Processing Underpinnings of Chronotype x Time-of-Day Interactions: A Study of a Conditional Automaticity Account of (A)synchrony Effects.

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Abstract

Chronotype and time-of-day interactions are often manifest in differences between performance at times-of-day matching the individual's chronotype (on-peak) and off-peak performance. However, it is not clear which processing variables determine whether on- or off-peak benefits/costs will occur. We hypothesized that only processes entangled by conditional automaticity (CA) would manifest (a)synchrony effects: on-peak enhancement of core voluntary top-down control and off-peak augmentation of conditioned automatic processes. CA is an unconscious processing bias that reflects the enhancement of pathways linked, but not directly relevant, to the control structure of an ongoing, or recently completed, explicit task. Participants were 34 evening-types performing on-peak and 31 off-peak, and 30 morning-types on-peak and 29 off-peak. We used a spatial Stroop task to probe (i) top-down voluntary executive control, (ii) bottom-up CA (facilitation of the response opposite to the one currently under controlled inhibition), and (iii) an unconscious/automatic top-down control process autonomous wrt (i) and (ii), namely, a bias favoring response alternations over repetitions. Expected results were derived from a detailed processing model based on the CA hypothesis and supported by our results, namely, wrt to off-peak enhancements being restricted to conditional-automatic processes, coupled with off-peak impediment of the controlled process that conditioned that automaticity, and wrt to the absence of (a)synchrony for processes not bound by conditional automaticity, irrespective of either their top-down or involuntary character.

Keywords: chronotype; synchrony and asynchrony effects; conditional automaticity; prediction of outcome-response theory; spatial Stroop task

Several studies have found that, for some cognitive tasks, chronotype interacts with the time of day, yielding on-peak and off-peak performances that differ substantially (e.g., Hahn et al., 2012; May, 1999; May & Hasher, 1998; Schmidt et al., 2015). Chronotype refers to the individual differences that exist in the circadian rhythmicity of several physiological variables (e.g., body temperature, melatonin and cortisol production) (Adan, 2015; Simor & Polner, 2017). The time at which the peak of these cycles occurs varies between individuals and influences sleep schedules and preferences in timing of daily activities (Schmidt, Collette, Cajochen, & Peigneux, 2007). Morning types (M-types) favor waking up at early hours and feel more efficient during the first part of the day, which is thus said to be their optimal or on-peak time, whereas evening types (E-types) rise at later hours and prefer to perform demanding daily activities in the late afternoon/evening, thus being off-peak in the morning and having their on-peak time at those later hours (Baehr, Revelle, & Eastman, 2000; Gomes, 2005). Most chronotypes are intermediate, falling between these two more extreme patterns of diurnal preferences.

“Synchrony effect” was the term coined to refer to a difference between cognitive performance at on- and off-peak times favoring testing times matching the individual’s chronotype, a finding that emerged early on in studies that probed the relation between chronotype and cognition (May & Hasher, 1998; May, Hasher, & Stoltzfus, 1993). However, on- and off-peak times do not map straightforwardly onto the quality of performance at those times. The nature of the cognitive processes that are most central for the execution of the task at hand likely determines whether a synchrony effect is in fact observed, with better performance during on-peak times, or an asynchrony effect, with better performance during off-peak times (Delpouve, Schmitz, & Peigneux, 2014; May, Hasher, & Foong, 2005; Rothen & Meier, 2016; Rowe, Valderrama, Hasher, & Lenartowicz, 2006; Wieth & Zacks, 2011), or no impact from the interaction between diurnal type and time-of-day (ToD). Synchrony effects are most commonly found in tasks that require deliberate, strategic management of action, for instance, when the adequacy of habitual responses must be pondered, eventually leading to the rejection of such responses in favor of less dominant but contextually appropriate ones (May & Hasher, 2017). The association between this type of cognitive processes and enhanced on-peak performance is exemplified by studies that used problem solving tasks (May, 1999), working memory tasks (Rowe, Hasher, & Turcotte, 2009; Yoon, May, & Hasher, 1999), tasks probing executive function (Goldstein, Hahn, Hasher, Wiprzycka, & Zelazo, 2007; Hahn et al., 2012; May & Hasher, 1998; Schmidt et al., 2007), verbal fluency tasks (Iskandar et al., 2016), comprehension of narrative text (Natale & Lorenzetti, 1997), analytic thinking and resistance to stereotyping (Bodenhausen, 1990; Hossain & Saini, 2013), suppression of irrelevant information and of unwarranted responses (Hasher, Chung, May, & Foong, 2002; Hasher, Zacks, & May, 1999; Intons-Peterson, Rocchi, West, McLellan, & Hackney, 1998; May, 1999; May & Hasher, 1998; Schmidt et al., 2012), visual and verbal explicit memory tasks (Fabbri, Mencarelli, Adan, & Natale, 2013; May et al., 1993; Petros, Beckwith, & Anderson, 1990), and rejection of false memories (Intons-Peterson, Rocchi, West, McLellan, & Hackney, 1999). In contrast, asynchrony effects have been observed for tasks in which performance mainly reflects an implicit level of processing, partly or totally removed from conscious awareness. In most of the studies that have unveiled asynchrony effects, the interpretation of results equates the operations that take place at this level with automatic processes, and proceeds by assuming that automaticity is hindered by the exertion of executive control (Bocanegra & Hommel, 2014; Kiefer, 2007, 2012). According to this view, the beneficial effects of off-peak times-of-day for certain tasks are in fact a side-effect of the impediment of executive control at those times, that likely results in the loosening of top-down constraints that impinge upon automatic processes (e.g., Delpouve et al., 2014; May et al., 2005). Asynchrony effects amenable to this type of explanation have been observed, for example, for implicit learning (Delpouve et al., 2014), implicit memory retrieval (May et al., 2005), incidental memory encoding (Rothen & Meier, 2016), implicit retrieval of distractor information (Rowe et al., 2006), and solving problems by insight (Wieth & Zacks, 2011). However, the literature on asynchrony effects is scarce and, to our knowledge, has yet to discuss the features that distinguish processes prone to asynchrony effects from those that are seemingly impervious to the interaction between diurnal type and time-of-day. Studying the nature of this distinction may well lead to a more complex understanding of the cognitive underpinnings of (a)synchrony effects. The absence of effects of on-/off-peak time is usually observed when successful performance depends on well-learned knowledge (e.g., tests of vocabulary and lexical access), or when the prevalent response is correct (e.g., tests of processing speed) (Borella, Ludwig, Dirk, & de Ribaupierre, 2011; Hasher, Goldstein, & May, 2005; Hasher et al., 1999; May & Hasher, 1998; Song & Stough, 2000). Tasks such as these, refractory to both synchrony and asynchrony effects, typically pose minimal requirements in respect to executive control and, importantly in what the absence of asynchrony effects is concerned, bear no connection to any other current or previous task set that requires executive control. In contrast, tasks that elicit asynchrony effects are usually linked by design to another task that requires some degree of executive control (e.g., implicit memory retrieval tasks rely on a previous explicit task set that embedded the presentation of the material to be probed during the implicit memory task). The concept of "conditional automaticity" has been coined (Bargh, 1989; Logan, 1989) to refer to the particular type of unconscious processes deployed in implicit-processing tasks, and has yet to be brought to bear upon the discussion of (a)synchrony effects. This type of automaticity is deemed "conditional" since it bears a dependency upon the processing of a current or recently completed explicit task. We believe that a powerful explanatory hypothesis for (a)synchrony effects, amenable to be specified as a processing model, can be derived from the concept of "conditional automaticity”. The term “conditional automaticity” denotes automatic modulations of ongoing processing that emerge as temporary byproducts of the explicit task set, namely, of the attentional amplification of both relevant and irrelevant task-congruent processing pathways. The latter are related, but not directly relevant, to the task’s explicit goals and their subsidiary amplification is deemed responsible for the performance modulations observed in the implicit-processing task (see also Kiefer, 2007; Kiefer, 2012). In keeping with this view, both asynchrony and synchrony effects would reflect a less efficient management of attentional amplification at off-peak times, which results in a disproportionate enhancement of information and processing pathways that are related, but not relevant to the task set, and in the correlative depletion of resources available to process relevant stimulus and response features. Accordingly, if performance at on- and off-times on a control-demanding task is contrasted at, a synchrony effect should ensue; if another task is performed in close temporal proximity to the executive task, and that task has been designed to benefit from enhanced processing of features related, albeit irrelevant, to the executive task set, an asynchrony effect should be observed; if the task that is scrutinized does not involve processing pathways that have previously been enhanced due to the exertion of executive control, nor does it require the deployment of such control, no effect of on/off-peak times should be observed.

