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Shifting attention between visual dimensions as a source of the task switch cost

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Running head: Attention shifting as source of task-switch cost.

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Abstract

"Task-switching" experiments have documented a puzzling phenomenon: advance warning of the switch reduces but does not eliminate the "switch cost". Theoretical accounts have posited that the "residual" switch cost arises whilst selecting the relevant stimulus-response mapping, leaving earlier perceptual processes unaffected. We put the latter assumption to the test by seeking electrophysiological markers of encoding a perceptual dimension. Participants categorized a colored letter as vowel/consonant or its color as "warm"/"cold". Orthogonally to these classifications, some colors were eight times more frequent than others, and the letters were in upper or lower case. Color frequency modulated the EEG amplitude at around 150 ms when participants repeated the color classification task. When participants switched from the letter task to the color task this effect was significantly delayed. Thus, even when prepared for, a task switch delays or prolongs encoding of the relevant perceptual dimension.

Human behavior can be remarkably flexible – we can readily switch among simple cognitive tasks following minimal instruction. However, the limits of this flexibility are illustrated by laboratory phenomena such as the task "switch cost" – longer response time (RT) and more errors when the task changes on successive trials compared with repeating the same task (Kiesel et al., 2010; Vandierendonck, Liefooghe, & Verbruggen, 2010). Providing an opportunity for preparation by pre-cuing the task usually reduces the switch cost substantially (e.g., Monsell & Mizon, 2006) – suggesting effective proactive task-set control. However, extending the preparation interval beyond around a second usually leaves an asymptotic "residual" switch cost indicative of the limits of proactive control.

That the residual switch cost cannot be eliminated, even under optimal conditions (e.g., Niewenhuis & Monsell, 2002), is puzzling. Many attribute the residual cost to "passive" persistence of task-set from the previous trial(s) – "task-set inertia" (Allport, Styles & Hsieh, 1994; Yeung & Monsell, 2003), or to associative reactivation of competing task-sets on task-switch trials (Mayr, Kuhns & Hubbard, 2014; Waszak, Hommel & Allport 2003, 2005). Others attribute it to intrinsic limitations of preparation, either because some components of "task-set reconfiguration" cannot occur in advance of the stimulus (e.g., Rogers & Monsell, 1995; Meiran, 2000) or because proactive task-set reconfiguration sometimes "fails to engage" (DeJong, 2000). But these accounts have generally shared an assumption: that the residual switch cost arises at a relatively late stage – during the response selection process – as a result of competition from the alternative task's stimulus-response (S-R) rules (see Elchlepp, Lavric & Monsell, 2015, for a review). For example, suppose the participant sees on each trial one of several letters presented in one of several colors, and is asked to classify either the letter (as vowel vs. consonant)

or its color (as "warm" vs. "cold", see Figure 1). When the task changes from letter to color, the selection of the relevant response rule (e.g., "left-hand response for cold") may suffer interference from activation of the letter task's S-R rules.

But might the residual switch cost arise (at least in part) because earlier, perceptual, stimulus-encoding processes are prolonged? For example, might color encoding be less efficient when switching from the letter task even after ample opportunity to prepare for the change in dimensions? To probe the contribution of such an attentional handicap to the residual task switch cost, we aimed to "engineer" electrophysiological markers for processing of the perceptual dimension associated with each task. For example, to obtain a marker for color processing we presented some colors more frequently than others and contrasted the EEG signals for frequent and infrequent colors. Note that participants were not asked to attend or respond to color frequency; the color frequency contrast was orthogonal to the required categorization in the color task. To determine whether having just switched from the letter task delayed processing of color, we could then compare the latencies of the color frequency EEG markers on switch versus repeat trials.

We adopted a similar approach in a recent study (Elchlepp et al., 2015). A string of red and blue letters was classified either by its linguistic properties (word versus non-word in one experiment, semantic category in another), or by a perceptual property (symmetry versus asymmetry of the color pattern across the string). EEG markers of linguistic processing (the difference between words and non-words at about 200 ms, or between high- and low-frequency words at about 250 ms) were delayed when switching to the linguistic task, and this delay accounted for a very substantial proportion of the RT switch cost. Although this is evidence that a task switch prolonged some process(es) preceding response selection, it remains possible

that they were post-perceptual linguistic processes (e.g., identifying a word and/or retrieving its meaning), and that attentional selection of a perceptual attribute (letter shapes versus color pattern) was unaffected by a (prepared) task-switch. The present study tested the effect of task switching on perceptual processing more directly.

METHOD

Participants. Twenty-one right-handed University of Exeter students (17 female, 4 male) aged 18-36 years (M=20.6) were paid £20, plus ≤ £2.60 bonus (see Procedure), to take part in the experiment. Participants gave informed consent in accordance with the University of Exeter, School of Psychology Ethics Committee Guidelines. Sample size was determined based on our previous study (Elchlepp et al., 2015), where with a similar methodology and N =18 we obtained medium size effects in key analyses of ERP latency. Here, the number of participants had to be a multiple of 7 in order to counterbalance the order of blocks with a long vs. short preparation (cue-stimulus) interval (see detailed description below). We therefore tested 21 participants.

