the effect of switching both task and modality on the same trial would be expected to be additive when compared to the effect of switching either task or modality alone. In addition to obtaining both an effect of task switching and modality switching, Hunt & Kingstone also obtained a sub-additive effect of simultaneously switching both the sensory modality and task (though this was indeed greater than the effect of switching either alone). From such findings, they proposed that control processes mediating these kinds of switches are separable, yet linked. More generally, they concluded that control processes do not operate in full independence of the modality in which a task is being performed. Rather, the processes of task switching and modality switching are subject to their respective processing bottlenecks, which are at least partially distinct from any common bottleneck operating when both task and modality are switched (see also Duncan et al., 1997; Jolicoeur, 1999).

A parallel issue when considering switch costs is the ability of participants to prepare for the switch. The effects of increasing the preparation time, prior to a switch of task, have been extensively studied (e.g. Gade & Koch, 2007; Meiran, 1996; Rogers & Monsell, 1995; Wylie et al., 2008). One consistent finding is that switch costs decrease as the amount of time subjects have to prepare for a forthcoming switch increases, through typically not to zero. In the study by Hunt and Kingstone (2004), there was a long preparation interval (~2500 ms) on every trial. Plus, repetitions and switches of task were fully predictable across trials. While it might be that these attributes of the paradigm afforded maximal opportunity to engage in preparatory processes prior to each switch of task, it could also be that this interval was overly long for participants to have been maximally prepared when the stimulus was presented. Because few task-switching studies use preparatory intervals longer than 1000 ms, it is difficult to know whether switch costs begin to increase when preparatory intervals become exceedingly long. One possibility is that maximal preparation is achieved within the first second and then wanes. One of the aims of the current experiments was to determine the effects of switching task and modality using a preparatory interval that can be more easily interpreted relative to the existing literature (Experiment 1). Second, while Hunt and Kingstone (2004) provided participants with a very long interval to prepare for each task, the sensory modality of the stimulus (visual or auditory) was completely random, only becoming evident upon stimulus presentation. Thus, they were allowed no time to prepare for the forthcoming sensory modality. It is therefore not entirely clear whether the cost associated with switching task and that associated with switching modality should be directly comparable. Our second aim was to manipulate subjects' foreknowledge of the sensory modality of the forthcoming stimulus to investigate subjects' ability to prepare for a switch of sensory modality.

Our third aim was to better understand the relationship between task switching and modality switching. Hunt and Kingstone (2004) showed that the interaction between these variables was sub-additive, but important questions remain. Here, we use correlational analyses to investigate this issue. We reasoned that the switch costs elicited by switching between two visual tasks or between two auditory tasks (i.e., within-modality switches of task) should be positively correlated with one another. This follows an underlying premise in the task-switching literature that the switch cost measures a cognitive process that is not dependent upon the specific tasks that are used. The array of tasks that have been used to study switch costs is very large, yet the switch costs that have been elicited have been thought to reflect the operation of a common cognitive process. Some have interpreted this cost as the time taken to reconfigure the system for the new task (e.g., Meiran, 1996; Rogers & Monsell, 1995; Rubinstein et al., 2001), others as more reflective of interference or competition between alternative stimulus–response mappings (e.g., Allport, Styles, & Hsieh, 1994; Wylie et al., 2004b). Regardless of the interpretation, if this assumption is valid, one would expect that if a given participant exhibited a large switch cost when switching between tasks A and B, that participant would also show a large switch cost when switching between tasks C and D. That is, switch costs should positively correlate. While this framework leads to strong predictions about the correlations between within-modality switch costs (i.e., when the sensory modality repeats), we were less sure about the correlations of across-modality switch costs (i.e., when the sensory modality switches). If switching task is dependent upon a process of reconfiguration, one might expect positive correlations between across-modality switches for much the same reasons as one would expect positive correlations between within-modality switches. However, if it is competition that is largely responsible for the switch cost, one might not expect across-modality switch costs to correlate. This is because the segregation of the two modalities should result in less competition between tasks, and therefore this putative competitive process should account for less of the RT on switch trials when subjects switch from one modality to another.

The present study further examined the proposition that switch costs will diminish when effective preparation of the appropriate neural circuits is possible and/or when these neural circuits are distinct either anatomically or functionally (Wylie et al., 2006) by examining task switching between functional subdivisions within a sensory modality and/or between sensory modalities. More specifically, we investigated the ability to switch between tasks requiring the categorization of a given object (the 'what' task), and the localization of where it was presented in space (the 'where' task). In addition, on any given trial these stimuli were presented either visually or acoustically. Experiment 1 cued participants as to the task, but not the sensory modality of the stimulus, whereas Experiment 2 cued participants as to both the upcoming task and sensory modality. Multiple lines of evidence support the existence of partially segregated functional and anatomic pathways for processing the identity and location of stimuli (so-called 'what' and 'where' pathways, respectively) within both the visual system (e.g., Haxby et al., 1994; Ungerleider & Mishkin, 1982) as well as the auditory system (e.g., Alain, Arnott, Hevenor, Graham, & Grady, 2001; De Santis, Clarke, & Murray, 2007; Kaas & Hackett, 2000; Maeder et al., 2001; Rivier & Clarke, 1997; Romanski et al., 1999; Tardif, Spierer, Clarke, & Murray, 2008; Tian, Reser, Durham, Kustov, & Rauschecker, 2001; see also Chan & Newell, 2008; De Santis, Spierer, Clarke, & Murray, 2007 for evidence concerning the somatosensory system). By using tasks that are thought to recruit functionally specialized pathways in each sensory modality and by varying across trials the sensory modality in which the task was performed, we attempted to minimize the interference, or cross-talk, between the brain activity associated with the tasks subjects performed on successive trials. If a large portion of the switch cost is indeed due to such interference, then reducing the interference should result in a reduction in the switch cost.

Here, we show that switch costs are indeed smaller when participants perform tasks mediated by anatomically and functionally distinct neural pathways. We also replicate the sub-additive effect of switching both task and modality that Hunt and Kingstone (2004) reported, as well as the finding that switch costs are smaller when the sensory modality switched relative to when it repeated. Our results using a correlation analysis extend Hunt and Kingstone's (2004) inference regarding the extent of independence between mechanisms mediating switching task and switching modality by showing that switch costs are only correlated between the senses when the sensory modality of the task repeated, but not when it switched.