The aim of the present study is twofold. One of our goals is to clarify the relation between (a)synchrony effects and the nature of the processes evoked by the task set. Most published research suggests that voluntary executive control is hampered at off-peak times; however, it is not clear which of the features of this type of process is linked to off-peak costs, namely, whether it is its regulatory top-down nature (which does not imply conscious awareness and voluntariness) or its voluntary character, derived from the explicit awareness of the regulating goal. In respect to asynchrony effects, it is again not clear which is the processual aspect that is linked to off-peak benefits, namely, automaticity (in the sense of autonomy from top-down regulatory processes), or involuntary deployment (which may in some cases occur in a top-down regulatory process). We specifically intended to confront the conditional automaticity account of (a)synchrony effects with two alternatives, namely, that (a)synchrony expresses an effect on top-down control *per se* or, instead, an effect on involuntary/unconscious processes, regardless of their role in controlling/regulating other processes. Our other goal is to overcome what we consider to be a relevant limitation of previous research on (a)synchrony effects: Most of the tasks employed to probe these effects are usually either too complex to allow to single out specific cognitive processes and ascertain how each of them (or their interaction) is affected by on- and off-peak times, or too simple, focusing on a single process, whereas most naturally occurring cognition involves the interaction of multiple processing streams. We therefore probed (a)synchrony effects using a task that was on the one hand simple enough to allow for a precise identification of the main cognitive processes underpinning performance, and, on the other hand, a task bearing a precisely controlled degree of complexity, so that the impact of (a)synchrony on processual interactions could be assessed.

Cognitive Underpinnings of the Experimental Task

In accordance with these goals, we designed a conflict task that elicits two contrasting top-down processes, namely, a conscious control process of response-conflict detection and resolution, and an unconscious expectancy-driven response bias, favoring a current-trial response opposite the one given in the previous trial. Whereas the process of conflict detection and resolution is an executive process similar to those typically prone to synchrony effects (e.g., May & Hasher, 1998; Schmidt et al., 2012), the unconscious bias can be viewed either as prone to a synchrony effect (given that it is a top-down control process), an asynchrony effect (given its involuntary/unconscious character), with greater bias at off-peak times, or as impervious to (a)synchrony effects (given that it is not related with the explicit task set, and therefore not an instance of conditional automaticity). Conditional automaticity should emerge in the task as a strengthening of the lateral inhibition circuit connecting the task's two alternative motor responses, thereby increasing the likelihood of automatic execution of the response opposite to the one currently under controlled inhibition. Specifically, we set up a spatial Stroop task in which response repetition was also manipulated. We address below the task's features that engage each of the two top-down control processes and discuss different theoretical accounts pertaining to these processes, that will be instrumental in defining our expected results.

Conscious Executive Control

In a trial of a classic spatial Stroop task (Funes, Lupianez, & Milliken, 2007; Luo, Lupianez, Funes, & Fu, 2013; Luo & Proctor, 2013), an arrow is displayed on the left/right side of a computer screen, and participants must respond to the left/right direction of the arrow, ignoring its left/right position on the display. Similar to the Simon task (Simon, 1969), stimulus' appearance automatically prompts a response that shares that stimulus' spatial code, making the response linked to the irrelevant stimulus' dimension the prevalent response (Kornblum, Hasbroucq, & Osman, 1990; Lu & Proctor, 1995). Two types of trials result from this setup, congruent (C, in which the arrow's direction matches its onscreen position) and incongruent trials (IC, in which direction mismatches position). In IC trials, two conflicting action plans emerge, one that would yield a response on the side matching the (irrelevant) stimulus' position, the other complying with the arrow's direction and therefore yielding the correct response.