Apparatus, Stimuli and Procedure. The experiment was conducted using E-Prime 1.1 (Psychology Software Tools, Pittsburgh, PA) on a PC with a 16-inch CRT screen positioned 60 cm in front of participants' eyes. On each trial, a colored letter was displayed against a grey background, in Arial font (max. 1cm x 1cm). Participants were required to categorize the letter as a vowel or consonant, or its color as "warm" or "cold" (see Figure 1). For half the participants the left arrow key was the response for vowel or warm color and the right arrow key for consonant or cold color; for the other participants, the response mappings for the color task were reversed. The 288 stimuli were four vowels (A, E, I, U) and four consonants (B, H, N, R), each

presented in both upper and lower case, and in nine "warm" and nine "cold" colors. Most letters (including those we used) differ in their upper and lower case form. If the letters were displayed in a constant location, then it would be logically possible for participants doing the color task to focus ("zoom in") spatial attention on a small region of the screen, and "zoom out" on letter task trials. To avoid inducing such shifts in the spread of spatial attention when the task switched, we jittered the letter's display coordinates unpredictably among eight locations within a 2 cm radius around the center.
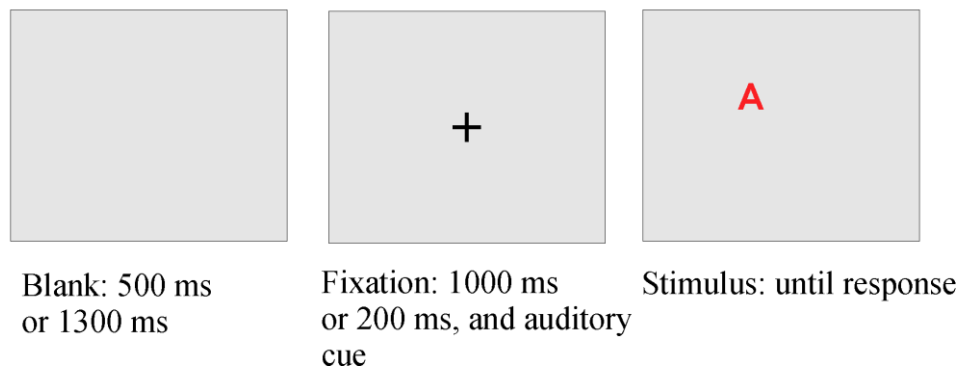

Fig. 1. Trial structure and example of a stimulus.

Each trial started with a blank screen (see Figure 1), followed by a central fixation cross presented simultaneously with one of four auditory cues (each 500 ms in duration): "letter" or "symbol", and "color" or "paint". The cue changed on every trial (even on task repeat trials) to unconfound the effects of a task switch from those of a cue change (cf. Monsell & Mizon, 2006). The fixation cross was replaced by the stimulus letter, which stayed on the screen until a response was given; if the response was incorrect the word "ERROR" was shown for 1200 ms. To examine the effects of

preparation on performance, the cue-stimulus interval (CSI) was manipulated between blocks of 48 trials, but constant within a block. In 24 of the 28 blocks after practice the CSI was 1000 ms and in the remaining 4 it was 200 ms; the short CSI was regularly interspersed among the long CSI in the following positions, for every three participants: 1-8-15-22; 2-9-16-23; 3-10-17-24; 4-11-18-25; 5-12-19-26; 6-13-20-27 and 7-14-21-28. Irrespective of CSI, the response-stimulus interval was a constant 1500 ms, except following an error.

For each CSI, the ratios of switch:repeat, vowel:consonant, and warm:cold color trials were 1:2, 1:1 and 1:1, respectively. To seek an EEG marker of processing the shape of the letter, we examined the Event-Related Potential (ERP) difference between uppercase and lowercase letters (their size was matched). To derive an analogous marker in the color task, we presented some colors frequently and some infrequently (in a ratio of 8:1, see Figure 2). Note that these marker dimensions, case and color frequency, were orthogonal to the response classification (e.g., an uppercase letter was equally often a vowel or consonant, and an infrequent color equally often "warm" or "cold") so that any effect of the marker on the ERP could not reflect the evolving response decision. Subject to these constraints, the order of trials was randomized anew for each participant. Each block began with a "warmup" trial, with randomly allocated letter and color attributes, to determine the switch-repeat status of the following trial, the first trial analyzed.
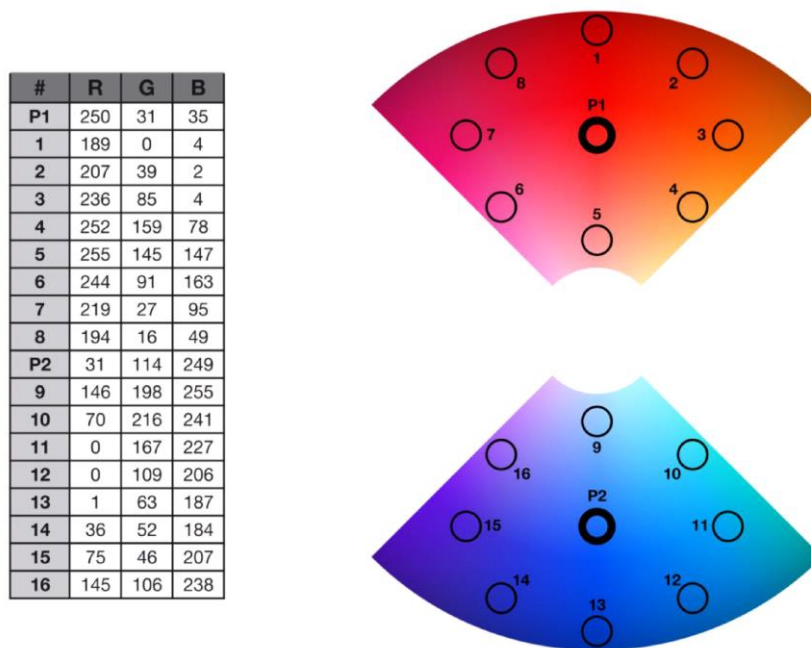
Colour selection

