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Intertrial RT variability affects level of target-related interference in cued task switching

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Abstract

In cued task switching, performance relies on proactive and reactive control processes. Proactive control is evident in the reduction in switch cost under conditions that promote advance preparation. However, the residual switch cost that remains under conditions of optimal proactive control indicates that, on switch trials, the target continues to elicit interference that is resolved using reactive control. We examined whether posttarget interference varies as a function of trial-by-trial variability in preparation. We investigated target congruence effects on behavior and target-locked ERPs extracted across the response time (RT) distribution, using orthogonal polynomial trend analysis (OPTA). Early N2, late N2, and P3b amplitudes were differentially modulated across the RT distribution. There was a large congruence effect on late N2 and P3b, which increased with RT for P3b amplitude, but did not vary with trial type. This suggests that target properties impact switch and repeat trials equally and do not contribute to residual switch cost. P3b amplitude was larger, and latency later, for switch than repeat trials, and this difference became larger with increasing RT, consistent with sustained carryover effects on highly prepared switch trials. These results suggest that slower, less prepared responses are associated with greater target-related interference during target identification and processing, as well as slower, more difficult decision processes. They also suggest that neither general nor switch-specific preparation can ameliorate the effects of target-driven interference. These findings highlight the theoretical advances achieved by integrating RT distribution analyses with ERP and OPTA to examine trial-by-trial variability in performance and brain function.

KEYWORDS
congruence, ERPs, OPTA, reactive control, task switching

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1 | INTRODUCTION

The ability to flexibly adapt behavior to meet changing contextual demands is the hallmark of cognitive control. A large body of research has used variations of the task-switching paradigm to study cognitive control processes (for recent reviews, see Jamadar, Thienel, & Karayanidis, 2015; Vandierendonck, Liefooghe, & Verbruggen, 2010) and has shown that both proactive and reactive control processes play a role in effective cognitive flexibility (Braver, Gray, & Burgess, 2007). In task-switching paradigms, task switch trials are associated with poorer performance than task repeat trials. This switch cost varies when there is advance warning of an impending switch in task. For instance, in cued-trial paradigms, increasing the cue-target interval (CTI) reduces response time (RT) switch cost. This reduction in switch cost is taken as evidence that, given advance information, proactive or endogenous control processes (e.g., Rogers & Monsell, 1995; Rubinstein, Meyer, & Evans, 2001) can reduce switch cost by biasing the system toward the relevant task set (i.e., loading or maintaining the relevant task set). However, in most contexts, a residual switch cost persists even at very long CTIs, when there is ample time to fully engage proactive control processes and prepare for the upcoming switch trial (Meiran, 1996). This residual switch cost has been shown to arise partly from a failure to effectively activate proactive control processes on some proportion of trials (i.e., failure-to-engage model; De Jong, 2000; Poboka, Karayanidis, & Heathcote, 2014). However, residual switch cost has also been shown to arise from greater interference on switch than on repeat trials, resulting in a need for reactive or exogenous cognitive control to optimize target processing (e.g., Allport, Styles, & Hsieh, 1994; for review, see Vandierendonck et al., 2010). More recently, Mayr, Kuhns, & Hubbard (2014) proposed that residual switch costs may arise from shifting between updating and maintenance modes in working memory. In this study, we examine whether advance preparation impacts the level of target-related interference. Specifically, we use single-trial analysis of ERPs to examine the effects of general and switch-specific preparation on target-locked ERPs.

1.1 | Target-related interference in task switching

In task-switching paradigms, residual switch cost is attributed to interference arising from the carryover of activation of the irrelevant task set, or from inhibition of the relevant task set on the preceding trial resulting in task-set inertia (Allport et al., 1994; Wylie & Allport, 2000). At long CTIs, effective proactive control may reduce or eliminate the impact of carryover effects by resetting the goal and preemptively activating the relevant task set, thereby reducing switch cost. Interference may be augmented by the inherent properties of the target itself; that is, the stimulus contains properties from distinct task sets that are incongruently mapped (e.g., Meiran, 2000; Waszak, Hommel, & Allport, 2003).

Target-related interference can vary across trials, depending on the properties of the target. In task-switching paradigms, when the two tasks are defined on distinct stimulus sets (e.g., letter and number classification tasks), targets can be either univalent or bivalent. Univalent targets only include features of the relevant task (e.g., a letter for a letter classification task). Bivalent targets include features from both tasks (e.g., a letter and a number) and elicit greater target-related interference than univalent targets, because participants need to focus on the feature that is relevant on that particular trial and ignore the feature of the irrelevant task. Bivalent targets can be congruent (i.e., both target features are mapped to the same response), incongruent (i.e., the target features are mapped to different responses), or neutral (i.e., the second feature is not associated with either task). For instance, stimulus *A3* is congruent if both vowel and odd are mapped to a left-hand response, but incongruent if vowel is mapped to a left-hand and odd to a right-hand response. A neutral target would be *A#*, where the nonalphanumeric character is not mapped to any response. Neutral and congruent targets elicit less target-related interference than incongruent targets (e.g., Rogers & Monsell, 1995).

Although target-related interference is greater on switch compared to repeat trials, repeat trials are not resistant to target-related interference. This is not surprising since repeat trials with bivalent targets are conceptually similar to interference trials in other paradigms, such as the flanker task or the Simon task. This is evidenced by the mixing cost; that is, repeat trials produce poorer performance in mixed-task blocks than in single-task blocks (Los, 1996), even for highly prepared and practiced young adults (e.g., Whitson, Karayanidis, & Michie, 2012). This persistent residual mixing cost suggests that, compared to repeat trials completed in a single-task block, repeat trials intermixed with switch trials are prone to greater target-related interference and/or require greater resource allocation.

1.2 | ERP indices of target-related interference in task switching

In cued-trial paradigms, ERP amplitude differences between switch and repeat trials in the cue-target interval are believed to index proactive control processes, whereas differences after target onset are believed to index reactive control processes (for reviews, see Karayanidis et al., 2010; Karayanidis & Jamadar, 2014). Cue-locked ERP amplitude shows a

number of positive and negative differences between switch and repeat trials, including an early frontal positivity, a protracted switch negativity, a large parietal switch positivity, and a centroparietal contingent negative variation (CNV)-like negativity (Astle, Jackson, & Swainson, 2008; Elchlepp, Lavric, Mizon, & Monsell, 2011; Lavric, Mizon, & Monsell, 2008; Nicholson, Karayanidis, Poboka, Heathcote, & Michie, 2005). In target-locked ERPs, switch trials are characterized by a larger frontocentral N2 followed by a smaller centroparietal P3b than repeat trials (Barcelo, 2003; Hsieh & Cheng, 2006; Karayanidis, Coltheart, Michie, & Murphy, 2003; Kieffaber & Hetrick, 2005; Lavric et al., 2008; Miniussi, Marzi, & Nobre, 2005; Nicholson et al., 2005; Poulsen, Luu, Davey, & Tucker, 2005; Wylie, Javitt, & Foxe, 2003).