Different theories have offered detailed accounts of the processing of response-conflict. Conflict monitoring theory (CMT) (Botvinick, Braver, Barch, Carter, & Cohen, 2001), advocates the existence of a dedicated conflict monitoring system, crucially dependent upon the anterior cingulate cortex (ACC), that automatically responds in situations in which response conflict is present, signalling the need for increased cognitive control and relaying this request to the prefrontal regions that instantiate the required processes. The prefrontal control system then resolves the conflict by enhancing the activation of the task-relevant stimulus' dimension. Another approach is the prediction of response-outcome theory (PRO), (Alexander & Brown, 2010, 2011) according to which conflict effects derive from the prediction of multiple responses and not from response conflict/incompatibility *per se*. According to PRO, the ACC responds to the presence of multiple action plans in the stimulus context (e.g., a plan based on the arrow's onscreen position: *if arrow-position = x then response-side = x*; and another on the arrow's direction: *if arrow-direction = x then response side = x*) by computing predictions of specific responses (e.g., left-right, linked to the respective motor codes) for those plans. The ACC also anticipates the positive and negative outcomes associated with each of those responses[1] (Kennerley, Walton, Behrens, Buckley, & Rushworth, 2006). The action plans yielding predicted responses with an unacceptable cost (e.g., high error probability) are suppressed, suspending activation influx to the corresponding motor codes, and only the action plan yielding the response associated with the least amount of effort or risk is left active (Botvinick, 2007; Brown & Braver, 2005). According to PRO, suppression occurs through feed-back from the predicted outcome signal, that instantiates an "amend-veto" function (Alexander & Brown, 2010). In a conflict task, assignment of high error probability to a predicted response must result from a comparison to the criteria that defines unwarranted responses in the task set. In our spatial Stroop task, unwarranted responses are those that are

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[1] The core processes detailed in PRO involve mappings between existing action plans in a stimulus context and predictions of the responses and outcomes that are likely to result (Alexander & Brown, 2011). These action plans are abstract functions projecting the value of a given stimulus feature onto a response (e.g., if stimulus at position x, response at position x). PRO is to a large extent a learning theory and therefore has a primary focus on the process of learning the aforementioned mappings, as it unfolds in tasks in which the correct response is not instructed but must be learned by trial-and-error using feedback. However, PRO also describes the mechanisms that make use of those mappings when they were fully learned or directly defined by the task's instructions. Accordingly, PRO also models performance in tasks in which the required response is clearly defined by instructions, such as conflict tasks in which participants must select task-appropriate responses when competing alternatives are also present (Alexander & Brown, 2011; Yeung, 2013). It is the set of mechanisms that PRO proposes in respect to this type of task that is of interest in our present work.

mapped from the irrelevant stimulus dimension (i.e., those resulting from the plan *if arrow-position* = *x*, *then response-side* = *x*), and are identified by a match between their spatial code and that of the stimulus. Studies that compared CMT and PRO accounts of performance patterns on a spatial Stroop task (Pires, Leitão, Guerrini, & Simões, 2018) favoured PRO. Accordingly, and we will henceforth use PRO to frame the processing underpinnings of our spatial Stroop task.

Unconscious Response Bias

The spatial Stroop task that we have used further includes direction-only (DO) trials. In DO trials the arrow is displayed in the centre of the computer monitor. The stimulus therefore contains only task-relevant direction information, and a single action plan emerges in DO trials, always yielding a correct response. The C and IC trials of interest in this study are systematically preceded by a DO trial; in half of the C and IC trials, there is repetition of the correct response of the previous DO trial, while in the other half there is alternation. The *n*-1 DO trial is in turn preceded by another DO trial, and always requires response alternation. This relation between the correct responses in the n^{th} (C or IC) trial and those in the *n*-1 and *n*-2 trials (DO) is known to create first order response sequence effects, solely dependent upon the nature of the *n*-1 trial, and higher order sequence effects, involving longer sequences of trials (Perruchet, Cleeremans, & Destrebecqz, 2006; Proctor & Vu, 2006; Soetens, 1998; Soetens & Notebaert, 2005). At long response-stimulus intervals (RSIs) (e.g., 1000 ms in Soetens, 1998), a small but consistent first-order benefit is observed in the RT data for response-alternation trials, coupled with a cost for repetition trials (cost-benefit), and a higher order cost-benefit pattern also occurs, markedly favouring continuation trials, i.e., those that maintain the repetition/alternation status of a run of two or more previous trials of the same type. All RSIs in our task are long, varying between 1200 - 1400 ms, a circumstance that should originate a first order response-alternation benefit and response-repetition cost, as well as a higher-order strengthening of this effect, since trials *n*-1 and *n*-2 create a response-alternation context for the n^{th} trial, favouring a further alternation (Proctor & Vu, 2006; Soetens, 1998; Soetens & Notebaert, 2005). The first order cost-benefit sequence effect that emerges at long RSIs is usually ascribed to a generic expectancy of alternation (Proctor & Vu, 2006; Soetens, 1998), viewed as related to the gambler's fallacy (Wagenaar, 1972), the belief that in random sequences alternations are more likely than repetitions. Soetens and Notebaert (2005) attribute the cost-benefit pattern at long RSIs, observed for trials interrupting/continuing runs of multiple repetitions or alternations, to subjective expectancy formation, building up over multiple trials (Audley, 1973; Soetens, 1998; Soetens & Notebaert, 2005). In fMRI studies, this cost-benefit pattern has been linked to the modulation of the activity of the ACC by stimulus history (Jones, Cho, Nystrom, Cohen, & Braver, 2002), with lower ACC activation in expectancy-congruous trials. Importantly, the literature consensually considers these particular subjective expectancies to be low level mechanisms, i.e., that instantiate an unconscious bias towards continuations or alternations beyond volitional control (Audley, 1973; Kirby, 1980; Proctor & Vu, 2006; Soetens, 1998; Soetens & Notebaert, 2005; Sommer, Matt, & Leuthold, 1990). Formation and deployment of a low-level expectancy, such as the alternation bias, does not involve a control structure driven by an awareness-accessible goal, in contrast to the control setup that, expressing the task set, explicitly aims to suppress responses on the same side of the stimulus in IC trials (e.g., Funes et al., 2007; Luo et al., 2013; Luo & Proctor, 2013). Instead, sequence/rhythmicity related low-level expectancies are probably best understood as forms of attentional pacing driven by an underlying entrainment activity (Barnes & Jones, 2000). The specific entrainment that subtends the alternation bias links the current trial's response to the response before last, yielding an action plan before the stimulus is displayed, namely, *if n-2 response-side = x then response-side = x*. A prompt response prediction may then follow, resulting in the paced focusing of specific left/right spatial code that yields the alternation preference. Even though this low-level expectancy is a top-down process, in that it controls the assemblage of an action-plan and the selection of a motor response’s spatial code, it should lack the distinctive features of a conscious process, namely, wide-spread neural activity and recurrent loops within a brain-scale network that includes fronto-parietal areas (Dehaene, 2001; Dehaene, Changeux, Naccache, Sackur, & Sergent, 2006; Rozier et al., 2019). These features, in that they imply complex attentional amplification of networked pathways, are arguably crucial for conditional automaticity effects to emerge, and are notoriously absent in unconscious representations, which are confined to specific brain regions. In the case of low-level expectancies, the temporal lobe, including hippocampal regions, is recurrently involved, without recruitment of the global workspace that is the hallmark of conscious processing (Dehaene, 2001; Dehaene et al., 2006; Lisman & Redish, 2009; Rozier et al., 2019).