2. Materials and methods

2.1. Experiment 1: Pre-trial cuing of task, but not sensory modality

2.1.1. Participants

Sixteen (10 women; 6 men) unpaid volunteers, aged 21–36 years (mean ± *SD* = 26.9 ± 1 years), provided written informed consent to participate in the experiment and were included in the analyses presented here. Data from an additional four participants were excluded due to high (i.e., >25%) error rates. The Ethics Committee of the Faculty of Biology and Medicine of the University of Lausanne approved all procedures. Thirteen of the 16 participants were right-handed, one was left-handed, and two were ambidextrous (Oldfield, 1971). None of the subjects had current or prior neurological or psychiatric illnesses. All had normal or corrected-to-normal vision and reported normal hearing.

2.1.2. Stimuli and task

Each trial entailed the following sequence of events. First, an auditory–visual cue stimulus was centrally presented for 500 ms that signaled which of the two tasks (left vs. right spatial discrimination or living vs. man-made object categorization) should be completed on a given trial. This was followed by 650 ms of no stimulation (i.e., central fixation cross only). Then, the target stimulus (either visual or auditory) was presented for 500 ms. This was in turn followed by a variable inter-trial interval of 2.5-3.0 s, during which time a central fixation cross was present and participants performed button-press responses via a serial response box.

Cues were always simultaneous auditory–visual stimuli. The visual part of the cue was a centrally presented ellipse or a triangle (black on white) of a similar size as the target stimuli (described below). The auditory part of the cue was either a smoothly ascending (260–450 HZ) or descending (650–450 Hz) frequency-modulated tone. Cues were presented for 500 ms. The spatial discrimination task was cued by an ellipse with an ascending tone. The categorization task was symbolized by a triangle with a descending tone.

Visual target stimuli were 30 black-on-white line drawings selected from either a standardized set (Snodgrass & Vanderwart, 1980) or obtained online and modified to stylistically resemble those from the standardized set. Half of the pictures were of living objects, and the remaining half were of man-made objects. Images subtended ~5° visual angle and were presented for 500 ms on a CRT monitor (Philips Brilliance 202P4) either to the left or right of the central fixation cross at an eccentricity of ~4° with respect to the center of the image. In total, this generated 60 stimuli (i.e., 30 drawings × 2 lateralizations).

Auditory target stimuli were 30 sounds corresponding to each of the line drawings described above. These sounds were selected from a database we have previously used to investigate the brain mechanisms of auditory object discrimination (detailed in Murray, Camen, Gonzalez Andino, Bovet, & Clarke, 2006). Each sound (500 ms duration; 22 kHz digitization) was modified (Adobe Audition 1.0; www.adobe.com) to be monaural in each channel. This generated 60 total stimuli (i.e., 30 sounds × 2 channels). Sounds were presented via insert earphones (Etymotic model ER-4P; www.etymotic.com). The volume of sounds was 73dB SPL (measured using a CESVA SC-L sound pressure meter; www.cesva.com). Prior psychophysical investigation by our group has demonstrated that the sounds used in this study were readily categorized and identified (cf. Table 1 in Murray et al., 2006).

2.1.3. Procedure

The cue stimulus signaled which task should be performed on the upcoming trial, but provided no information about whether the target stimulus would be auditory or visual. Thus, on each trial participants had to prepare both sensory modalities. The cued task was pseudo-randomized across trials, with a maximum of three repetitions of the same task. The target stimulus was defined along three parameters: (1) sensory modality (visual or auditory), perceived location (left or right of midline), and object category (living vs. man-made). In this way, target stimuli were always bivalent with respect to the to-be-performed task and were univalent with respect to the stimulated sensory modality.

Participants were comfortably seated 110 cm from the computer monitor and were instructed to fixate a centrally appearing cross during each block of trials. Participants responded by pressing one of four vertically arranged buttons on a serial response box that was placed directly in front of them. Responses were made with the right hand, which was also oriented to be aligned with the response buttons by folding the arm comfortably with the elbow outward. The upper two buttons were used for the object classification task; the uppermost of these was to indicate a living object and the lowermost a man-made object. The lower two buttons were used for the spatial discrimination task; the uppermost of these was to indicate a left-sided stimulus and the lowermost a right-sided stimulus.[2] A sheet of paper indicating the coding of the response buttons was placed next to the response box for subjects to consult if needed. Participants were instructed to perform as quickly and as accurately as possible.

The experiment took place in a dimly lit, sound-attenuated booth (Eckel, Canada). Stimulus delivery and behavioral response recording was controlled by E-prime (Psychology Software Tools, Inc.; www.pstnet.com/eprime). Each participant completed three blocks of trials (~80 trials in each block with a total of 240 trials for the three blocks altogether). There were equal numbers of trials requiring completion of the location and recognition task and equal numbers of trials wherein the test stimulus was visual or

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[2] In this way, there was no overlap between response set and the two tasks.

auditory. The total duration for participating in the experiment was approximately 20 min, with breaks of a few minutes between blocks. However, this design did not guarantee an identical number of switch and repeat trials for each task and each sensory modality stimulated. For example, the design naturally lends itself to yielding a higher number of trials wherein either the sensory modality and/or the task switches rather than repeats, because only 25% of trials involved repetitions of both the sensory modality and task. We therefore generated a set of eight different randomized lists of trials that varied in their task and stimulus presentation order. This minimized the possibility that any effects followed from a specific task or stimulus sequence. In addition, to fully counterbalance the presentation of visual and auditory stimuli in the same switch/repeat trial circumstances, an inversion of each of these eight lists was created (i.e., each picture was replaced by the associated sound and vice versa, but conserving the order of the tasks to be performed). In total, there were therefore 16 different lists—i.e., one per subject.

2.2. Experiment 2: Pre-trial cuing of both task and sensory modality

2.2.1. Participants

Fourteen (11 women; 3 men) unpaid volunteers, aged 22–34 years (mean ± *SD* = 28.1 ± 1 years), provided written informed consent to participate in the experiment and were included in the analyses presented here. None of these individuals participated in Experiment 1. The Ethics Committee of the Faculty of Biology and Medicine of the University of Lausanne approved all procedures. All but one of the participants was right-handed (Oldfield, 1971). No one had current or prior neurological or psychiatric illnesses. All had normal or corrected-to-normal vision and reported normal hearing.