#	R	G	B
P1	250	31	35
1	189	0	4
2	207	39	2
3	236	85	4
4	252	159	78
5	255	145	147
6	244	91	163
7	219	27	95
8	194	16	49
P2	31	114	249
9	146	198	255
10	70	216	241
11	0	167	227
12	0	109	206
13	1	63	187
14	36	52	184
15	75	46	207
16	145	106	238

Fig. 2. The "warm" (top right) and "cold" (bottom right) color categories and their RGB values (note that infrequent colors had the same mean values as the frequent colors); the two frequent colors are indicated by bold circles and letter P in the label.

The session started with four single-task practice blocks of 64 trials (two blocks per task). In the next two 64-trial blocks (one for each CSI) participants practiced switching between the tasks. In the following 28 experimental blocks, which contained 48 trials each, the EEG was acquired. In addition to a £20 participation fee, a score computed for each block (mean RT/10 + errors x 5, cf. Lavric, Mizon, & Monsell, 2008) lower than the running average of the preceding blocks with the same CSI was rewarded with a £0.10 bonus.

EEG acquisition and processing. The EEG was continuously sampled at 500 Hz with a bandpass of 0.016-100 Hz, the reference at Cz and the ground at AFz using 64 Ag/AgCl active electrodes (62 on the scalp and one on each earlobe; impedance ≤10

kΩ) connected to BrainAmp amplifiers (Brain Products, Munich, Germany). The EEG was filtered off-line with a 20 Hz low-pass filter (48 dB/oct). Only long CSI trials were used for EEG analyses. To correct the eye-blink and eye-movement artifacts, we ran an Independent Component Analysis (ICA, as implemented in Vision Analyzer, BrainProducts, Munich, Germany). ICA components from every participant's EEG were inspected and components with characteristic eye-blink and eye-movement topographies were subtracted from the EEG. The EEG was then re-referenced to the linked ears, segmented from -100 ms pre-cue onset to 1500 ms following the cue and then baseline corrected using the pre-cue baseline This long segment was divided into a segment comprising the cue interval (-100 to 1000 ms time-locked to the cue) and one comprising the stimulus interval (-100 to 500 ms time-locked to the stimulus). Trials with errors, trials following errors (unclassifiable as a switch/repeat) and the first trial of each block were discarded. The rest were visually inspected for residual artifacts, such as muscle activity and large drifts, and those containing such artifacts removed. On average 18% of the trials were removed. The remaining segments were averaged for each participant and experimental condition.

ERP latency. To identify dimension-specific ERP markers, grand-average dimension-related difference waves were computed by subtracting for the color task the ERP for frequent colors from the ERP for infrequent colors and, and for the letter task, the ERP for uppercase letters from the ERP for lowercase letters. In each difference wave we sought features/peaks that were comparable for the switch and repeat conditions – these features had to originate from amplitude differences of the same polarity and scalp distribution for switches and repeats. Individual participants' data are typically too noisy for identifying the difference wave features

unambiguously. Hence, we employed the "jackknifing" method developed to address this problem (Miller, Patterson & Ullrich, 1998) – it uses all the possible averages over all-but-one participants' data (rather than individual participants' ERPs) to compute the t-statistic.

ERP amplitude. Switch vs. repeat amplitude differences were not per se the focus of the current investigation; they have been extensively documented in previous research (see Karayanidis et al., 2010; Karayanidis & Jamadar, 2014, for reviews, and Lavric et al., 2008; Elchlepp, Lavric, Mizon & Monsell, 2012; Elchlepp et al., 2015; Elchlepp, Lavric, Chambers & Verbruggen, 2016, for some examples). Of more interest was the impact of switching versus repeating the task on the amplitude of the ERP effects (if any) of the "marker" variables color frequency and letter case – for which we tested in ANOVAs performed on stimulus-locked ERP segments. This being said, the presence of a main effect of switch on pre-stimulus amplitude was of some importance. In particular, we sought to identify a previously-documented ERP correlate of preparation for a switch – a protracted positive-polarity amplitude modulation arising in the switch condition (relative to repeat ERP) typically from ~400-500 ms following the onset of the task cue and extending to the end of the preparation interval (e.g., Lavric et al., 2008). The presence of this "posterior switch positivity" in the cue-locked ERP segments, along with behavioral evidence of effective preparation for a switch (the switch by CSI interaction), would confirm that participants used the long CSI for effective preparation.