The target-locked frontocentral N2 is elicited in a number of paradigms that require reactive control, such as interference detection and suppression, inhibition and error monitoring (Folstein & van Petten, 2008; Yeung, Botvinick, & Cohen, 2004). For example, N2 is larger for stimuli associated with high interference in the Eriksen flanker task (Gehring, Gratton, Coles, & Donchin, 1992; Hsieh, Liang, & Tsai, 2012) and the Simon task (Spapé, Band, & Hommel, 2011). The N2 is associated with preresponse conflict monitoring processes initiated in the anterior cingulate cortex (Yeung et al., 2004). In some tasks, the N2 shows a broader peak, often resulting in what appears as two partially overlapping components. For example, incongruent color-naming trials in the Stroop task elicit a second, later centroparietal negativity around 400–450 ms (West, 2003). This late N2 is sensitive to interference at the level of target processing rather than response selection (Szücs & Soltesz, 2012). The P3b is associated with decision processes linking perception to action (Verleger, Jaśkowski, & Wascher, 2005) and context updating (Donchin & Coles, 1988). Typically, P3b amplitude decreases and latency increases with increasing attentional and working memory load (Donchin, Kris, Hashore, Coles, & Gratton, 1986; Kok, 1997) and with decreasing stimulus discriminability (Linden, 2005).

In task switching, the amplitude of the target-locked frontocentral N2 is larger for switch than repeat trials (Hsieh & Liu, 2008; Karayanidis et al., 2003; Poulsen et al., 2005), as well as for repeat trials presented in a mixed-task block relative to trials in a single-task block (Goffaux, Phillips, Sinai, & Pushkar, 2006; Jost, Meyer, & Rosler, 2008; Karayanidis, Whitson, Heathcote, & Michie, 2011). This increase in N2 amplitude with increasing level of interference is accompanied by a reduction in P3b amplitude, consistent with greater decision difficulty. While both N2 and P3b are sensitive to target congruence (i.e., whether the target is neutral, congruent, or incongruent), the interaction between congruence and trial type differs across the two components. For N2, target congruence and trial type do not interact (Hsieh & Liu, 2008), indicating similar levels of target-related interference on both switch and repeat trials. However, the effect of target congruence on P3b amplitude has been shown to be larger for switch than repeat trials (Elchlepp et al., 2011). That is, while target-related interference affects both switch and repeat trials, it is resolved earlier and therefore has a weaker effect on decision processes for repeat trials. Importantly, these findings indicate that target-locked ERPs in task switching show a pattern of N2 and P3b modulation that is similar to that seen in classic interference paradigms.

1.3 | Effects of proactive control on target-related interference

Although advance preparation has been shown to improve task-switching performance, it remains unclear whether it modulates the amount of interference encountered during target processing. The fact that residual switch cost remains even with very long preparation intervals (Meiran, 1996) and after extensive task practice (Whitson et al., 2012) suggests that target-related interference may affect performance even under optimal preparation conditions. ERP studies show robust switch-repeat differences in both target-locked N2 and P3b at long preparation intervals, although the trial effects are smaller and less prolonged when compared to short preparation intervals (Jost et al., 2008; Karayanidis et al., 2003; Nicholson et al., 2005). However, these studies cannot make a direct link between effectiveness of advance preparation and reduction of target-related interference. For instance, it is possible that this residual switch cost emerges from the failure to engage in proactive control on some proportion of trials (De Jong, 2000; Poboka, Karayanidis, & Heathcote, 2014). Most studies examining the link between target-related interference and advance preparation compare mean performance across blocks with short versus long preparation intervals. However, these studies cannot provide a pure measure of target-related interference that is uncontaminated by trials that show intermittent failures to engage in proactive control. Furthermore, for ERP data at short CTIs, the cue-locked switch-positivity extends into the posttarget interval and contaminates target-locked ERPs, making it difficult to directly compare the N2 and P3b across short and long CTI blocks.

In this study, we examine target-locked ERPs derived across the RT distribution in order to investigate sources of target-related interference. RT distribution analyses show large intertrial variability in switch cost even at long preparation intervals. A residual RT switch cost (i.e., switch cost under long CTI conditions) remains significant even for the fastest, and presumably most prepared, trials (De Jong, 2000; Karayanidis, Provost et al., 2011; Nieuwenhuis & Monsell, 2002; Poboka et al., 2014), suggesting that faster switch

responses that are the most prepared also show target-related interference. The amplitude of the cue-locked switch positivity also varies across the RT distribution (Karayanidis, Provost et al., 2011) with larger switch positivity for faster, and presumably more prepared, responses.

Karayanidis et al. applied a modified form of Woestenburg, Verbaten, van Hees, and Slangen's (1983) orthogonal polynomial trend analyses (OPTA) technique to extract cue-locked ERPs at each semidecile across the RT distribution. OPTA uses time series data as a covariate in a regression model of the EEG signal to produce low-trial ERP waveforms with high signal-to-noise ratio (see Method). This approach has been implemented using time on task (Karayanidis et al., 2000; Kenemans, Verbaten, Melis, & Slangen, 1992) and RT distribution (Karayanidis et al., 2011) as covariates to extract ERP waveforms that vary across levels of the covariate. Karayanidis, Provost et al. (2011) showed that, for switch trials, the amplitude of the cue-locked centroparietal positivity reduced with increasing switch trial RT and increasing RT switch cost. In contrast, the corresponding positivity for repeat trials did not vary with RT. Importantly, even the most prepared switch trials (i.e., the fastest 10%), which showed the largest centroparietal positivity, still produced a significant (albeit small) residual RT switch cost, suggesting that they are not impervious to target-related interference. In contrast, the amplitude of the frontocentral pretarget negativity varied with RT for both switch and repeat trials, a finding consistent with a general CNV-like component that reflects readiness to process the target. These findings indicate that both switch-specific and general task preparation processes contribute to RT switch cost. Importantly, for the present study, the fastest switch trials were associated with greater switch-specific and general advance preparation than other switch trials, but continued to show a significant residual RT switch cost. This suggests that, on prepared switch trials, residual switch cost is likely to result from target-related interference that is resistant to advance preparation, whereas on unprepared switch trials it is likely to result from a mixture of reconfiguration and target-related interference processes.

In this study, we test the above premise by examining whether the level of advance preparation impacts target-locked ERP components associated with target-related interference. We specifically examine the effects of general task preparation, switch-specific preparation, and failures to engage in advance preparation on target-related interference. We hypothesize that, if target-related interference effects are not amenable to advance preparation and are only driven by target properties, the effect of target congruence on target-locked ERP components will not vary with RT decile or trial type. Alternatively, if general task preparation facilitates target processing by establishing a bias toward the relevant task set, more prepared switch and repeat trials will show smaller effects of target congruence on target-locked ERP components than less prepared trials. Finally, if switch-specific preparation reduces target-related interference on switch trials, over and above any effect of general preparation, we would expect a significant three-way interaction between target congruence, RT decile, and trial type on target-locked ERPs. Specifically, the interaction between target congruence and trial type will be smaller or eliminated at fast RTs; that is, fast, highly prepared switch trials would show a disproportionate reduction in target congruence effects. We test these hypotheses using the OPTA technique and target-locked ERPs from the same data set as Karayanidis, Provost et al. (2011). We examined target-locked N2 amplitude to index target-related interference and P3b amplitude and latency to index efficiency of subsequent decision processes.