2.2.2. Stimuli, task, and procedure

The stimuli, task, and the procedure were identical to those of Experiment 1, except that the pre-trial cues were informative about both the upcoming task and sensory modality of the target stimulus. Thus and in contrast to Experiment 1, participants only had to prepare for task performance in one sensory modality. The information conveyed by the cues was always valid with regard to the sensory modality of the upcoming stimulus. There were four different cue stimuli, which were always simultaneous auditory–visual stimuli. The visual part of the cue was a centrally presented ellipse or a rectangle (black on white) of a similar size as the target stimuli. The spatial discrimination task was cued by an ellipse and higher frequencies. The categorization task was cued by a rectangle and lower frequencies. Visual stimulation was cued by vertically elongated and ascending stimuli and auditory stimulation by horizontally elongated and descending stimuli. Participants were presented with samples of the cues prior to the experiment to familiarize them with the associated tasks.

2.2.3. Data analyses

Data from each Experiment were separately analyzed with the SPSS software package (version 15.0.1). Reaction times (RTs) and accuracy were analyzed using repeated measures ANOVA. The eight different conditions generated a $2 \times 2 \times 2$ design with within-participant factors of the sensory modality of the target stimulus (visual vs. auditory), the status of the to-be-performed task (i.e., task-set; switch vs. repeat), and modality status (switch vs. repeat). It is important to note that because, in Experiment 1, only the task and not the sensory modality of the target stimulus was cued, the performance cost of switching modality could not be explained by the encoding of the cue.

In addition, task-related 'switch costs' were calculated for each sensory modality as the RT difference between trials where the task switched and trials where the task was repeated (with respect to the previous trial). These were in turn calculated as a function of whether the sensory modality switched or repeated. Pearson correlations were then calculated between task-related switch costs from each sensory modality when the sensory modality repeated and when the sensory modality switched. This was done in order to assess whether switch costs were related across the senses and whether such depended on the stability of the sensory modality in which the task was performed across trials Fig. 1.

3. Results

3.1. Experiment 1

3.1.1. Reaction times

Mean RTs are displayed in Fig. 2a as a function of whether the to-be-performed task (i.e., task-set) switched or repeated. Data are shown separately for each sensory modality of the target stimulus and for trials where the sensory modality of the target stimulus switched or repeated. The $2 \times 2 \times 2$ repeated measures ANOVA with these data identified a significant main effect of the sensory modality of the target stimulus ($F_{(1,15)} = 16.483$; $p = .001$), with RTs being generally faster with visual than with auditory stimuli. There was also a significant main effect of whether the task was switched or repeated relative to the previous trial ($F_{(1,15)} = 47.261$; $p < .001$), with RTs being generally faster when the task repeated than when it switched. That is, all situations led to a reliable switch cost. There was also a significant interaction between task switching and modality switching ($F_{(1,15)} = 12.694$; $p = .003$). This resulted from a smaller difference between task-

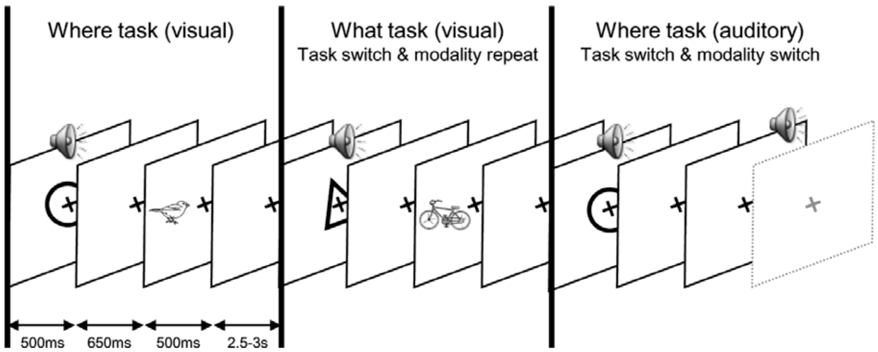

Fig. 1. Illustration of the experimental paradigm across three possible successive trials (see Section 2 for details). Each trial began with the presentation of an auditory–visual cue (500 ms duration) that indicated the task for the upcoming stimulus (but not the sensory modality). This was followed by a blank screen for 650 ms and then the imperative stimulus (500 ms). Finally, there was a blank screen presented for 2.5–3.0 s during which time participants indicated their response.