For the above pre- and post-stimulus analyzes, amplitudes from long-CSI trials were averaged over electrodes along the anterior-posterior (4 levels: frontal anterior, frontal posterior, parietal, occipital) and laterality (3 levels: left, middle, right) dimensions: anterior frontal left (Fp1, AF7, F9, F7, F5, F3), anterior frontal

middle (Fpz, AF1, AF2, F1, Fz, F2), anterior frontal right (Fp2, AF8, F4, F6, F8, F10), posterior frontal left (FT7, FC5, FC3, T7, C5, C3), posterior frontal middle (FC1, FCz, FC2, C1, Cz, C2), posterior frontal right (FC4, FC6, FT8, C4, C6, T8), parietal left (TP7, CP5, CP3, P5, P3), parietal middle (CP1, CP2, P1, Pz, P2), parietal right (CP4, CP6, TP8, P4, P6, P8), occipital left (P7, PO7, PO5, O1), occipital middle (PO1, POz, PO2, Oz), occipital right (P8, PO8, PO6, O2). For the cue-locked (preparation) analysis, we used the factors task, switch, region and laterality; for the stimulus-locked interval where the tasks were examined separately, color frequency was added as a factor for the color task and case for the letter task. In all ANOVAs, significance levels were adjusted using the Huynh-Feldt correction for violations of sphericity (but unadjusted degrees of freedom are reported).

RESULTS

Anonymised raw behavioral and EEG data are deposited in the Open Research Exeter data repository http://hdl.handle.net/10871/24754.

Behavioral results. An ANOVA on the mean reaction time with the factors CSI, switch, task, letter case and color frequency (see Table 1 for descriptive and inferential statistics) found longer RTs for switch than repeat trials and for the short CSI than the long CSI. This switch cost reduced with a longer CSI, and was larger in the color task than in the letter task. Separate ANOVAs by task revealed for the color task shorter RTs for repeats than for switches, for frequent than for infrequent colors and for the long than for the short CSI. The switch cost was reduced with an increase in CSI by 54 ± 15 ms[1], or $55\pm15\%$. There was a larger color frequency effect for repeats than for switches. In the letter task the main effects of switch and CSI were

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[1] In the presentation of descriptive statistics, the mean contrast is followed by ±SE of the mean, unless stated otherwise.

also significant, as was the reduction in switch cost (by 50±15 ms, or 30±9%) with an increase in CSI. An ANOVA on error rates with the same factors revealed significantly more errors for switches than repeats and for the short than for the long CSI. The reduction in the error switch cost with an increase in CSI was marginally significant.

<INSERT TABLE 1 ABOUT HERE>

ERPs: Latency Analyses. We inspected the dimension-related grand-average difference waves for clear deflections elicited by the marker variables (color frequency and letter case) on both switch and repeat trials, in order to analyze the latency of such deflections. We could not confidently identify such deflections in the case-related difference wave. But in the difference wave reflecting the effect of color frequency (infrequent minus frequent: see Figure 3*A*) three peaks were identified in the posterior electrodes with similar time-course and scalp distribution in the switch and repeat conditions (see Figure 3*B*). These peaks (two maxima and the intervening minimum) reflect similar effects of color frequency on posterior ERPs for switch and repeat trials: the first maximum resulted from more negative-going amplitudes for frequent colors than for infrequent colors; the dissipation of this difference resulted in the following minimum (2nd peak) in the difference wave; the 3rd peak resulted from a larger N1 component for frequent colors. The three peaks were somewhat larger over the right scalp – hence, to minimize the number of statistical tests and increase the signal-to-noise ratio via spatial averaging, we averaged the difference waves for the following electrodes: P2, P4, P6, P8, PO2, PO6, PO8, O2. Before analyzing their latency, we ascertained that each of these peaks represented a significant departure from the baseline (or the preceding peak) using the same "jackknifing" method (Miller et al., 1998) as for the latency analyses below. The amplitude of the first peak