2 | METHOD

The data used to conduct the target-locked OPTA analysis were originally published in Nicholson et al. (2005). OPTA on cue-locked ERPs was presented in Karayanidis, Provost et al. (2011).

2.1 | Participants

Twenty-four students (18–30 years of age, $M = 22.2$ years, 15 female) enrolled in an introductory psychology course from the University of Newcastle completed the experiment. Three participants were excluded from the ERP analysis because they did not show clear ERPs across all conditions, leading to spurious latency and amplitude measures across deciles.

2.2 | Paradigm

A gray rectangular box was divided into four quadrants and continuously displayed on a CRT monitor at a distance of 90 cm (Figure 1). Participants switched randomly between two tasks: a letter classification task (vowel/consonant) and a number classification task (odd/even). Responses were mapped to left and right index fingers, and task-response mapping was counterbalanced across participants. In order to counterbalance the mapping between eye shift (vertical/horizontal) and trial type (switch/repeat), the letter task was assigned to the top two quadrants for half the participants and to the right two quadrants for the other half. The number task was assigned to the remaining two quadrants in each configuration. Each trial began with a cue that highlighted (from gray to white) the quadrant in which the next target would be presented, and that remained on throughout the duration of the trial. Targets were pairs of characters (Times

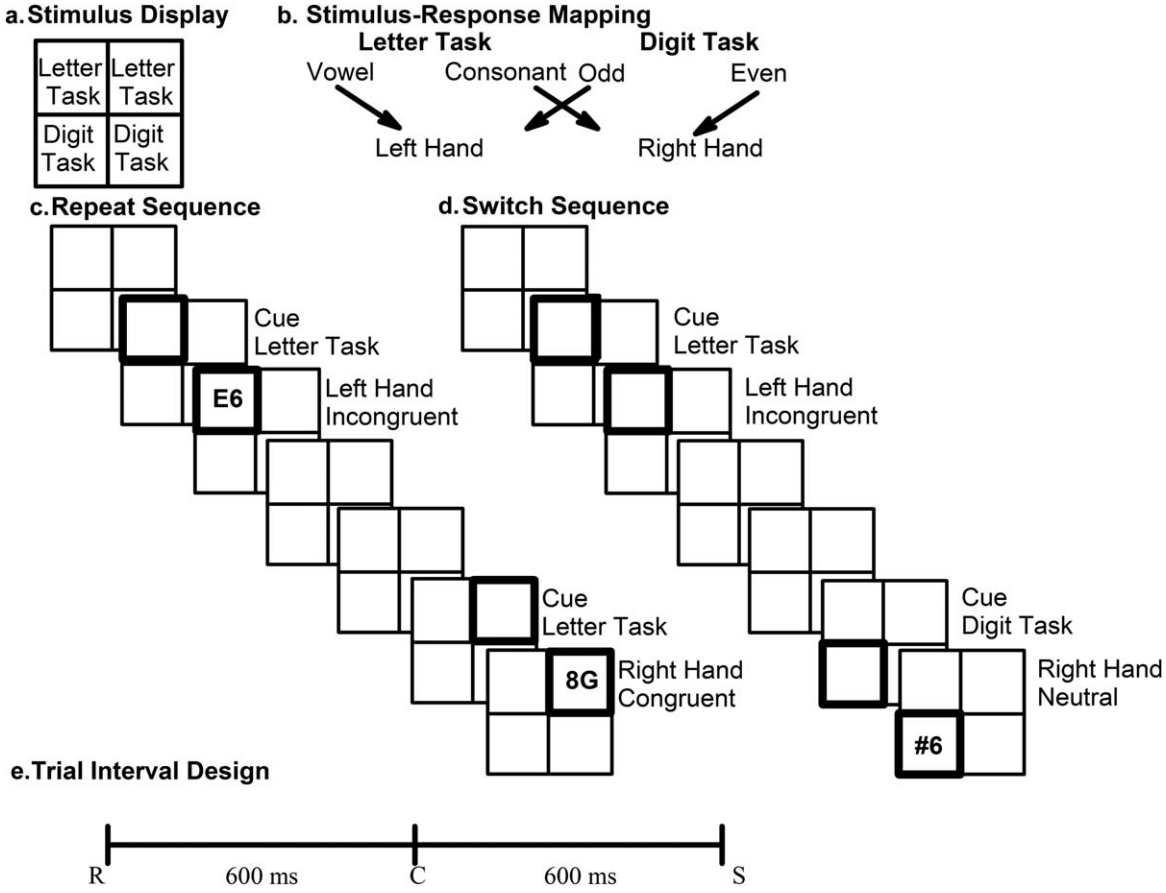

FIGURE 1 Task-switching paradigm. (a) Stimulus-display grid was shown for the duration of the experiment, and adjoining quadrants were associated with one of the two tasks. (b) Example of stimulus-response mapping. (c) Repeat sequence with incongruent and congruent target. (d) Switch sequence with incongruent and neutral target. (e) Response to cue to stimulus intervals

New Roman typeface). One character was selected from a relevant task set (e.g., one of eight letters, *G, K, M, R, A, E, I, U*, or numbers, *2–8*). On neutral trials (33%), the second character was a nonalphanumeric character (*#, %, ?, **) that was not mapped to either task (e.g., *A#*). On bivalent trials, targets were a letter-digit pair (e.g., *A4*), with equal probability that the letter and the number were mapped to a response with the same hand (congruent trials) or different hands (incongruent trials). Character position (e.g., *A4* vs. *4A*) randomly varied across trials. The target remained on screen until a response was recorded or 5,000 ms elapsed. The response-target interval (1,200 ms) and the cue-target interval (CTI, 600 ms) were fixed across the block (three blocks of 100 trials). On average, 33–48 trials were included for each cell, after excluding the first four trials of every block, error, and posterror trials.

2.3 | EEG recording

EEG was acquired from 12 scalp electrodes with linked mastoid reference (500 Hz/channel; NeuroScan Acquire, Compumedics, Ltd., Abbotsford, Australia; Grass Neurodata system (Model 12), Grass Technologies, West Warwick, RI; bandpass: 0.01–30 Hz, −6 dB down). Vertical and horizontal electrooculogram (EOG) was recorded bipolarly from electrodes attached to the supraorbital and infraorbital ridges of the left eye and the outer canthi of both eyes, respectively. EOG was used to correct eyeblink artifact in the EEG signal (Semlitsch, Anderer, Schuster, & Presslich, 1986); sections with movement artifact or channel saturation were removed on visual inspection. Target-locked EEG epochs were extracted over an interval spanning 200 ms before and 2,000 ms after target onset. ERPs were baseline corrected from 0–100 ms after target onset to reduce carryover of switch versus repeat differences from the cue-locked pretarget negativity (Karayanidis, Provost et al., 2011).