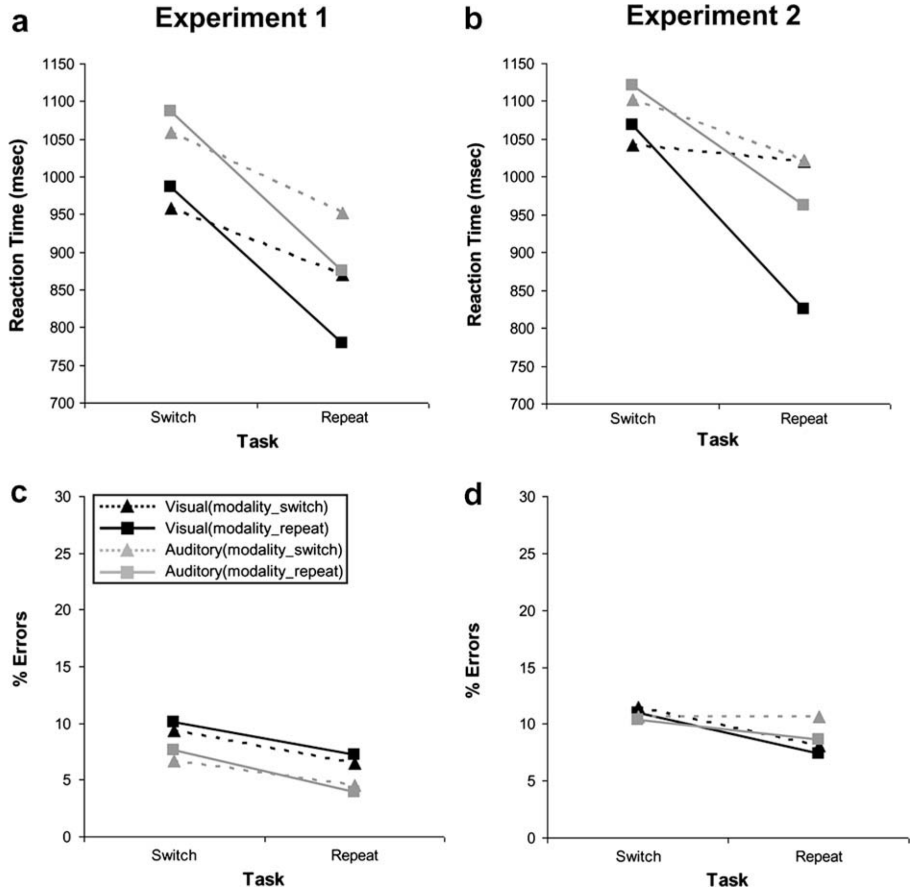

Fig. 2. Behavioral results. The left side of this figure illustrates results from Experiment 1 (a and b), while the right side illustrates results from Experiment 2 (c and d). (a and c) Mean reaction times as a function of whether the task switched or repeated are displayed for each sensory modality and separately for trials when the modality of the stimulus switched and repeated. (b and d) Mean percentages of errors for the same conditions are displayed following the same conventions as in (a and b).

switch and task-repeat trials when the modality switched than when it repeated. That is, participants benefited on trials when the task switched if the sensory modality of the task also switched. No other main effects or interactions of this analysis reached the 0.05 significance criterion.

Because one of our hypotheses was that switch costs would be lessened when subjects switched modality, we performed a *t*-test (two-tailed, paired) between task-switch and task-repeat trials, when the modality switched. For both sensory modalities, the difference was significant (visual: 958 ms vs. 870 ms; $t_{(15)} = 3.46$; $p = .003$; auditory: 1059 ms vs. 952 ms; $t_{(15)} = 2.93$; $p = .01$). These results indicate that switch costs remained reliable in each sensory modality when the sensory modality switched, even though the switch costs were reduced relative to when the sensory modality repeated (as indicated by the above interaction in the ANOVA).

3.1.2. Error rates

Mean error rates (%) are displayed in Fig. 2b as a function of whether the to-be-performed task (i.e., task-set) switched or repeated. As above, data are shown separately for each sensory modality of the target stimulus and for trials where the sensory modality of the target stimulus switched or repeated. The $2 \times 2 \times 2$ repeated measures ANOVA with these data identified a significant main effect of the sensory modality of the target stimulus ($F_{(1,15)} = 18.582$; $p = .001$), with higher error rates for visual than auditory stimuli. There was also a significant main effect of whether the task was switched or repeated relative to the previous trial ($F_{(1,15)} = 11.454$; $p = .004$), with lower error rates when the task repeated than when it switched. No other main effect and none of the interactions reached the .05 significance criterion. In this way, error rates exhibited a prototypical pattern observed with task-switching paradigms, irrespective of the sensory modality of the target stimulus switching or repeating. As such, these data will not be discussed in further detail.

3.1.3. Correlations between switch costs

Task-related switch costs were calculated for each sensory modality and also as a function of whether the sensory modality of the target stimulus switched or repeated. The correlation between the magnitudes of switch costs across the senses was then evaluated using Pearson's correlation coefficient (Fig. 3). Switch costs were positively correlated between vision and audition when the sensory modality of the target repeated across trials ($r_{(14)} = .522$; $p = .038$), but not when it switched across trials ($r_{(14)} = -.109$; $p = .687$).[3]

3.2. Experiment 2

3.2.1. Reaction times

Mean RTs are displayed in Fig. 2c as a function of whether the to-be-performed task (i.e., task-set) switched or repeated. Data

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[3] Inspection of Fig. 3 suggests that the reliable correlation might be due to the contribution of one very slow subject (an outlier). Closer inspection of the data from this individual, however, showed that while s/he had large switch costs, his/her RT data was not anomalous. Indeed, his/her mean RT (across all conditions) was *faster* than the group mean, as well as being within one standard deviation of the group mean.

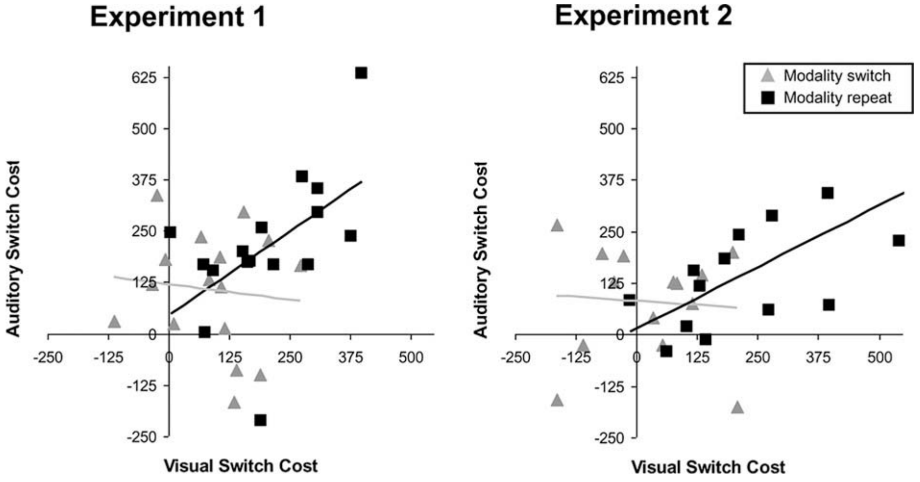

Fig. 3. Correlation analysis. The relationship between auditory and visual task switch costs is displayed separately for trials when the sensory modality of the imperative stimulus switched or repeated (gray triangles and black squares, respectively). The left panel displays this relationship in Experiment 1, and the right panel that in Experiment 2.

are shown separately for each sensory modality of the target stimulus and for trials where the sensory modality of the target stimulus switched or repeated. The 2 × 2 × 2 repeated measures ANOVA with these data identified a significant main effect of the sensory modality of the target stimulus ($F_{(1,13)} = 7.570$; $p = .016$), with RTs being generally faster with visual than with auditory stimuli. There was also a significant main effect of whether the modality had just switched or repeated ($F_{(1,13)} = 6.135$; $p = .028$), with RTs being generally faster for trials where the modality of the task repeated. Finally, there was also a significant main effect of whether the task was switched or repeated relative to the previous trial ($F_{(1,13)} = 25.502$; $p < .001$), with RTs being generally faster when the task repeated than when it switched. That is, all situations led to a reliable switch cost. There was also a significant interaction between task switching and modality switching ($F_{(1,13)} = 12.211$; $p = .004$). This resulted from a smaller difference between task-switch and task-repeat trials when the modality switched than when it repeated. As in Experiment 1, participants benefited on trials when the task switched if the sensory modality of the task also switched. No other main effects or interactions of this analysis reached the 0.05 significance criterion.