A Model of (A)synchrony Effects Under the Conditional Automaticity Hypothesis

In the dual route model of conflict tasks (Kornblum et al., 1990; McBride, Boy, Husain, & Sumner, 2012; Ridderinkhof, 2002; Ridderinkhof, van den Wildenberg, Wijnen, & Burle, 2004), two processing routes interact, one unavoidably related, but irrelevant or, in some trials, detrimental to task performance, the other appropriately instantiating the task set. The former is a fast direct processing route, drawing on connectivity between perceptual and motor areas *via* subcortical structures (Schlaghecken, Bowman, & Eimer, 2006), the latter is an indirect processing route that operates more slowly *via* cortical structures, and converges with the direct route in determining a motor response by means of task-appropriate voluntary response selection/inhibition. The executive control setup in our spatial Stroop task corresponds to this indirect processing route. It consists of processing pathways selectively enhanced so as to instantiate the task set (i.e., in the spatial Stroop task, pathways that establish a S-R mapping template for the correct response[2], and that instantiate the criteria defining unwarranted responses, namely, those bearing a spatial code that matches the stimulus’). The conditional automaticity hypothesis entails that during off-peak performance enhancement of these processing pathways will be less efficient, resulting in increased concurrent activation of pathways associated, but not relevant (Anderson & Folk, 2014), to task performance. These latter pathways belong to the direct route, which, in a spatial Stroop task, fosters automatic mapping of stimuli’s spatial codes onto responses’ motor programs, and inhibitory lateral connectivity between the alternative motor response channels involved in the task (Botvinick et al., 2001; Bowman, Schlaghecken, & Eimer, 2006; Schlaghecken et al., 2006; Shenhav, Botvinick, & Cohen, 2013). For a particular pathway within the direct route to be apt for drawing activation from the indirect route instantiating the executive control setup, it must deliver an output congruous with that of the executive process (Kiefer, 2007). Arguably, the crux of the “activation leakage” from the indirect to the direct route is the process of setting up, in an IC trial, the pathway for suppression of action plans bearing predicted responses with negative outcomes, corresponding to PRO’s “amend-veto function” (Alexander & Brown, 2010). This is because controlled suppression of a predicted response in IC trials is systematically associated with the execution of the opposite (correct) response. Therefore, the control setup systematically cooperates with the low level lateral inhibition circuit: when one of the response channels is inhibited by the control setup, the other channel will be automatically released from the inhibitory signal it had been receiving within the lateral inhibition circuit, lowering its execution threshold, and facilitating the execution the action

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[2] This mapping establishes the direction-based action plan. In IC trials, this plan is enacted when the automatic position-based plan is suppressed. In C trials, the mapping template may be instrumental when the (disadvantageous)) deployment of the control setup happens to outrun the incremental activation of the single motor program that both action plans support. I such C trials, control momentarily leads to the suppression of all plans with predicted responses on the same side as the stimulus, which include the direction-based plan. The absence of active mappings of stimulus information onto motor programs should prompt a controlled recruitment of the mapping template for the correct response in order to regenerate the direction-based plan, which is now the sole plan available and may yield an unimpeded motor response.

plan linked to the arrows' direction in IC trials. Under the conditional automaticity hypothesis, when the control setup is deployed to suppress an action plan, an enhanced automatic facilitation of the response opposite to the one currently under controlled inhibition should occur. Importantly, the enhancement of the lateral inhibition circuit feeds from the process of activating the executive control pathways, and therefore should result in a proportionally delayed deployment of the control setup. This tradeoff is expected to be magnified off-peak, delaying the availability of control and, when it comes to be enacted, facilitating overt responses opposite to the one under controlled inhibition, even in absence of support for the accuracy of those responses, namely, even when they do not match the predicted response for the action plan linked to the arrow's direction. The observation, common in the literature, of an increased occurrence, on a given trial, of incorrect responses that correspond to the alternative of a response inhibited in the previous trial (Klapp & Hinkley, 2002; McBride et al., 2012; Schlaghecken et al., 2006) likely is due to such response facilitation mechanisms induced by the release from lateral inhibition.