was significantly different from baseline, for both repeats, $t(20)=2.71$, $p=0.013$ and switches, $t(20)=2.62$, $p=0.016$. The amplitude of the second peak was significantly different from that of the first (repeat, $t(20)=2.43$, $p=0.025$; switch, $t(20)=2.33$, $p=0.03$); the amplitude of the third peak was significantly different from the amplitude of the second for repeats, $t(20)=3.73$, $p=0.001$, and marginally for switches, $t(20)=2.02$, $p=0.057$.
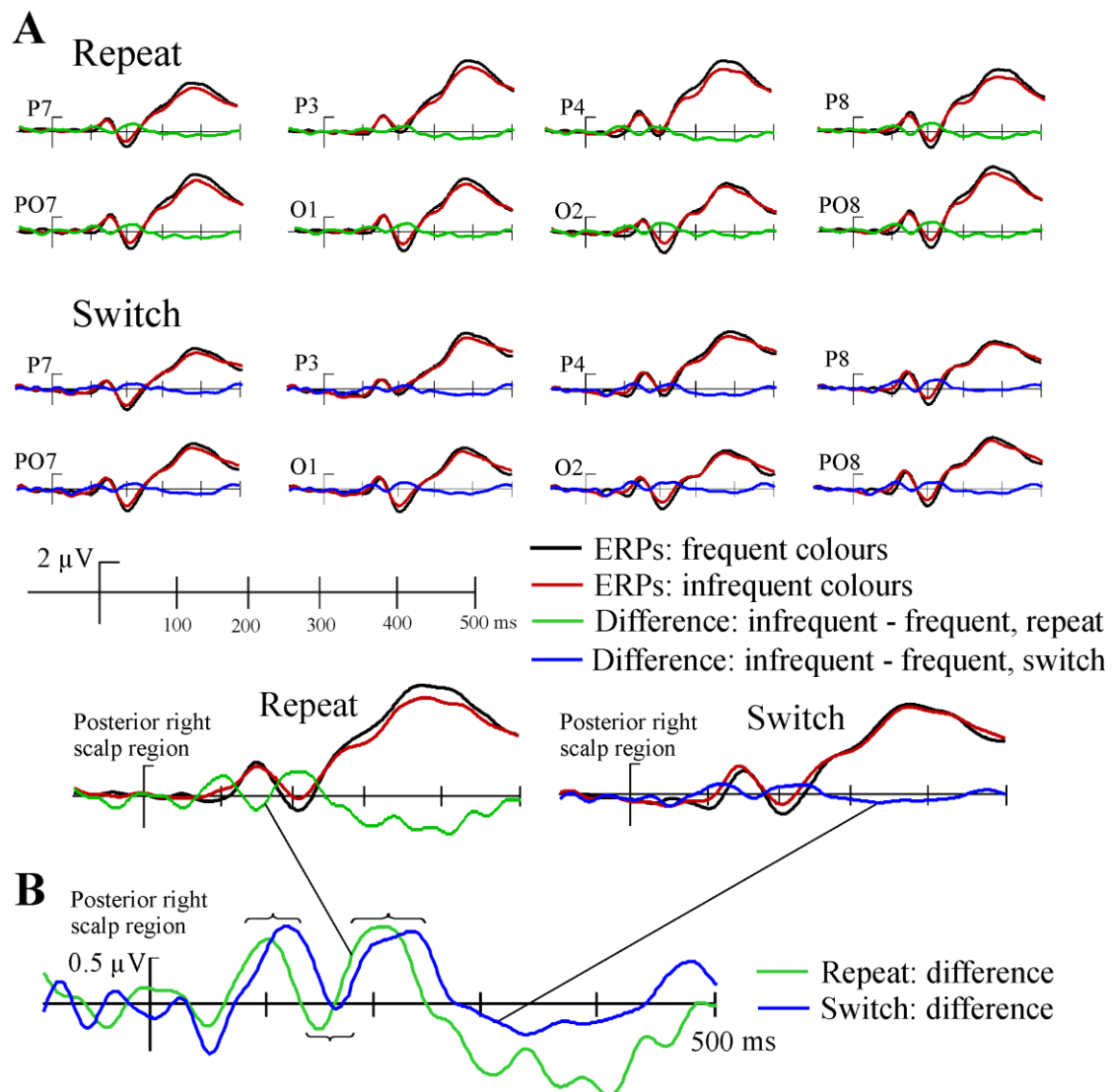

Fig. 3. *A.* ERPs for the infrequent vs. frequent color contrast (in the color task) and the resulting difference waves in a set of representative posterior electrodes and the

scalp region submitted to statistical analysis. **B.** Overlay of magnified switch and repeat difference waves; braces indicate the peaks analyzed.