As in the analysis of Experiment 1, we performed a *t*-test (two-tailed, paired) to determine if the difference between task-switch and task-repeat trials was reliable when the modality switched. For the auditory task, this difference was reliable (1103 ms vs. 1023 ms; $t_{(13)} = 2.22$; $p = .043$). However, for the visual task, the difference was not reliable (1043 ms vs. 1021 ms; $t_{(13)} = .67$; $p = .51$). Because the only difference between Experiment 1 (in which we found reliable task-switch costs for both tasks when the modality switched) and Experiment 2 (in which the task-switch cost was abolished for the visual task) was that subjects had foreknowledge of the modality in Experiment 2, it appears that subjects can use this foreknowledge to effectively prepare for a switch of task in some cases (i.e., for the visual task, though less so for the auditory task).

3.2.2. Error rates

Mean error rates (%) are displayed in Fig. 2d as a function of whether the to-be-performed task (i.e., task-set) switched or repeated. As above, data are shown separately for each sensory modality of the target stimulus and for trials where the sensory modality of the target stimulus switched or repeated. The 2 × 2 × 2 repeated measures ANOVA with these data identified a significant main effect of task-set ($F_{(1,13)} = 6.115$; $p = .028$), with generally lower error rates for repeat trials than switch trials. No other main effect and none of the interactions reached the 0.05 significance criterion. In this way, error rates exhibited a prototypical pattern observed with task-switching paradigms, irrespective of the sensory modality of the target stimulus switching or repeating. As such, these data will not be discussed in further detail.

3.2.3. Correlations between switch costs

Task-related switch costs were calculated for each sensory modality and also as a function of whether the sensory modality of the target stimulus switched or repeated. The correlation between the magnitudes of switch costs across the senses was then evaluated using Pearson's correlation coefficient (see Fig. 3). As was the case for Experiment 1, switch costs were positively correlated between vision and audition when the sensory modality of the target repeated across trials ($r_{(12)} = .698$; $p = .006$), but not when it switched across trials ($r_{(12)} = -.072$; $p = .811$).

4. Discussion

We investigated the performance costs associated with switching tasks and/or switching sensory modalities. Tasks required the analysis of either the identity or spatial location of environmental objects ('what' and 'where' tasks, respectively) that were presented either visually or acoustically on any given trial. In Experiment 1, pre-trial cues informed participants of the upcoming task, but not of the sensory modality. In Experiment 2, pre-trial cues informed participants of both the upcoming task and sensory modality. In both experiments, switch costs between tasks were significantly smaller when the sensory modality of the task switched versus when it repeated. In addition, switch costs between the senses were correlated only when the sensory modality of the task repeated across trials and not when it switched. The collective evidence not only supports the independence of control processes mediating task switching and modality switching, but also the hypothesis that switch costs reflect competitive interference between neural circuits that in turn can be diminished when these neural circuits are distinct.

Our results show that there is a reliable switch cost—i.e., an RT difference between trials where the task repeats vs. switches relative to the previous trial—when the sensory modality of the target stimulus remains constant (within-modality switches). When the modality switches, subjects exhibit smaller switch costs when the forthcoming modality is not known (in solid agreement with Hunt and Kingstone (2004)). However, when the forthcoming modality is known, subjects are able to switch task without incurring a switch cost (at least in the case of the visual task). These findings replicate and extend Hunt and Kingstone's (2004) observation of sub-additive interactions between task switching and modality switching. This pattern of results is difficult to reconcile with the proposition that switch costs and modality costs arise from a common 'bottleneck' in the cognitive system. If such were the case, switching task and modality would always result in larger switch costs than when switching task alone. Inasmuch as our data do not conform to this prediction (see Fig. 2), our results appear to invalidate the idea of a common bottleneck in executive processes.

Instead, the results are in broad agreement with the idea that when the interference between tasks is lessened, the switch cost also diminishes. Here, we attempted to lessen the interference between the tasks in two ways: we used tasks that rely on partially distinct anatomical pathways (the 'what' and 'where' pathways), and we used tasks in two modalities. Because the processing pathways within each modality will necessarily overlap to some extent, we anticipated that switching task within modality would result in switch costs—a prediction supported by several decades of task-switching research. However, when the modality switched, we anticipated that switch costs would be smaller because of the anatomical separation of the sensory modalities. The strongest version of this idea would predict zero switch costs when the modality switched. In partial support of this idea, we found that the switch cost was eliminated for one modality (vision), when the forthcoming modality was cued (Experiment 2). However, in both experiments, our data support the broader hypothesis concerning competitive interference at the level of task-related activity across trials as an underlying basis of switch costs.