Expected Results

In respect to conscious executive control, the conditional automaticity hypothesis and PRO theory lead to the prediction of on- off-peak[3] differences in the deployment of the control setup, consisting in greater off-peak enhancement of direct route pathways (namely, greater automatic facilitation of responses opposite to those under controlled inhibition) and lessened activation of the direct route (less efficient/slower deployment of the control setup, namely, of the processes that yield predicted responses for existing action plans and test the match between the spatial code of those responses and that of the stimulus, to assign outcome predictions). As for the low-level expectancy favoring response alternations, the conditional automaticity

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[3] For clarity, we will often use the expression "on- off-peak" to refer to the interaction between chronotype and time-of-day, which were in fact entered as distinct variables in our analyses.

hypothesis entails that it should remain constant across on- and off-peak times. This is because formation and deployment of the alternation bias does not involve awareness-accessible goals. Therefore, it lacks the complex attentional amplification of networked pathways that subtends the trade-off between enhancement of indirect/direct route pathways and correlated (a)synchrony effects. Also, the alternation bias bears no dependencies in respect to the control processes prompted by the task set. Accordingly, it cannot be conceived as an instance of conditional automaticity that, on account of this feature, would be prone to off-peak enhancement.

Even though response repetition/alternation is not expected to interact with on- off-peak times of day , an interaction of each of these variables with (in)congruency is anticipated: the alternation bias consists of an action plan that is present before stimulus presentation and should therefore influence the moment of deployment of the control setup that manages response/outcome predictions and suppression of action plans, with different consequences in C and IC trials, modulated by the repetition and alternation status of the required response; in turn, deployment of the control setup is expected to be impeded off-peak, whereas the automatic production of responses opposite to the one currently under controlled inhibition should be enhanced. Therefore, a complex interaction involving response alternation/repetition, (in)congruency, and on- off-peak times is anticipated. We discriminate below, for each of the four types of trials that express the interaction between the variables response repetition and (in)congruency, the predictions regarding the effects of on- vs off-peak times, and present in detail the processing account that subtends those predictions. Figures 5 and 6 systematize this account in terms of on- and off-peak positive or negative contributions to speed and accuracy of the two main processes associated with control deployment, namely, in figure 5, the process of setting up a match-test between the spatial code of current predicted responses and that of the stimulus, in order to assign response-outcome predictions to existing action plans, and, in figure 6, the process (conditional upon control deployment) of automatic facilitation of responses opposite to those currently under controlled inhibition.

Congruent alternation trials. Trials in which the correct response is an alternation relative to the previous trial potentially benefit from the alternation bias. When such alternation trials are congruent (figure 1), the response predictions generated by the ACC for the relevant and irrelevant stimulus' dimensions overlap and, consequently, performance is hindered by the deploying the executive control setup. In fact, given this overlap, correct responses in doC$^{R\neq}$ trials are on the same side as the stimulus, and computing outcome predictions would momentarily result in the suppression of action plans that yield that response. On-peak's optimal promptness in control deployment is expected to foster this type of detrimental suppression. This is because the alternation bias consists in an action plan that is in place before the stimulus is displayed, and, accordingly, for which a predicted response will be available before the plans linked to the actual stimulus' dimensions can be assigned their respective predicted responses. An on-peak executive system is likely to efficiently keep on processing the alternation action plan, forecasting a negative outcome for its predicted response as soon as a spatial code for the stimulus is available, since the alternation response is on the same side as the stimulus. Suppression of the alternation plan ensues. The setup responsible for this suppression will be in place when the predicted responses for the action plans linked to the stimulus dimensions become available, resulting in the suppression of those plans. Additional time will be required for the direction-based plan to be regenerated and for the motor code linked to the corresponding response to gather enough activation for enactment. Automatic production of the response opposite to that of the supressed plan should not significantly hamper accuracy, since on-peak enhancement of the pathways that implement the task set should be optimal, minimizing activation leakage to the related pathway that supports automatic production of non-inhibited responses. In turn, an off-peak executive system should be less prompt in yielding an outcome prediction for the alternation response, allowing time for response predictions to emerge for the actions plans linked to the actual stimulus dimensions. The overlap of all predicted responses, in the absence of a suppression signal, would rapidly lead to the execution of the corresponding motor response, which was introduced before stimulus' onset by the alternation bias. Off-peak accuracy can however be compromised in those cases in which an outcome prediction does come to be computed for the alternation response: in this circumstance, an impulsive response to the opposite side is more likely to be produced due to off-peak facilitation of the automatic production of the response opposite to the one currently inhibited. Overall, we predict slower on-peak correct responses, and lower off-peak accuracy. Considering the two main alternatives to conditional automaticity in respect to the sources of (a)synchrony effects, the following hypotheses ensue: if the top-down character of a process were the determinant of (a)synchrony effects, the alternation bias would be stronger on-peak and weaker off-peak, reducing the off-peak speed advantage, and rendering off-peak impulsive opposite-to-inhibited incorrect responses less likely. Hence, an asynchrony effect would still prevail, but inferior to that predicted by the conditional automaticity hypothesis, mainly driven by a small off-peak speed advantage. If voluntary processes were hampered off-peak whereas involuntary processes are enhanced, the alternation bias and the tendency to produce impulsive opposite-to-inhibited responses would be stronger off-peak, leading to hindered off-peak accuracy and improved speed, whereas a weaker on-peak bias would preserve speed at those times. Again, an asynchrony effect inferior to that predicted by the conditional automaticity hypothesis, would be expected, also driven by an off-peak speed advantage.

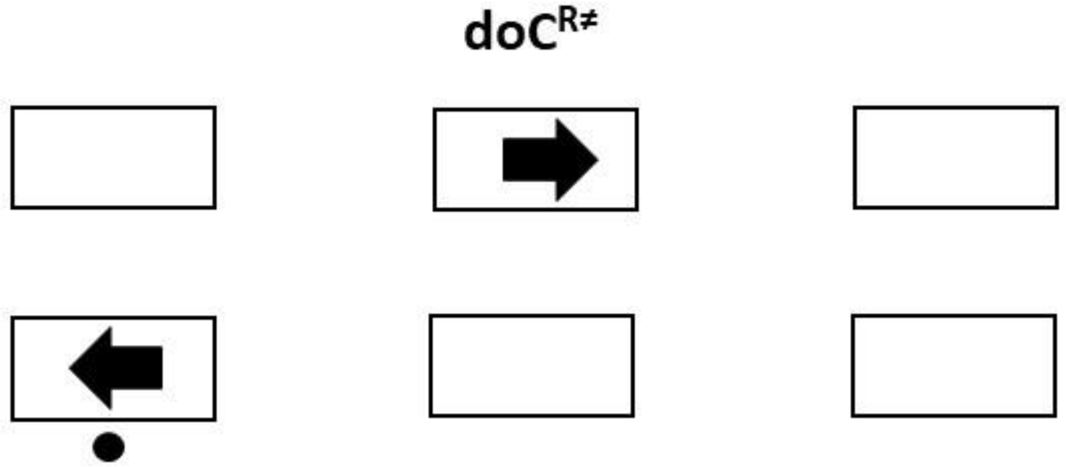


Figure 1. DO - C trial sequence with a correct response for the C trial opposite to the DO trial's. The dot represents the response supported by the alternation bias. The direction-based and position-based plans support the same response.