2.4 | OPTA analysis

OPTA was used to estimate the variability of the EEG signal across the RT distribution. OPTA generates a polynomial regression model of ERP components in the frequency domain to estimate how the component changes with a covariate, in this case RT (Woestenburg et al., 1983; for more details, see Karayanidis, Provost et al., 2011). Briefly, OPTA transforms the EEG data into the frequency domain and

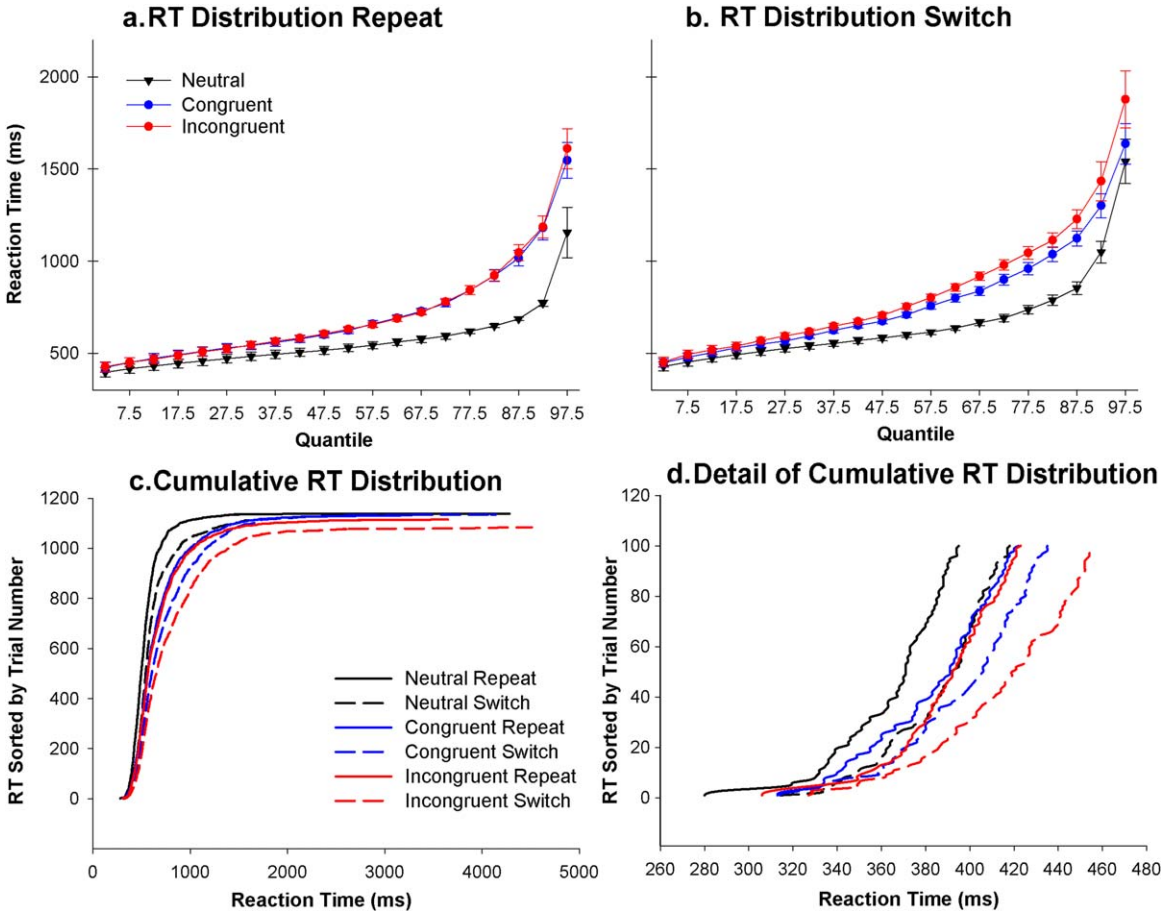

FIGURE 2 Behavioral results. Mean RT at the midpoint of each semidecile for (a) repeat and (b) switch trials at each level of congruence. Bars represent standard error (Morey, 2008). (c) Cumulative distribution of ranked RT against trial number for all RT values depicted by trial type and congruence. (d) Detail of the cumulative distribution showing only the fastest 100 RT ranked trials

applies an orthogonal polynomial regression equation to each component of the frequency profile, using RT as the covariate. We used a modified version of the OPTA technique implemented in MATLAB (Mathworks Inc., Natick, MA) to study variation in target-locked ERP amplitude and latency with RT.

For each participant, trial type (switch, repeat), and congruence (neutral, congruent, incongruent), target-locked epochs were ranked based on RT, and the rank order statistic was used as a covariate in OPTA (i.e., the epoch with the shortest RT, i.e., fastest, was assigned a covariate value of 1, the next shortest 2, and so on). Thus, for all analyses, a positive linear effect of decile reflects an effect of increasing RT. Ranked EEG epoch data were transformed into the frequency domain using a fast Fourier transform (FFT). A polynomial regression equation was applied at each frequency using the order statistic as the covariate and polynomial terms up to the 5th order. We tested whether inclusion of higher-order polynomial terms affected the outcome, and found that each order coefficient (0th, 1st, 2nd, … 5th) was used less frequently as order increased. The 5th order coefficient was only deemed significant in around 5% of analyses, that is, the probability expected by chance under the null (see also Woestenburg et al., 1983). The regression was run for 0 to Nyquist-1 frequencies; frequencies that did not contribute significantly (i.e., $p > .05$) to the signal were removed, and the retained polynomial functions were used to generate RT-ranked predicted frequency profiles of each individual trial. These predicted frequency profiles were transformed back into the time domain with an inverse FFT, yielding an RT-ranked waveform for each condition for each participant. For each participant, individual waveforms were created for each trial type from the middle of each interdecile range (i.e., 5%, 15%, … 95%), and group average waveforms were created by averaging waveforms at each of these deciles.

2.5 | Statistical analysis

Across conditions, target-locked ERPs were characterized by early visual components, including a centrally maximal N1 and a large frontally maximal P2. The N2 was comprised of two peaks: an early N2, most clearly seen for repeat trials centrally, and a late N2, more strongly evident for