Based on the results of Wylie et al. (2006) and of Yeung, Nystrom, Aronson, and Cohen (2006), we propose that when tasks rely on networks that are at least partially anatomically/functionally distinct, subjects can activate them prior to the presentation of the imperative (task) stimulus (i.e., in response to the cue) and perform the tasks with relatively little switch costs. Our present results suggest that such does not entirely depend on knowing the sensory modality of the upcoming stimulus. In Experiment 1 of the current paradigm, this would have resulted in increased activity for the cued task in both modalities on every trial, because the cue provided information only about the task and not the sensory modality in which it would be performed. Of course, it is not possible to empirically demonstrate the subjects used the cue to prepare for the forthcoming task with the data from these experiments because only one cue-to-target interval was used. Indeed, there is some evidence from within-modality switching experiments that subjects do not always use the cue-to-target interval to prepare, when only a single CTI is used (e.g., Koch & Allport, 2006). However, it is not clear to what extent such results apply to the current design. In that work, it was shown that varying the timing of the CTI induced preparation; here, we varied the modality, which might have achieved the same end. Clearly, this issue will benefit from continued investigation. More germane is the fact that from our behavioral results it is not possible to know whether activity in the currently relevant (task-relevant) network began prior to stimulus delivery. Regardless of this detail, we furthermore propose that the persisting activity of previous trials would then interfere with task-related activity of the subsequent trials, which would be expected to lead to differential effects on switch cost and benefits depending on whether the task and/or modality switched. The model would predict that a task repetition within different modalities (modality switch) is associated with worse performance (slower RT) than a task repetition within the same modality (modality repeat), because in the first case there is less functional overlap and thus less repetition benefit. In contrast, a task switch within different modalities (modality switch) should be associated with better performance (faster RT) than a task switch within the same modality (modality repeat), because in the first case there is less functional overlap and thus less switch cost. Our data are in keeping with this hypothesis. When both the task and modality are repeated, then the activity generated on the current trial appeared to add to the persisting activity from the previous trial, since the subjects' responses were relatively fast (Fig. 2a, right rectangles). When the task repeated but the modality switched, then subjects showed less benefit of the persisting activity from the preceding trial, because it was in a different modality and relied on distinct neural circuitry. Consequently, their responses were somewhat slower (Fig. 2a, right triangles). When the task switched and the modality repeated, this led to the slowest reaction times (Fig. 2a, left rectangles). This is presumably because there was both persisting activity in the neural circuitry associated with the preceding task as well as activity in the circuitry associated with the forthcoming task, both of which were in the same modality. Thus, when the target stimulus was presented, the activity in these two competing networks was more similar and hence competed maximally. However, when both the task and modality switched, this competitive interference was smaller (Fig. 2a, left triangle), due to less inter-digitization between the circuitry associated with the preceding and the current tasks (given that the tasks are in separate modalities).

The finding that task switch costs can be eliminated when the sensory modality is switched (Experiment 2) provides strong support for this model. The functional and anatomical separation between the visual and auditory modalities should reduce the extent to which a task performed in one modality affects the activity in the brain areas associated with a different task in the other modality. This should result in less competition between the networks underlying the performance of the two tasks. If a large part of the switch cost is due to competition between such networks, one would expect this manipulation to abolish the switch cost. The fact that the switch cost was indeed eliminated for the visual modality provides the first evidence of this kind. Of course, the task switch cost for the auditory modality was not eliminated by the same manipulation, and the reason for this difference must await further research. For example, it might be that readying the auditory system requires more time than readying the visual system. Manipulating the amount of time prior to a switch of task/modality—the cue-to-target interval—is therefore clearly one avenue of future research (this would also address whether it is only the so-called 'residual' switch cost that can be abolished by switching modality).

It is also worthwhile to consider our results alongside the literature concerning interactions between the sensory modalities. For example, when the modality switches and the task repeats, the persisting activity in the circuitry associated with the repeating task (in the other modality) may support or increase the anticipatory activity in the network associated with the forthcoming task, relative to when both the task and modality switch. More specifically in terms of our understanding of multisensory interactions between functionally specialized neural pathways within the visual and auditory systems, the present results support the possibility that interactions between the senses may also be organized along functionally specialized neural pathways (e.g., Chan & Newell, 2008; Molholm, Martinez, Shpaner, & Foxe, 2007; Sestieri et al., 2006). Whether or not such an organization, if present, already manifests in those interactions documented to occur at lower anatomic levels (e.g., Cappe & Barone, 2005; Falchier, Clavagnier, Barone, & Kennedy, 2002; Ghazanfar & Schroeder, 2006; Kayser, Petkov, Augath, & Logothetis, 2007; Martuzzi et al., 2007; Rockland & Ojima, 2003; Romei, Murray, Merabet, & Thut, 2007) and at early latencies (e.g. Giard & Peronnet, 1999; Molholm et al., 2002; Romei et al., 2007) remains to be determined by future research, though the observation of these latter interactions despite anesthetics or passive conditions would suggest that they may be functionally less specialized.

4.1. Correlational analyses

In order to better understand the under-additive interaction shown in our data as well as in the data reported by Hunt and Kingstone (2004), we performed correlational analyses (Fig. 3). Our reasoning was that while most models of task control predict that within-modality switches should be correlated, this is not the case for across-modality switches. If there is some process that must be completed on all switch trials, then both within- and across-modality switches should be correlated. This is because this process should be active when a subject switches task and the modality repeats, and when the subject switches task and the modality switches. However, if a large part of the switch cost represents the time taken to overcome competition from the other task, one might expect correlations only between within-modality switches and not between across-modality switches, for the following reason. If it is the case that the competition evidently underlying a substantial portion of the switch cost is resolved in a similar way or by a common mechanism, regardless of the modality of the task, this result makes sense. Thus, when the modality repeats, this mechanism would mediate the competition arising from a switch of task (regardless of the modality of the stimuli). However, when the modality switches, there is far less competition, and therefore this mechanism contributes less to the time required to switch task. This mechanism could be conceptualized as a 'central executive', or indeed as any mechanism that serves to increase the influence of the currently relevant task-set (goal) when interference from other possible task-sets is high.

While we have interpreted these data as supporting the idea that a large part of the switch cost reflects competition/interference from previously relevant task-sets (and therefore partially active brain networks), it is worth pointing that these data are also interpretable within a framework of binding effects. That is, on every trial, the task is bound to the sensory modality. When the task and modality repeat, no change in the binding is necessary, and RTs are short; when one changes (e.g., the task), subjects derive a relative benefit when the other (e.g., the modality) changes as well (cf. Gade & Koch, 2007). One of the reasons that both a competition/interference explanation and a binding explanation fit these data could be because they are different descriptions of the same functional mechanisms. Further work in this area will be required to determine if this is the case.