As can be seen in Figure 3*B*, all three peaks appear shifted to the right in the switch condition relative to the repeat condition. To obtain a quantitative estimate of this temporal shift and subject it to statistical analysis, we defined a 220-ms-long portion of the difference wave comprising all three peaks (51-270 ms following stimulus onset, see Figure 4*A&B*), and temporally displaced it in steps of 1 ms by up to 40 ms back in time (towards stimulus onset) and up to 20 ms forward (towards the response) – to enable steps of 1 ms, the ERPs were up-sampled in the Vision Analyzer software using spline interpolation from 500 Hz (the sampling rate during EEG acquisition) to 1000 Hz. For each step, we computed a bivariate Pearson correlation between the switch and repeat time-series. This resulted in 61 correlations (60 steps plus the zero-shift correlation) – a cross-correlation function reflecting the synchrony between the maxima and minima in the switch and repeat difference wave (see Figure 4*D*). "Sliding" the switch difference wave back towards stimulus onset (as shown in Figure 4*C*) resulted in a very substantial increase in the correlation – from r=.52 to the maximum correlation of r=.97 (see Figure 4*D*), which corresponded to a shift of 17 ms in the grand-average difference wave – an estimate of the delay in the color frequency effects on switch trials. To assess the delay statistically, we computed for each leave-one-out "jackknifing" observation the temporal displacement of the switch time-series corresponding to the maximum of the cross-correlation function, and compared the thus obtained mean displacement of 17.4±8 ms to zero; the delay was significant, $t(20)=2.2$, $p=.04$.
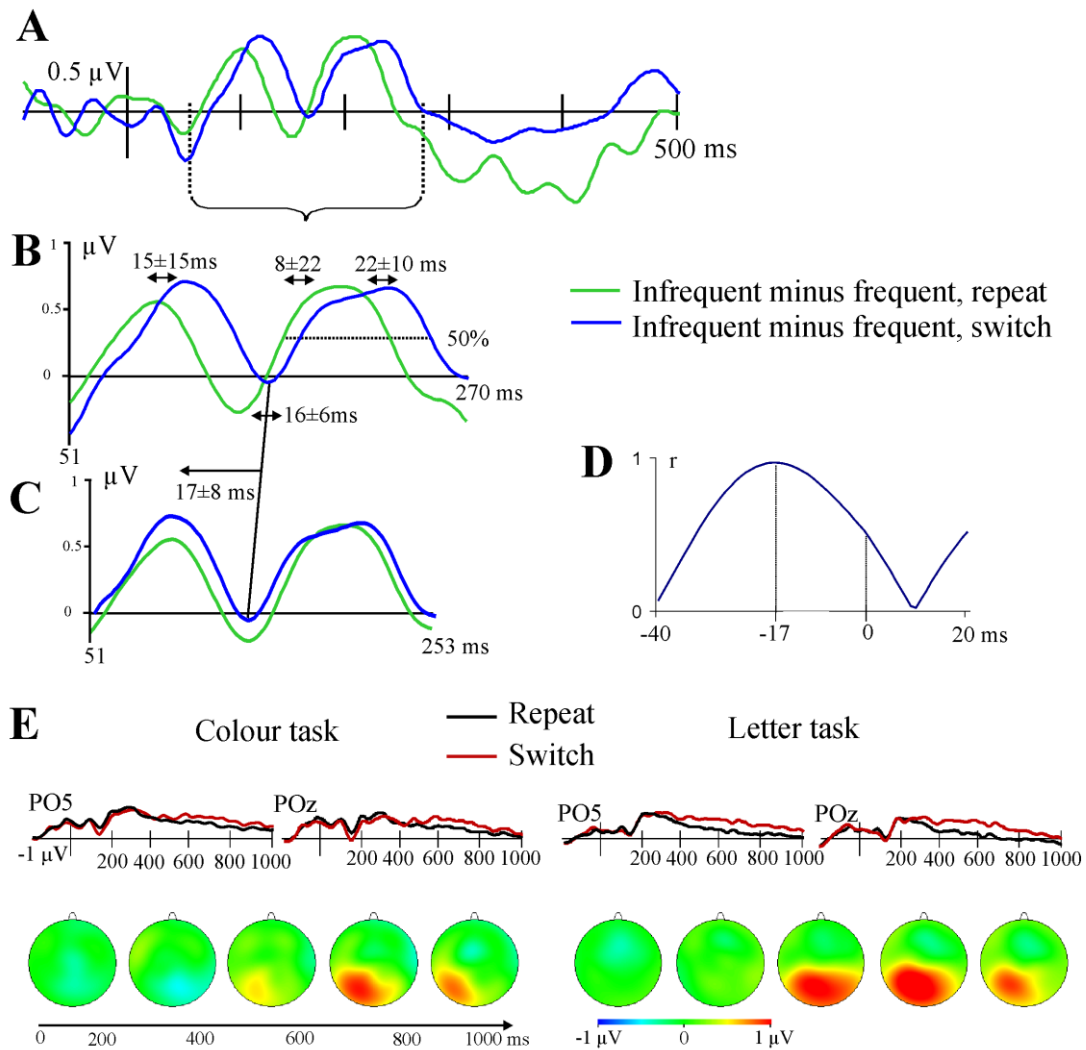
Fig. 4. *A.* The color frequency difference waves for the switch and repeat conditions (see also Fig. 3*B*) with a brace indicating the analyzed window. *B.* The analyzed portions of the difference waves with the mean estimated delay (± standard error) for each of the four features of the difference wave subjected to analysis. *C.* Illustration of the temporal shift in the analyzed portion of the switch difference wave for which the cross-correlation between the switch and repeat difference waves is maximal. *D.* Cross-correlation function; the vertical lines indicate the correlation values corresponding to panels B (zero shift in the switch difference wave) and C (-17 ms shift). *E.* Cue-locked (preparation) ERPs: switch and repeat waveforms in representative electrodes (top) and scalp distribution of the switch-repeat difference –

the "posterior positivity" indicative of task-set preparation.

In addition to this analysis of the overall shift in a portion of the difference wave, we also estimated the latencies of individual features of the difference waves (see Figure 3*B*), and compared these latencies for the switch and repeat conditions (see Figure 4*B*). This analysis could provide more fine-grained temporal information, e.g., the earliest feature for which the switch-induced delay was statistically detectable. For the first and second peaks, we obtained the latency using automated peak detection for the following intervals: 70-130 ms and 130-170 ms, respectively. The first peak had a latency of 101 ms in the repeat grand-average difference wave; switching delayed it by 15±15 ms, but not significantly so, $t(20)=0.34$. The second peak's latency was 144 ms for the repeats; switching delayed it by 16±6 ms – a significant effect, $t(20)=2.73$, $p=.013$.

The third peak ended in a broad plateau, particularly for switches, hence estimating its latency based on the peak was not appropriate – small amplitude variations on the plateau can result in large latency variations. Hence, we extracted instead the latencies for the amplitude rising to 50% of the maximum (cf. Kiesel et al., 2008) and falling to 50% of the maximum. Repeat amplitudes rose to criterion at 272 ms vs. 280 ms for switches – a non-significant delay of 8±22 ms, $t(20)=0.39$, $p=.7$. The amplitude fell to criterion at 327 ms for repeats vs. 349 ms for switches, a significant delay of 22±10 ms, $t(20)=2.14$, $p=0.045$.