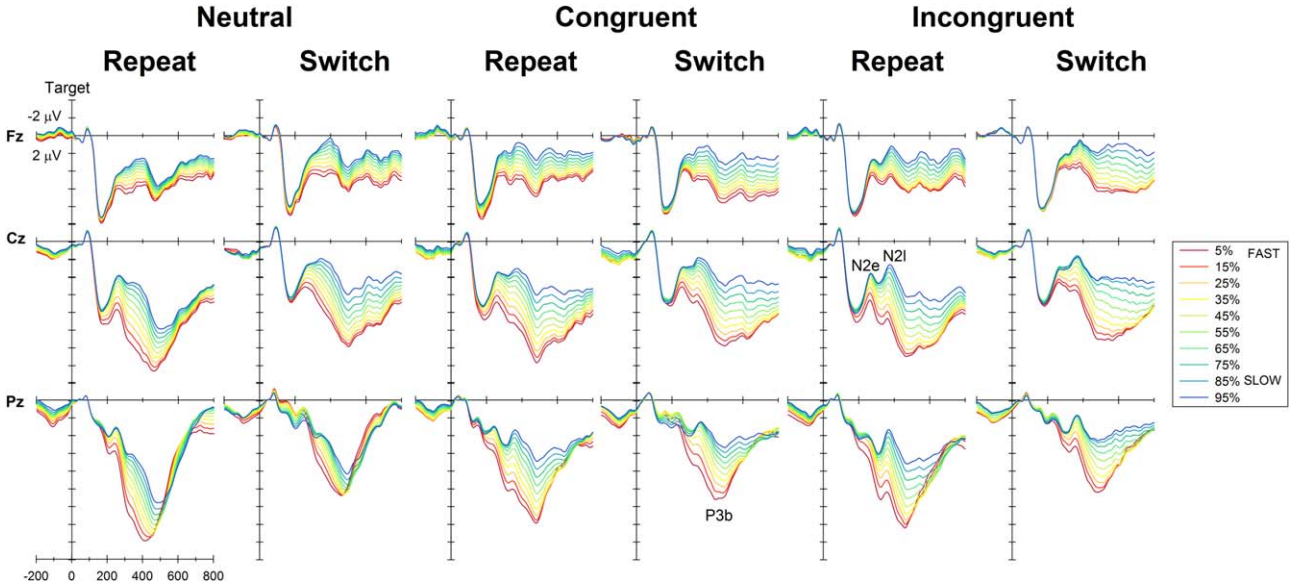

FIGURE 3 ERP waveforms derived from OPTA for repeat and switch trials at each level of congruence. Each waveform represents the midpoint of the decile (i.e., 5th percentile for 1st decile). The fastest 10% of trials are shown in red and the slowest 10% of trials are shown in blue

incongruent targets, followed by a large parietal P3b. Amplitude measurement windows for N2 and P3b were defined on the basis of visual inspection of the grand-averaged ERP waveforms extracted across all deciles, trial types, and conditions to identify windows for each component.

As seen in Figure 3, waveforms showed a substantial differentiation as a function of decile, in both the posttarget, but also in the pretarget interval. In order to visually align the waveforms and highlight posttarget effects, we used a 0–100 ms posttarget baseline in Figure 3. Although it is possible that this posttarget baseline interval may inadvertently accentuate main effects of decile and interactions between decile and other factors, we interrogated the data in a number of ways to confirm that the pattern of findings reported here was not specific to the baseline used. Briefly, we first confirmed that use of different baselines (−200/0, −50/50, 0/100 ms) did not change the pattern of effects on ERP components of interest, but simply varied in the degree to which they removed early posttarget decile effects on N1 and P2. We ran analyses for early N2, late N2, and P3 using each of the above baselines, and found comparable patterns of decile main effects and interactions with other factors. We then ran the analyses reported in the paper, which use peak-to-peak measures for early and late N2 (against P2) and for P3 (against early N2). In addition, we reran these peak-to-peak analyses with different baselines for late N2 (against early N2) and P3 (against late N2), and again found a highly consistent pattern of results. Finally, a similar pattern of findings was obtained in analyses of other conditions from this experiment with a different response-cue interval (150 ms) but the same (600 ms) or a longer (1,050 ms) cue-target interval (Nicholson et al., 2005). For all amplitude measures, we used peak-to-peak measures to avoid contamination from carryover of pretarget effects. More specifically, we used small mean amplitude windows to measure early N2 (240–280 ms) and late N2 (350–390) at Cz. These were analyzed as peak-to-peak measures against mean P2 amplitude over 150–190 ms. P3b peak amplitude and peak latency were measured at Pz over 350–700 ms. Mean amplitude of the early N2 over 225–265 ms at Pz was used as a baseline for P3b amplitude.

RT was analyzed with a 2 Trial Type (repeat, switch) × 3 Congruence (neutral, congruent, incongruent) × 20 Semidecile repeated measures generalized linear models (GLM). ERP amplitude and latency measures were analyzed using a 2 Trial Type (repeat, switch) × 3 Congruence (neutral, congruent, incongruent) × 10 Decile repeated measures analyses of variance (ANOVA). To examine behavioral and ERP effects for the fastest, most prepared trials, RT and ERP measures were analyzed at the fastest semidecile or decile, using a 2 Trial Type × 3 Congruence repeated measures ANOVA. Across all analyses, level of significance was set to $\alpha = .05$. Greenhouse-Geisser corrected p values and corresponding epsilon values are reported where appropriate. Significant effects of target congruence were examined using paired contrasts across the three levels.

3 | RESULTS

3.1 | Reaction time

Figure 2 (a, b) shows mean RT at each semidecile and each trial type for neutral, congruent, and incongruent targets. RT increased with increasing semidecile, $F(19, 437) = 83.55$, $p < .001$, $\eta_p^2 = .784$, $\varepsilon = .058$, with significant linear, quadratic, and cubic trends (all $ps < .001$) showing gradual

increase in the fast RT range followed by a rapid increase in the long RT range. There was a significant switch cost, $F(1, 23) = 34.41$, $p < .001$, $\eta_p^2 = .599$, which increased for slower trials (Trial Type × Semidecile: $F(19, 437) = 9.57$, $p = .001$, $\eta_p^2 = .294$, $\varepsilon = .100$). There was a significant effect of congruence, $F(2, 46) = 80.55$, $p < .001$, $\eta_p^2 = .778$, $\varepsilon = .924$, that increased across the RT distribution (Congruence × Semidecile: $F(38, 874) = 16.07$, $p < .001$, $\eta_p^2 = .411$, $\varepsilon = .091$). Both incongruent and congruent trials had slower RT than neutral trials (both $ps < .001$) but did not differ from each other. These congruence effects increased linearly across the RT distribution.

Both the Congruence × Trial Type interaction and the three-way interaction between congruence, trial type, and semidecile were significant before Greenhouse-Geisser correction, $F(2, 46) = 3.39$, $p < .042$, $\eta_p^2 = .129$, $\varepsilon = .669$; $F(38, 874) = 1.844$, $p < .002$, $\eta_p^2 = .074$, $\varepsilon = .068$. However, neither effect survived Greenhouse-Geisser correction ($p = .064$, $p = .156$, respectively). Incongruent trials showed a larger switch cost than neutral trials (130 ms vs 80 ms), but this effect was only marginally significant ($p = .054$).

To test for interference effects at the fastest, most prepared responses, we reran the above analyses at the first semidecile (i.e., fastest 2.5% of responses). This produced the same pattern of results, with significant main effects of trial type and congruence, $F(2, 46) = 19.69$, $p < .001$, $\eta_p^2 = .461$; congruence: $F(2, 46) = 15.78$, $p < .001$, $\eta_p^2 = .41$, the latter arising from a significant difference between neutral trials and both congruent and incongruent trials (both $ps < .001$). Notably, however, the interaction between trial type and congruence was not significant, $F(2, 46) = .348$, $p = .667$, $\eta_p^2 = .015$, $\varepsilon = .863$.