In conclusion, this study supports the idea that a substantial portion of the cost of switching from one task to another derives from competition between persisting activity in the neural network associated with the task on the previous trial and activity in the neural network associated with the task on the current trial. When these networks are segregated, the competition is lessened and the switch cost is accordingly smaller. This study also demonstrates that the networks associated with the 'what' task and the 'where' task used here are not completely segregated across the senses, inasmuch as the task switch cost was not reduced to zero when the modality changed across trials. Finally, these data suggest that a common mechanism resolves the competition, regardless of whether the task was in the visual or auditory modality. The functional imaging literature on task switching suggests several areas that might be associated with this mechanism, including the inferior frontal cortex (BA 6, 8, 44; Brass & von Cramon, 2002; Wylie et al., 2004a, 2004b, 2006), and parietal cortex (BA 7, 40). Using this paradigm in combination with imaging methodologies such as EEG and fMRI, and/or TMS, should provide important insights into how these areas affect the control of actions.

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References

Alain, C., Arnott, S. R., Hevenor, S., Graham, S., & Grady, C. L. (2001). "What" and "Where" in the human auditory system. *Proceedings of the National Academy of Sciences of the United States of America, 98*, 12301–12306.

Allport, D. A., Styles, E. A., & Hsieh, S. (1994). Shifting intentional set: Exploring the dynamic control of tasks. In C. Umilta & Moscovitch (Eds.), *Attention and performance XI* (pp. 107–132). Cambridge, MA: MIT Press.

Allport, D. A., & Wylie, G. R. (1999). Task-switching: Positive and negative priming of task-set. In G. W. Humphreys, J. Duncan, & A. M. Treisman (Eds.), *Attention space and action: Studies in cognitive neuroscience* (pp. 273–296). Oxford: Oxford University Press.

Allport, D. A., & Wylie, G. R. (2001). Task-switching, stimulus-response bindings, and negative priming. In S. Monsell & J. S. Driver (Eds.), *Control of cognitive processes: Attention and performance XVIII* (pp. 35–70). Cambridge, MA: MIT Press.

Brass, M., & von Cramon, D. Y. (2002). The role of the frontal cortex in task preparation. *Cerebral Cortex, 12*, 908–914.

Brass, M., & von Cramon, D. Y. (2004). Decomposing components of task preparation with functional magnetic resonance imaging. *Journal of Cognitive Neuroscience, 16*, 609–620.

Cappe, C., & Barone, P. (2005). Heteromodal connections supporting multisensory integration at low levels of cortical processing in the monkey. *European Journal of Neuroscience, 22*, 2886–2902.

Chan, J. S., & Newell, F. N. (2008). Behavioral evidence for task-dependent "what" versus "where" processing within and across modalities. *Perception & Psychophysics, 70*, 36–49.

De Santis, L., Clarke, S., & Murray, M. M. (2007). Automatic and intrinsic auditory "what" and "where" processing in humans revealed by electrical neuroimaging. *Cerebral Cortex, 17*, 9–17.

De Santis, L., Spierer, L., Clarke, S., & Murray, M. M. (2007). Getting in touch: Segregated somatosensory what and where pathways in humans revealed by electrical neuroimaging. *Neuroimage, 37*, 890–903.

Duncan, J., Martens, S., & Ward, R. (1997). Restricted attentional capacity within but not between sensory modalities. *Nature, 387*, 808–810.

Falchier, A., Clavagnier, S., Barone, P., & Kennedy, H. (2002). Anatomical evidence of multimodal integration in primate striate cortex. *Journal of Neuroscience, 22*, 5749–5759.

Gade, M., & Koch, I. (2007). Cue-task associations in task switching. *The Quarterly Journal of Experimental Psychology (Colchester), 60*, 762–769.

Ghazanfar, A. A., & Schroeder, C. E. (2006). Is neocortex essentially multisensory? *Trends in Cognitive Sciences, 10*, 278–285.

Giard, M. H., & Peronnet, F. (1999). Auditory–visual integration during multimodal object recognition in humans: A behavioral and electrophysiological study. *Journal of Cognitive Neuroscience, 11*, 473–490.

Gondan, M., Lange, K., Rösler, F., & Röder, B. (2004). The redundant target effect is affected by modality switch costs. *Psychonomic Bulletin & Review, 11*, 307–313.

Haxby, J. V., Horwitz, B., Ungerleider, L. G., Maisog, J. M., Pietrini, P., & Grady, C. L. (1994). The functional organization of human extrastriate cortex: A PET-rCBF study of selective attention to faces and locations. *Journal of Neuroscience, 14*, 6336–6353.

Hunt, A. R., & Kingstone, A. (2004). Multisensory executive functioning. *Brain and Cognition, 55*, 325–327.

Jersild, A. T. (1927). Mental set and shift. *Archives of Psychology, 89*, 5–82.

Jolicoeur, P. (1999). Restricted attentional capacity between sensory modalities. *Psychonomic Bulletin & Review, 6*, 87–92.

Kaas, J. H., & Hackett, T. A. (2000). Subdivisions of auditory cortex and processing streams in primates. *Proceedings of the National Academy of Sciences of the United States of America, 97*, 11793–11799.

Kayser, C., Petkov, C. I., Augath, M., & Logothetis, N. K. (2007). Functional imaging reveals visual modulation of specific fields in auditory cortex. *Journal of Neuroscience, 27*, 1824–1835.

Koch, I., & Allport, A. (2006). Cue-based preparation and stimulus-based priming of tasks in task switching. *Memory & Cognition, 34*, 433–444.

Logan, G. D., & Bundesen, C. (2003). Clever Homunculus: Is there an endogenous act of control in the explicit task-cuing procedure. *Journal of Experimental Psychology: Human Perception and Performance, 29*, 575–599.

Maeder, P. P., Meuli, R. A., Adriani, M., Bellmann, A., Fornari, E., Thiran, J. P., et al. (2001). Distinct pathways involved in sound recognition and localization: A human fMRI study. *Neuroimage, 14*, 802–816.

Martuzzi, R., Murray, M. M., Michel, C. M., Thiran, J. P., Maeder, P. P., Clarke, S., et al. (2007). Multisensory interactions within human primary cortices revealed by BOLD dynamics. *Cerebral Cortex, 17*, 1672–1679.