Incongruent alternation trials. When the alternation trial is incongruent (figure 2) the response predictions generated by the ACC for the relevant and irrelevant stimulus' dimensions do not overlap. The presence of different predicted responses should require the deployment of the control setup, resulting in the identification and suppression of the action plan linked to the position of the current stimulus. However, given that there is response alternation in the trial, the action plan that instantiates the alternation bias prompts, before stimulus' onset, a response prediction congruous with the relevant, direction-based, action plan. Thus, the usual dominance of responses on the same side of the stimulus, which is the source of accrued difficulty in IC trials, should be to some degree curtailed by the early presence of the opposite (correct) predicted response. This circumstance is expected to attenuate the deleterious effect of a delayed and less efficient off-peak deployment of the control setup, given that correct responses can obtain without deployment of control. Such responses result from a process of incremental activation of the direction-congruent response, that we expect to be faster than the indirect selection of that response by means of controlled suppression of the position-based action plan. The former process initiates before stimulus onset when the motor code for the correct response starts to receive activation from the alternation action plan, and results in the production of that response as soon as further activation linked to the arrow’s direction brings that motor code past threshold. Events of off-peak control deployment that result in impulsive production of the response opposite to the one inhibited do not yield incorrect responses in alternation incongruent trials, and further foster the overall speed of off-peak correct responses, without adding to accuracy, since a fully controlled response would still be correct. At on-peak times, full engagement of the executive control setup is more likely, and should result in increased response latencies without a corresponding accuracy enhancement. However, this latency cost is expected to be mitigated by the early presence of the alternation plan and its predicted response, which should activate the template for the identification of negative outcomes. Hence, when a predicted response comes to be computed for the action plan linked to the stimulus position, this template will already be available and should promptly generate a negative outcome prediction, resulting in the suppression of that plan. Overall, we predict faster off-peak correct responses, and comparable on- and off-peak accuracy. Considering the two main alternatives to conditional automaticity, the following hypotheses ensue: if the top-down character of a process were the determinant of (a)synchrony effects, the alternation bias would be stronger on-peak, inducing faster correct responses, whereas a weaker off-peak bias would no longer provide a fast route to correct responses, as well as rendering error more likely. Hence, both speed and accuracy should be enhanced on-peak, yielding a strong synchrony effect. If voluntary processes were hampered off-peak whereas involuntary processes are enhanced, the alternation bias would be stronger off-peak, leading to faster and more accurate off-peak performance and yielding a strong asynchrony effect.

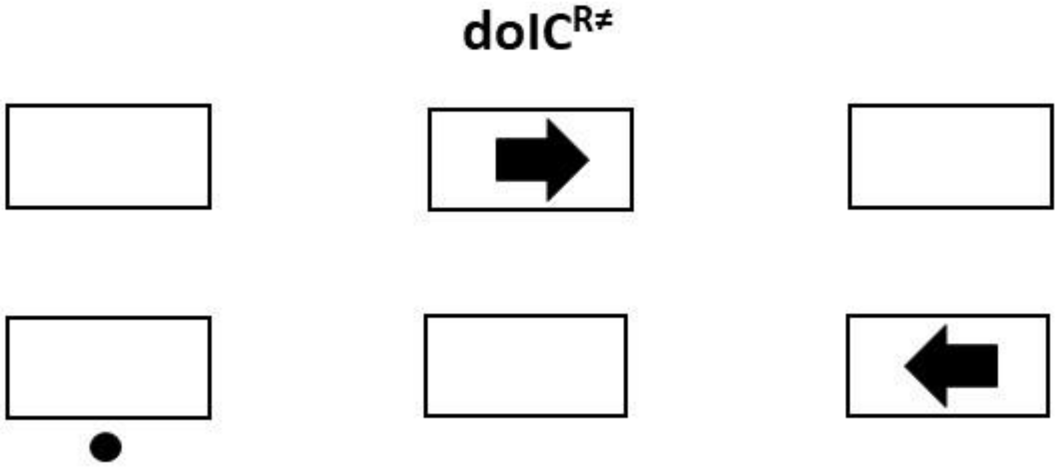


Figure 2. DO - IC trial sequence with a correct response for the IC trial opposite to the DO trial's. The dot represents the response supported by the alternation bias. The direction-based plan supports the same response and the position-based plan its opposite.