3.2 | Target-locked ERP data

Figure 3 shows ERP decile waveforms for repeat and switch trials at each level of congruence across three midline electrodes. Figure 4 compares mean scores for each component across deciles for trial type (left) and congruence (right). RT decile had a large effect on target-locked waveforms for all trial types. The fastest RT trials (5th percentile, red lines) showed the smallest early N2 (Cz, ~250 ms), a very small or absent late N2 (Cz, ~400 ms), and the largest and earliest P3b (Pz). In contrast, the slowest RT trials (95th percentile, blue lines) showed the largest and most discriminable early N2 (all trials) and late N2 (congruent and incongruent switch and repeat), as well as the smallest and latest parietal P3b.

3.2.1 | Early N2

As shown in Figure 4, early N2 amplitude increased linearly with increasing RT (decile: $F(9, 180) = 20.39$, $p < .001$, $\eta_p^2 = .505$, $\varepsilon = .123$; linear trend: $F(1, 20) = 21.32$, $p < .001$, $\eta_p^2 = .516$). Effects of trial type, congruence, and their interactions were not significant (all $ps > .07$). At the fastest RT decile (first data point in Figure 4), early N2 amplitude appears to be larger for switch than repeat trials and for congruent/incongruent than neutral trials. However, neither the effect of trial type nor the effect of congruence approached significance (all $ps > .22$).

3.2.2 | Late N2

Late N2 amplitude also increased linearly with increasing RT (decile: $F(9, 180) = 32.55$, $p < .001$; linear trend: $p < .001$; Figure 3–4). In addition, late N2 was larger for switch than repeat trials, $F(1, 20) = 10.27$, $p = .004$, $\eta_p^2 = .339$. Late N2 amplitude also varied with target congruence, $F(2, 40) = 10.06$, $p < .001$, $\eta_p{}^2 = .335$. It was larger for both congruent and incongruent compared to neutral trials ($p < .014$, $p < .001$, respectively), but did not differ between congruent and incongruent trials ($p = .094$). The effects of trial type and congruence did not vary across the RT distribution, and the interactions between type, congruence, and decile were not significant (all $ps > .298$).

At the fastest RT decile, late N2 amplitude did not differ significantly between switch and repeat trials ($p = .075$). In contrast, late N2 amplitude varied with congruence, $F(2, 40) = 5.05$, $p = .012$, being larger for incongruent than neutral trials ($p = .005$).

3.2.3 | P3b—Amplitude

As seen in Figure 3 and 4, P3b amplitude varied significantly with RT (decile: $F(9, 180) = 27.83$, $p < .001$, $\eta_p^2 = .582$, $\varepsilon = .214$). Significant linear and quadratic trends ($p < .001$) show that P3b amplitude was fairly stable at the fast end of the distribution, but reduced steadily at the slower end. P3b amplitude also showed a main effect of trial type, $F(1, 20) = 4.93$, $p = .038$, $\eta_p^2 = .198$, and a significant Trial × Decile interaction, $F(9, 180) = 14.2$, $p < .001$, $\eta_p^2 = .415$, $\varepsilon = .241$. As shown in Figure 4, P3b amplitude did not differ between switch and repeat trials at the fast end of the RT distribution, but declined faster for switch trials, resulting in an increasing switch-repeat difference in P3b amplitude with increasing RT decile.

P3b amplitude also showed significant effects of congruence, $F(2, 40) = 19.64$, $p < .001$, $\eta_p^2 = .495$, $\varepsilon = .78$, and Congruence × Decile, $F(18, 360) = 3.09$, $p < .001$, $\eta_p^2 = .134$, $\varepsilon = .18$. As shown in Figure 4, P3b amplitude was larger for neutral than incongruent or congruent trials (both $ps < .001$), and this effect increased at the slower end of the RT distribution ($p < .024$, $p < .015$, respectively). There was again no significant interaction between trial type and

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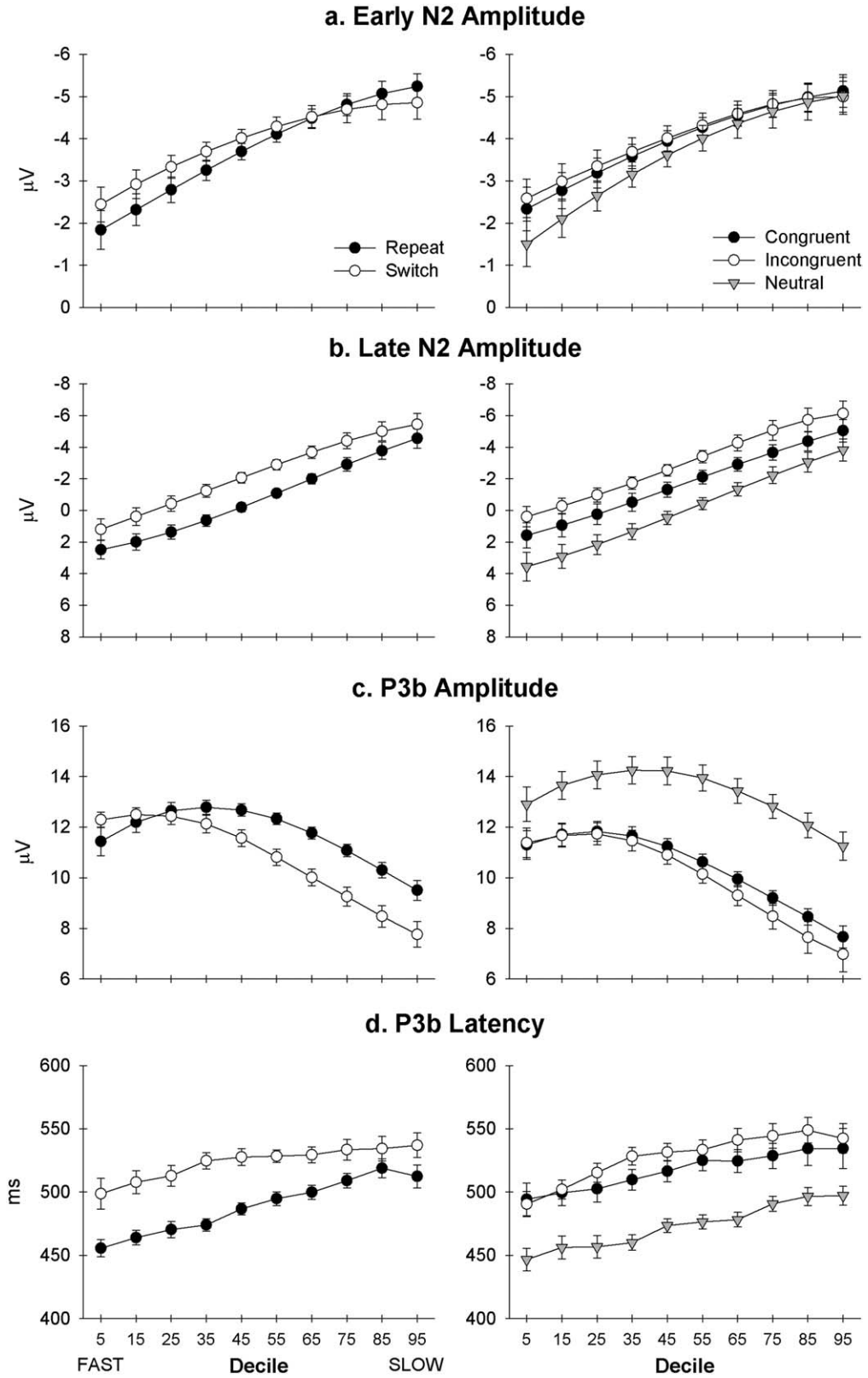