Meiran, N. (1996). Reconfiguration of processing mode prior to task performance. *Journal of Experimental Psychology Learning Memory & Cognition, 22*, 1423–1442.

Molholm, S., Ritter, W., Murray, M. M., Javitt, D. C., Schroeder, C. E., & Foxe, J. J. (2002). Multisensory integration of coherent auditory and visual stimulation is a feedforward, pre-perceptual cortical process: A high density electrical mapping and behavioral study. *Cognitive Brain Research, 14*, 115–128.

Molholm, S., Martinez, A., Shpaner, M., & Foxe, J. J. (2007). Object-based attention is multisensory: Co-activation of an object's representations in ignored sensory modalities. *European Journal of Neuroscience, 26*, 499–509.

Monsell, S. (1996). Control of mental processes. In V. Bruce (Ed.), *Unsolved mysteries of the mind: Tutorial essays in cognition* (pp. 93–148). Hove, UK: Erlbaum, Taylor, and Francis.

Murray, M. M., Camen, C., Gonzalez Andino, S. L., Bovet, P., & Clarke, S. (2006). Rapid brain discrimination of sounds of objects. *Journal of Neuroscience, 26*, 1293–1302.

Nicholson, R., Karayanidis, F., Poboka, D., Heathcote, A., & Michie, P. (2005). Electrophysiological correlates of anticipatory task-switching processes. *Psychophysiology, 42*, 540–554.

Norman, D. A., & Shallice, T. (1986). Attention to action: Willed and automatic control of behaviour. In R. J. Davidson, G. E. Schwartz, & D. Shapiro (Eds.), *Consciousness and self-regulation: Advances in research and theory*. Plenum Press.

Oldfield, R. C. (1971). The assessment and analysis of handedness: The Edinburgh inventory. *Neuropsychologia, 9*, 97–113.

Rivier, F., & Clarke, S. (1997). Cytochrome oxidase, acetylcholinesterase, and NADPH-diaphorase staining in human supratemporal and insular cortex: evidence for multiple auditory areas. *Neuroimage, 6*, 288–304.

Rockland, K. S., & Ojima, H. (2003). Multisensory convergence in calcarine visual areas in macaque monkey. *International Journal of Psychophysiology, 50*, 19–26.

Rogers, R. D., & Monsell, S. (1995). Costs of a predictable switch between simple cognitive tasks. *Journal of Experimental Psychology, 124*, 207–231.

Romanski, L. M., Tian, B., Fritz, J., Mishkin, M., Goldman-Rakic, P. S., & Rauschecker, J. P. (1999). Dual streams of auditory afferents target multiple domains in the primate prefrontal cortex. *Nature Neuroscience, 2*, 1131–1136.

Romei, V., Murray, M. M., Merabet, L. B., & Thut, G. (2007). Occipital transcranial magnetic stimulation has opposing effects on visual and auditory stimulus detection: Implications for multisensory interactions. *Journal of Neuroscience, 27*, 11465–11472.

Rubinstein, J. S., Meyer, D. E., & Evans, J. E. (2001). Executive control of cognitive processes in task switching. *Journal of Experimental Psychology: Human Perception and Performance, 27*, 763–797.

Sestieri, C., Di Matteo, R., Ferretti, A., Del Gratta, C., Caulo, M., Tartaro, A., et al. (2006). "What" versus "where" in the audiovisual domain: An fMRI study. *Neuroimage, 33*, 672–680.

Snodgrass, J. G., & Vanderwart, M. (1980). A standardized set of 260 pictures: Norms for name agreement, image agreement, familiarity, and visual complexity. *Journal of Experimental Psychology Human Learning, 6*, 174–215.

Spector, A., & Biederman, I. (1976). Mental set and shift revisited. *American Journal of Psychology, 89*, 669–679.

Spence, C., Nicholls, M. E. R., & Driver, J. (2001). The cost of expecting events in the wrong sensory modality. *Perception & Psychophysics, 63*, 330–336.

Tardif, E., Spierer, L., Clarke, S., & Murray, M. M. (2008). Interactions between auditory 'what' and 'where' pathways revealed by enhanced near-threshold discrimination of frequency and position. *Neuropsychologia, 46*, 958–966.

Tian, B., Reser, D., Durham, A., Kustov, A., & Rauschecker, J. P. (2001). Functional specialization in rhesus monkey auditory cortex. *Science, 292*, 290–293.

Ungerleider, L. G., & Mishkin, M. (1982). Contribution of striate inputs to the visuospatial functions of parieto-preoccipital cortex in monkeys. *Behavioural Brain Research, 6*, 57–77.

Wylie, G., & Allport, A. (2000). Task switching and the measurement of switch costs. *Psychological Research, 63*, 212–233.

Wylie, G. R., Javitt, D. C., & Foxe, J. J. (2003a). Task switching: A high-density electrical mapping study. *Neuroimage, 20*, 2322–2342.

Wylie, G. R., Javitt, D. C., & Foxe, J. J. (2003b). Cognitive control processes during an anticipated switch of task. *European Journal of Neuroscience, 17*, 667–672.

Wylie, G. R., Javitt, D. C., & Foxe, J. J. (2004a). Don't think of a white bear: An fMRI investigation of the effects of sequential instructional sets on cortical activity in a task-switching paradigm. *Human Brain Mapping, 21*, 279–297.

Wylie, G. R., Javitt, D. C., & Foxe, J. J. (2004b). The role of response requirements in task switching: Dissolving the residue. *Neuroreport, 15*, 1079–1087.

Wylie, G. R., Javitt, D. C., & Foxe, J. J. (2006). Jumping the gun: Is effective preparation contingent upon anticipatory activation in task-relevant neural circuitry. *Cerebral Cortex, 16*, 394–404.

Wylie, G. R., Murray, M. M., Javitt, D. C., & Foxe, J. J. (2008). Distinct neurophysiological mechanisms mediate mixing costs and switch costs. *Journal of Cognition and Neurosciencem*. doi:10.1162/jocn.2009.21009.

Yeung, N., Nystrom, L. E., Aronson, J. A., & Cohen, J. D. (2006). Between-task competition and cognitive control in task switching. *Journal of Neuroscience, 26*, 1429–1438.