ERP post-stimulus amplitude: Interactions between switch and dimension variables. We examined potential interactions between color frequency or letter case and switch in ERP amplitudes with ANOVAs performed on amplitudes averaged in five equal contiguous time-windows: 0-100 ms, 100-200 ms, 200-300 ms, 300-400

ms, 400-500 ms. In the color task, the effects of color frequency interacted significantly with switch in the 400-500 ms time-window $F(1,20)=5.7$; $p=.027$, reflecting a somewhat larger effect of color frequency on the P3 component (larger P3 for frequent colors) for the repeat condition – this was manifested in the late portion of the difference waves as the increased negative-polarity deflection for infrequent colors in the repeat condition compared to the switch condition (see Figure 3). For the letter task the effect of case did not reliably interact with switch/repeat in any of the time-windows.

ERP amplitude: Preparation for a switch. As one can see in Figure 4*E*, for both tasks, the ERPs time-locked to the cue contained the expected protracted posterior switch-induced deflection (the posterior positivity associated with preparation for a task-switch, see Method). Because in our previous task-switching studies (Lavric et al., 2008; Elchlepp et al., 2012; 2015), the positivity emerged at ~500-600 ms following cue onset, here we submitted to ANOVA the average amplitude 500-1000 ms following the cue onset. Switch interacted significantly with region, $F(3,60)=13.18$; $p=.001$, laterality, $F(2,40)=11.29$; $p=.0001$, and region and laterality, $F(6,120)=4.21$; $p=.001$ (there were no other significant effects of switch). Follow-up switch vs. repeat contrasts for each region confirmed the significance of the posterior positivity in the parietal left, $t(20) = 3.7$; $p =.012$; occipital left, $t(20) = 4.0$; $p =.012$ and occipital middle region, $t(20) = 3.5$; $p =.036$ (Bonferroni corrected p-values).

DISCUSSION

The task switch cost, in particular its "residual" component following preparation, has been commonly thought to arise during response selection (see Introduction), and until recently the only evidence of a task switch delaying an ERP was switch-induced

delays in the stimulus-locked Lateralized Readiness Potential (sLRP), a marker of response preparation that begins about 150 ms before response execution and presumably includes or follows response selection (e.g., Hsieh & Yu, 2003; Fiedler, Schröter, & Ulrich, 2009). Here we tested the proposal that for tasks that require shifts in the perceptual dimension attended to, a substantial portion of the switch-related processing delay arises well before response selection, consistent with "attentional inertia". This prediction was motivated by our recent finding that a switch from the task of judging the symmetry of color distribution across a letter string to reading a letter string resulted in a temporal shift of EEG effects that could unambiguously be linked to the processing of linguistic (lexical and semantic) properties of the string (Elchlepp et al., 2015). While this finding clearly demonstrated a relatively early locus (prior to response selection) of a substantial fraction of the residual task-switch RT cost, we could not tell whether it was identification of the letter string and activation of its meaning, or an earlier stage of encoding the relevant perceptual attributes (letter shape, identity and order versus the color pattern) that was prolonged. What was needed was an observation of a switch-induced delay in an EEG marker unambiguously linked to encoding of a perceptual dimension.

The present study has provided this observation. For one of the two tasks, color classification, we succeeded in identifying a marker of processing the relevant perceptual dimension – the ERP difference between infrequent and frequent colors. Although the use of this difference as a marker of color processing does not critically depend on assumptions about the form or functional interpretation of the observed ERP components (any plausibly early posterior ERP difference would have been of interest), it is reassuring that the difference comprises the amplification of an ERP component firmly linked to visual perception and visuo-spatial attention – the

posterior N1 (see Figure 3A). We subjected the critical portion of the infrequent-frequent difference wave, and its most prominent individual deflections, to statistical analysis of their latency – all were delayed on switch trials relative to repeats by 8 ms to 22 ms. The earliest deflection to be significantly delayed by a switch was a positive-polarity peak with a latency of 144 ms in the mean difference wave for repeat trials (160 ms for switches). This early handicap in processing color on switch trials (compared to task repetitions) had consequences at later processing stages, as indicated by the greater effect of color frequency for task repetitions than switches on ERP amplitude (larger increase in the P3 component for frequent compared to infrequent colors on repeat trials) and on performance (larger RT benefit for frequent compared to infrequent colors on repeat trials). The mean delays of 17 ms (in the cross-correlation analysis of the 220-ms interval of the difference wave) and 16 ms (in the analysis of the first significantly delayed peak within this interval) constitute a non-trivial fraction of the overall effect on RT (45±24 ms) of switching to the color task when CSI=1000 ms. However, the confidence intervals around the delay estimates (0.3 ms – 33.7 ms for the 220 ms interval, and 3.5 ms – 28.5 ms for the peak) preclude any firm conclusion at this stage on the exact proportion of the switch cost accounted for.