FIGURE 4 Amplitude measures (microvolts) across the RT distribution for the (a) early N2, (b) late N2, (c) P3b, and (d) P3b peak latency (milliseconds) for (left) switch and repeat trials and (right) each level of congruence. Consistent with Figure 3, each measure is given at the midpoint of the decile (i.e., 5th percentile for 1st decile), and negative is plotted up. Error bars show standard error

congruence, indicating that the size of the congruence effects did not vary with trial type. At the fastest RT decile, P3b amplitude did not differ between switch and repeat trials or congruence (both $ps > .15$).[1]

3.2.4 | P3b—Latency

P3b latency increased linearly across the RT distribution, $F(9, 180) = 9.13$, $p = .003$, $\eta_p^2 = .313$, $\varepsilon = .154$; linear trend: $p = .004$. P3b peaked later for switch than repeat trials, $F(1, 20) = 18.43$, $p < .001$, $\eta_p^2 = .48$. Although Figure 4 suggests that the effect of trial type reduced with increasing RT decile, the Trial Type × Decile interaction was not significant ($p > .06$). P3b peak latency also varied with congruence, $F(2, 40) = 19.16$, $p < .001$, $\eta_p^2 = .49$, peaking later for congruent and incongruent than neutral trials (both $ps < .001$), with no difference between congruent and incongruent trials.

At the fastest RT decile, P3b peaked nearly 60 ms earlier for repeat than switch trials, $F(1, 20) = 12.44$, $p = .002$, $\eta_p^2 = .383$. A significant main effect of congruence, $F(2, 40) = 8.82$, $p = .001$, indicated that P3b peaked later for congruent and incongruent than for neutral targets (both $ps < .001$) but did not differ between incongruent and congruent targets.

4 | DISCUSSION

Cued task-switching paradigms typically produce a significant residual switch cost that remains even at long cue-to-target intervals, which enable preparation before target onset. Using RT distribution analyses, Karayanidis, Provost et al. (2011) showed that this residual switch cost can be seen even in the fastest 5% of responses that are likely to be the most prepared. Thus, even the most prepared switch trials are more prone to target-related interference than repeat trials.

In this study, we examined the effects of target congruence on trial type across the RT distribution, to investigate whether the residual switch cost arising from stimulus-level interference is impacted by trial-by-trial variability in advance preparation. We reasoned that, if advance preparation specifically impacts task set uploading on switch trials, the effect of interference on the residual switch cost will be smaller for faster, more prepared as compared to slower, less prepared trials. If advance preparation has a more general biasing effect toward the relevant task set, congruence effects will reduce with preparation for both switch and repeat trials. Alternatively, if preparation does not impact stimulus-level interference, congruence effects will not vary across the RT distribution.

As expected, increasing RT was associated with a larger residual switch cost and a larger incongruence effect. While congruence effects tended to be larger for switch trials (consistent with Elschepp et al., 2011; Karayanidis et al., 2003; Poulsen et al., 2005) and slower trials, the interactions between target congruence and either trial type or RT decile were not significant. This suggests that neither general nor switch-specific preparation ameliorate the effects of target-driven interference on RT. Further, even on the most prepared trials, both congruent and incongruent targets elicited greater interference than neutral targets, which is also consistent with the argument that general preparation is not sufficient to eliminate target-related interference. That these fastest responses showed a significant residual switch cost that did not vary with target congruence suggests that even optimal task set preparation does not overcome interference driven by stimulus features for either switch or repeat trials.

4.1 | Changes in target-locked ERPs with trial-by-trial RT variability

We examined trial type and congruence effects as a function of RT on three target-locked ERPs: the early N2, which is sensitive to interference at the level of target identification (Gehring et al., 1992); the late N2, which indexes interference during target processing (West, 2003); and the P3b, which is sensitive to decision difficulty, particularly at the level of target-response transformations (Donchin et al., 1986; Kok, 1997). Both congruent and incongruent targets elicited a larger late N2 and a smaller and later P3b than neutral targets. These effects are consistent with other interference paradigms including the Eriksen flanker task, which shows an enhanced N2 and a delayed P3b on high conflict trials (Gehring et al., 1992); the Simon task, where incompatible stimulus-response displays show enhanced N2 amplitudes and delayed P3b compared to compatible stimulus-response displays (Strack, Kaufmann, Kehrer, Brandt, & Sturmer, 2013; Valle-Inclan, 1996; see also Spapé et al., 2011); and the Stroop task, which shows delayed P3b latencies for incongruent versus congruent trials (Szucs & Soltesz, 2012). The late N2 effect is compatible with the N450 effect reported in Stroop tasks, which shows a frontocentral distribution and is larger in incongruent than congruent Stroop trials (Szucs & Soltesz, 2012).

All target-locked ERP components varied across the RT distribution. Specifically, slower responses were associated with larger early N2 and late N2 amplitude, smaller P3b amplitude and later P3 latency. Thus, our results support the argument that slower, less prepared responses arise from

[1]Analyses measuring P3b amplitude against late N2 produced comparable but somewhat weaker results. The main effects of congruence and decile failed to reach statistical significance. However, the interactions between decile and both congruence and trial type remained significant.

greater target-related interference during target identification and processing, as well as slower, more difficult decision processes.

Consistent with previous task-switching studies (e.g., Karayanidis et al., 2003; Hsieh & Liu, 2008), switch trials produced larger late N2 and smaller P3b than repeat trials. Early N2 amplitude was not affected by trial type, suggesting that switch-specific preparation facilitates stimulus identification on switch trials, making them more like repeat trials. However, there were significant switch-repeat effects on both late N2 and P3b amplitude. For late N2, switch-repeat differences were maintained across the RT distribution, suggesting that increased interference on switch than repeat trials during target processing is independent of the efficiency of anticipatory switch-specific preparation. In contrast, trial type effects on P3b amplitude increased with RT, suggestive of a benefit of advance preparation on decision processes, even in the presence of target-related interference. Interestingly, the fastest, most prepared trials showed no effect of trial type on early N2, late N2, and P3b amplitudes, but a later P3b peak for switch than repeat trials. Thus, it appears that target-response decision processes on these most prepared trials were slower but not more difficult, suggesting that interference can delay response processes independently of whether it influences the difficulty of the decision that leads to that response.