Congruent repetition trials. In repetition trials, participants will be biased towards an incorrect response, i.e., an alternation. When the trial is congruent (figure 3), the response predictions generated by the ACC for the relevant and irrelevant stimulus' dimensions overlap and could dispense engagement of the control setup without loss in accuracy and with gain in speed. However, the alternation bias is likely to induce an on-peak executive system to fully deploy the control setup and suppress the action plans that yield a (correct) response on the same side as the stimulus. This is because the action plan yielding the response alternation relative to the previous trial is present before stimulus' onset. As in alternation C trials, the ACC should have generated a response prediction for this plan, and, on-peak, proceeded to process an outcome prediction by setting up a match-test between the response's and stimulus' spatial codes. This match, indicating a likely incorrect response, emerges not for the alternation plan but for the plans linked to the stimulus dimensions, which both yield the correct response, and results in the suppression of those plans. Whereas in alternation C trials the alternation action plan is supressed along with those linked to the stimulus' dimensions and no plans yielding an incorrect response are available, in a repetition trial the alternation plan does yield the incorrect response and will remain active at the moment when those linked to the correct response are suppressed. Accordingly, on-peak performance will be slowed down because executive control has to recognize that no action plan mapped from stimulus' information is available, set up the suppression of the unwarranted alternation plan, and maintain that suppression while the plans that yield the (correct) response are momentarily inhibited. If a correct response is to be produced, further time is necessary to regenerate the direction-based action plan (see footnote 2) and for its predicted response's motor code to be brought past enactment threshold. Hampered on-peak accuracy is also expected to result from this circumstance, since the incorrect alternation response will be available for execution throughout the time leading to the regeneration of the direction-based plan and while the corresponding motor program gathers activation. Given that executive control deployment should be less prompt off-peak, the correct response likely will not be slowed by momentary suppression of the action plans linked to the stimulus' dimensions and should instead obtain from the process of incremental activation of the correct motor code linked to those plans' predicted responses. When controlled inhibition does intervene off-peak, a loss in accuracy should occur due to the occurrence of automatic (incorrect) responses on the opposite side of the stimulus. Given the lessened likelihood of off-peak control deployment, a relative loss in on-peak vs. off-peak accuracy is expected to prevail. Overall, we predict slower on-peak correct responses, as well as hampered on-peak accuracy. Considering the two main alternatives to conditional automaticity, the following hypotheses ensue: if the top-down character of a process were the determinant of (a)synchrony effects, the alternation bias would be stronger on-peak and weaker off-peak, resulting in the same pattern of on-peak impediment, affecting speed and accuracy, as that predicted by the conditional automaticity hypothesis, i.e., a strong asynchrony effect. If voluntary processes were hampered off-peak whereas involuntary processes are enhanced, the alternation bias would be weaker on-peak, reversing both the speed and accuracy off-peak advantages and yielding a strong synchrony effect.

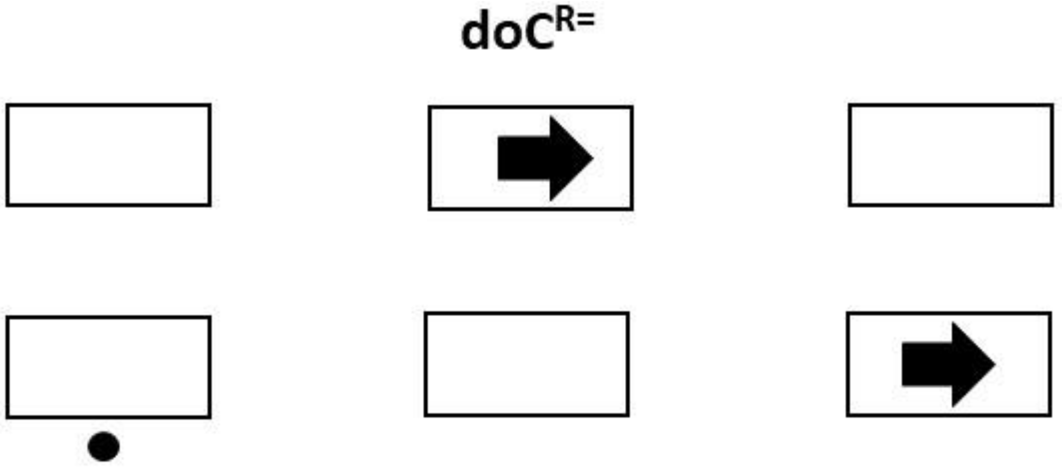


Figure 3. DO - C trial sequence with a correct response for the C trial repeating the DO trial's. The dot represents the response supported by the alternation bias. The opposite response is supported by the direction-based and position-based plans.

Incongruent repetition trials. When the repetition trial is incongruent (figure 4), the response predictions generated by the ACC for the relevant and irrelevant stimulus' dimensions do not overlap, whereas the alternation bias yields an incorrect response that overlaps with the response linked to the position of the current stimulus. In such trials, correct responses should require deployment of the control setup. At on-peak times, the synergy between the promptness of control deployment and the presence of the alternation action plan before stimulus' onset should allow an early prediction of a negative outcome for the alternation response, and the suppression of the corresponding action plan. This prediction should be generated as soon as the spatial code for the stimulus becomes available, and the match between that code and the response's is detected. The active template for negative outcome assignment should also prompt the suppression of the plan linked to the stimulus position, thus curtailing the major source of incorrect responses in IC trials. When the response prediction linked to the arrow direction becomes available, production of a correct response can ensue as soon as the activation of the corresponding motor code has reached threshold. At off-peak times, executive control is expected to be less prompt in generating the negative outcome prediction for the alternation response. This circumstance should increase the likelihood of that incorrect response being executed when the corresponding motor code receives additional activation from the response prediction linked to the stimulus position. As for trials in which off-peak control does come to suppress the response on the same side of the stimulus, a fast automatic (correct) response on the opposite side should be more likely than on-peak. Overall, we predict lower off-peak accuracy and faster correct responses. Considering the two main alternatives to conditional automaticity, the following hypotheses ensue: if the top-down character of a process were the determinant of (a)synchrony effects, the alternation bias would be stronger on-peak, enhancing the speed of correct responses, whereas a weaker off-peak bias would lend more time for the deployment of control, rendering it more likely, therefore benefiting accuracy. Hence, on- and off-peak RTs should be comparable, whereas accuracy should be enhanced on-peak, albeit to a lesser degree than that predicted by the conditional automaticity hypothesis, yielding a small synchrony effect. If voluntary processes are hampered off-peak whereas involuntary processes are amplified, the alternation bias would be stronger off-peak, potentiating incorrect responses, and weaker on-peak, thus enhancing response speed to a lesser extent: less accurate off-peak performance should result, coupled with fast correct responses due to automatic opposite-to-inhibited responses when control comes to be deployed off-peak, whereas on-peak speed should be enhanced to a lesser degree than that predicted by the conditional automaticity hypothesis, yielding an overall negligible (a)synchrony effect.