Attentional preparation for a specific form target or feature (Giesbrecht, Weissman, Woldorff & Mangun, 2006; Stokes, Thompson, Nobre & Duncan, 2009), for a color versus motion target (Chawla, Rees & Friston, 1999), or for a more abstract category of object (Peelen & Kastner, 2011) has been demonstrated in fMRI studies by differential pre-stimulus activation of visual cortex (see Eimer, 2014, for a review). Müller, Reimann and Krummenacher (2003) found that pre-cuing the dimension (color vs. form) of a singleton target in visual search reduced but did not

eliminate the cost of switching dimensions on search time. Our results extend these findings by demonstrating a limit to the efficacy of such attentional preparation. The early delay in a processing marker observed on task-switch trials, even after substantial preparation that reduced the switch cost, is evidence that attention has a tendency to "stick" to the no longer relevant dimension. This "attentional inertia" is likely to contribute substantially to the residual switch cost. We do not, however, claim that attentional inertia is the sole contributor to the switch cost in the present experiment or in our recent study (Elchlepp et al., 2015). The present data suggest – albeit imprecisely – a perceptual encoding delay of the order of a third to a half of the RT switch cost. It is therefore likely that the prolongation of later processes such as response selection also contributes to the residual switch cost.

We limited the number of CSIs in our design to two to maximize the number of observations in the smallest cells, hence, we cannot be certain that preparation had reached asymptote. However, the vast task switching literature, including many studies employing the same or similar tasks, shows that the switch cost nearly always reaches asymptote at a CSI shorter than 1 s. Evidence that our participants used the long CSI to prepare effectively is provided by the very substantial reduction in the RT switch cost at the longer interval (55% in the color task where the critical ERP analyses were performed), as well as a non-trivial reduction in the error switch cost (~30%), plus the posterior positivity seen in the ERP analysis of the preparation interval, known to be linked to effective preparation (Elchlepp et al., 2012; Karayanidis & Jamadar, 2014; Lavric et al., 2008).

The present finding is useful in other respects. First, it extends Elchlepp et al.'s (2015) observation that a task-switch delays early (pre-response-selection) electrophysiological markers of task-related processing from a linguistic classification

to a perceptual categorization task. Second, it addresses a possible drawback of Elchlepp et al.'s paradigm, in which the word recognition and symmetry tasks could conceivably have been associated with a somewhat different optimal distribution of spatial attention, so that the delay observed when switching could have partly reflected adjustment of this distribution. Given the unpredictable location of the single-letter stimulus used in the present paradigm, differences in the spread of spatial attention between the current tasks are very unlikely to have contributed to the processing delay.

To conclude, using a novel approach based on electrophysiological markers of dimension encoding, the current study provides evidence that when tasks require processing of different perceptual dimensions, a task switch can prolong perceptual processing of the stimulus, even with ample opportunity for preparation. This evidence is consistent with recent eye-tracking studies which have found that a task switch delays the allocation of spatial (Longman, Lavric & Monsell, 2013, 2016; Longman, Lavric, Munteanu & Monsell, 2014) and nonspatial (Mayr, Kuhns & Hubbard, 2013) attention to the relevant stimulus attribute, and with other evidence that some kinds of attentional shift can be resistant to proactive preparation (see Monsell, 2015, for review).

Author contributions

All authors were involved in developing the study concept and contributed to the design. Testing and data collection was performed by H. Elchlepp and M. Best. H. Elchlepp analyzed the behavioral data. H. Elchlepp and A Lavric analyzed the EEG data. H. Elchlepp and A. Lavric drafted the manuscript. S. Monsell extended the manuscript and provided critical revisions. M. Best provided additional comments. All authors approved the final version of the manuscript for submission.

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Table 1. Descriptive and inferential statistics for the significant effects in the behavioral analyses with standard errors and 95% confidence intervals for differences (color freq = color frequency).

	Means	dfs	F	p
RTs (ms)				
CSI	short: 702; long: 582	1,20	72.17	< .001
switch	repeat: 613; switch: 671	1,20	70.87	< .001
switch x CSI	switch cost:	1,20	31.14	< .001
	short CSI: 84±10, [105, 63];			
	long CSI: 33±7, [48, 18]			
Color Task:				
CSI	short: 704; long: 653	1,20	49.95	< .001
switch	repeat: 598; switch: 669	1,20	46.13	< .001
color frequency	frequent: 626; infrequent: 642	1,20	4.83	= .04
switch x CSI	switch cost:	1,20	16.92	< .001
	short CSI: 98±15, [129, 63];			
	long CSI: 45±10, [66, 24]			
switch x color frequency	Color frequency effect:	1,20	5.47	= .03
	repeat: 25±8, [42, 8];			
	switch: 6±8, [23, -11]			
Letter Task:				
CSI	short: 700; long: 602	1,20	82.81	< .001
switch	repeat: 628; switch: 674	1,20	55.32	< .001
switch x CSI	switch cost:	1,20	13.3	= .002
	short CSI: 70±13, [97, 43];			

long CSI: 22±6, [35, 9]

Errors (%)				
CSI	short: 7.1; long: 5.7	1,20	7.39	=.013
switch	repeat: 3.6; switch: 9.1	1,20	80.11	< .001
switch x CSI	switch cost	1,20	4.3	=.051
	short CSI: 6.1±1, [8, 4];			
	long CSI: 4.6±1, [7, 3]			