Target-level interference (congruence) produced larger late N2 and smaller P3b amplitudes for incongruent trials compared to neutral trials. Early N2 was not affected by target congruence, suggesting little interference from the irrelevant target feature on target identification. Late N2 was larger and P3b smaller and later for both congruent and incongruent targets compared to neutral targets across the RT distribution. Since target congruence did not interact with trial type, this suggests that sustained target-related interference affects both switch and repeat trials even for the fastest, fully prepared trials. Target congruence was influenced by trial-by-trial variability in RT only for P3b amplitude, suggesting that, while target congruence did not interfere with target identification and processing, it did influence the difficulty of the target-response decision process (in contrast to the effects of trial type). Together with the finding that the fastest, most prepared trials showed no effect of target congruence on P3b amplitude, these results suggest that general task preparation reduced the impact of target-related interference, specifically on the target-response transformation process.

Figure 2 and 4 show that, for both RT and ERP amplitude measures, congruent trials (i.e., trials where the distractor and imperative stimuli were linked to the same response) tended to fall closer to incongruent trials than to neutral trials. However, congruent and incongruent trials did not differ significantly on any of these measures. Thus, target bivalency had a larger effect at the level of target processing and decision selection than at the level of response selection. That is, the mere presence of a target feature from the competing task set was sufficient to induce interference regardless of whether that stimulus required a response from the same or different hand.

4.2 | The challenge of baseline selection in S1-S2 designs

As raised briefly in the Method section, the choice of baseline was a particularly difficult issue in the current paradigm.[2] Like many task-switching paradigms, we used a fixed cue-target interval in order to both maximize preparation to switch (Monsell & Mizon, 2006) and examine ERP effects within the CTI (Karayanidis, Provost et al., 2011). Fixed cue-target intervals often produce slow negative potentials that differ between conditions and only resolve after target onset (Rockstroh, Elbert, Canavan, Lutzenberger, & Birbaumer, 1989), which makes it challenging to measure the amplitude of ERP components in both cue-locked and target-locked waveforms. This is not the case only in task-switching paradigms; it first emerged in the context of typical S1-S2 paradigms used to elicit the CNV (e.g., Loveless, 1973; see review by Brunia, van Boxtel, & Böcker, 2011). There is no single recommended approach for reducing the impact of these pretarget negative shifts on posttarget ERPs. One approach is to extract epochs extending from before S1 (cue) onset to beyond the response to S2 (target) and use the same precue baseline for both cue-locked and target-locked ERPs. This approach is most suited in instances where the pretarget differences resolve before the measurement window of the posttarget components of interest. However, when there are sustained shifts in the ERP waveforms that are maintained posttarget, this may lead to spurious condition differences emerging in the posttarget ERPs. Peak-to-peak amplitude measures reduce the impact of carryover shifts by measuring the relative change in amplitude from one component to the next (i.e., anchoring peak measurement of a component to an earlier one; Picton et al., 2000). As long as it can be assumed that the effect of carryover shifts would be either constant or diminishing, this approach does not risk inflating posttarget effects. Alternative approaches include using principal or independent component analyses (PCA, ICA; e.g., Makeig, Jung, Bell, Ghahremani, & Sejnowski, 1997) across the entire interval to extract PCA/ICA components independently of baseline. While this approach has

[2]In fact, we struggled with this issue both when preparing the submitted manuscript and in robust but constructive discussions with a reviewer and the action editor. We would like to thank them both for their patience and their insightful comments throughout this process.

been applied successfully in some task-switching studies, considerable work is still needed to establish the number and equivalence of components across paradigm variations.

Importantly, the issue of baseline is not exclusive to S1-S2 paradigms or to ERP measures. It ranges from baseline measures to identify differential deficits in clinical versus healthy groups (e.g., Chapman & Chapman, 1978) to the use of baseline conditions to identify task-relevant neuronal activity in fMRI paradigms (e.g., Stark & Squire, 2001). All these contexts require careful consideration of how to best resolve the baseline problem for the specific context. In this paper, we chose to present peak-to-peak measures after confirming that the reported results are consistent when using different peritarget baselines and different preceding components as anchors.

4.3 | Conclusions

In summary, OPTA analyses on target-locked ERP data showed broad changes in ERP components across the RT distribution. Both early and late N2 amplitude increased, whereas P3b amplitude decreased and latency increased with increasing RT. Importantly, only RT and P3a amplitude showed significant changes in trial type and interference effects across the RT distribution. Both residual switch cost and congruence/incongruence effects increased independently with increasing RT. This is consistent with the hypothesis that general task preparation facilitates target processing by establishing a bias toward the relevant task set (i.e., more prepared switch and repeat trials showed smaller congruence effects on P3b amplitude than less prepared trials).

While the fastest, most prepared trials showed a significant residual switch cost and a congruency effect, this was not associated with modulation of P3b amplitude. Instead, these very fast responses showed evidence of target-related interference at the level of target processing (late N2) and a delay in decision processes (P3b latency), with the latter being independently impacted by trial type differences. These findings suggest that, even under task conditions that promote optimal proactive control (long cue-stimulus interval, highly practiced participants), there are multiple processes that impact trial-by-trial variability in RT.

4.4 | Afterword: Importance of integrative measures

The approach used in this paper highlights the important theoretical advances that can be achieved by integrating across different methodological approaches. RT distribution analyses have shown that conventional mean RT measures hide substantial trial-by-trial variability that may arise from fluctuations in arousal, attentiveness, etc. Traditional approaches extract ERP waveforms using signal averaging over many trials to improve the inherently low signal-to-noise ratio of ERP components (Coles & Rugg, 1995; Picton et al., 2000). However, the legitimacy of signal averaging relies upon the assumption that the ERP signal remains constant across repeated presentations of the same stimulus type. This assumption is questioned by the large trial-by-trial RT variability often found in RT distributions. Unlike conventional ERP signal averaging, OPTA allows the estimation of ERP components on an individual trial-by-trial level, resulting in a substantial increase in signal-to-noise ratio (Woestenburg et al., 1983). Karayanidis, Provost et al. (2011) showed that including RT as a covariate in the OPTA model produces a 2.5 times improvement of signal-to-noise ratio over conventional signal averaging.

This approach revealed a number of important insights about the nature of task switching that could not be achieved with conventional analyses. For instance, Karayanidis, Provost et al. (2011) showed that the broad, centroparietally maximal positivity for switch versus repeat trials that appeared to span across most of the cue-target interval in conventional ERP amplitude analyses arose, in fact, from differential modulation of two underlying components: a switch-specific component around 300 ms (i.e., the switch positivity) and a general component peaking just before target onset (i.e., the pretarget negativity). By comparing ERP waveforms from switch and repeat trials that were equated for RT, Karayanidis, Provost et al. (2011) was able to differentiate switch-specific and general preparation processes. In the current article, OPTA also offered unique insight, showing that the significant residual RT switch cost for the fastest, most prepared responses was not related to differential target processing or decision efficiency (amplitude of the early N2, late N2, or P3b), but to processes delaying the decision itself (P3b latency), possibly suggesting response selection interference.

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