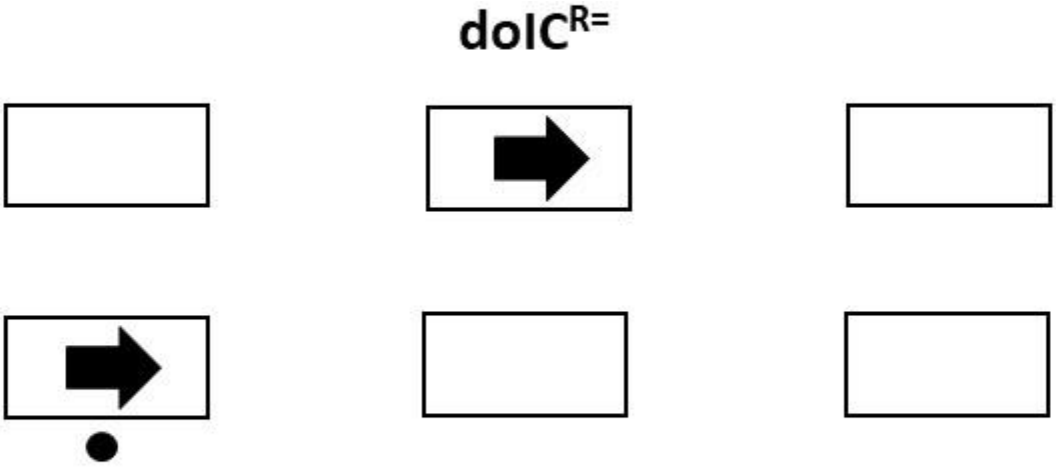
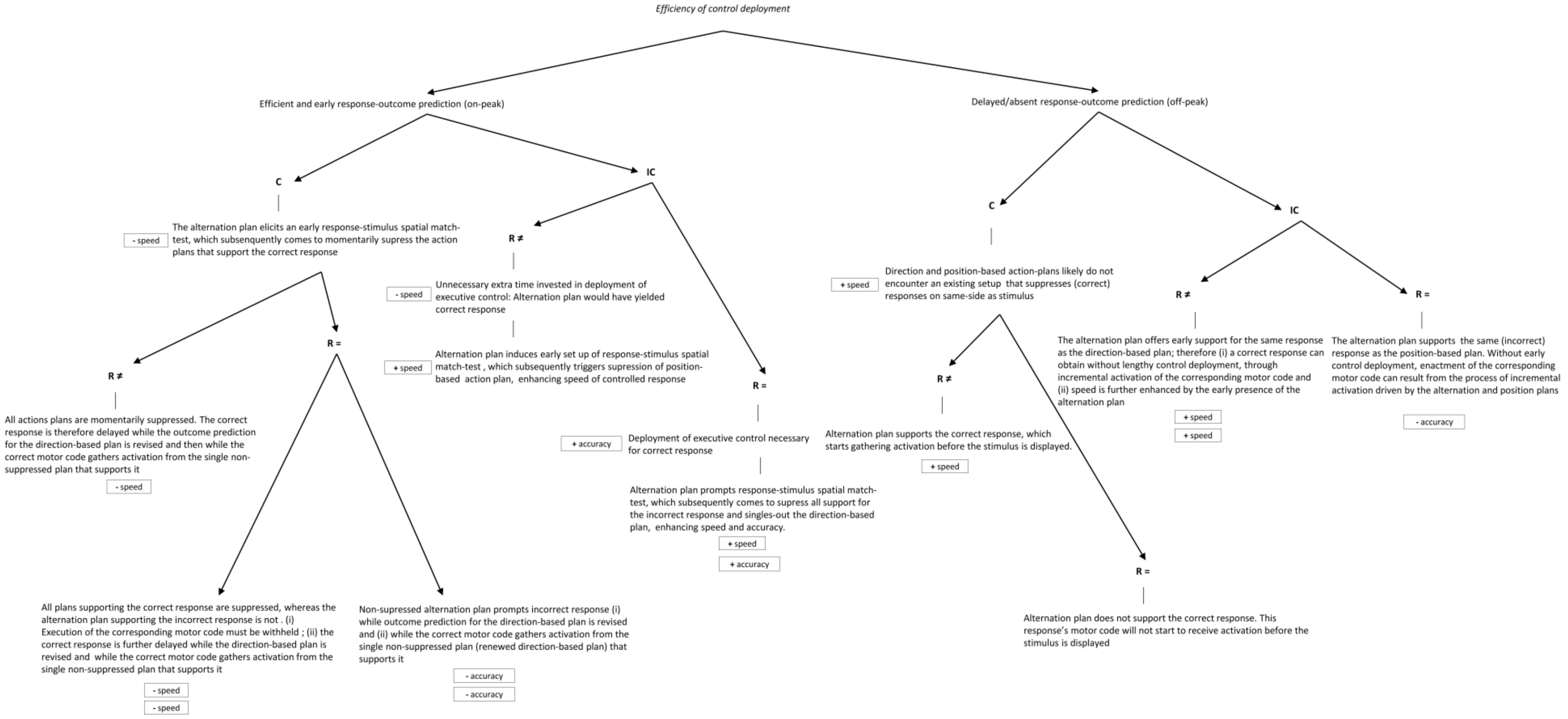


Figure 4. DO - IC trial sequence with a correct response for the IC trial repeating the DO trial's. The dot represents the response supported by the alternation bias action plan. The position-based plan supports the same response and the direction-based plan its opposite.



- speed
The alternation plan elicits an early response-stimulus spatial match-test, which subsenquently comes to momentarily supress the action plans that support the correct response

All actions plans are momentarily suppressed. The correct response is therefore delayed while the outcome prediction for the direction-based plan is revised and then while the correct motor code gathers activation from the single non-suppressed plan that supports it
- speed

All plans supporting the correct response are suppressed, whereas the alternation plan supporting the incorrect response is not . (i) Execution of the corresponding motor code must be withheld ; (ii) the correct response is further delayed while the direction-based plan is revised and while the correct motor code gathers activation from the single non-suppressed plan that supports it
- speed
- speed

Non-supressed alternation plan prompts incorrect response (i) while outcome prediction for the direction-based plan is revised and (ii) while the correct motor code gathers activation from the single non-suppressed plan (renewed direction-based plan) that supports it
- accuracy
- accuracy

- speed
Unnecessary extra time invested in deployment of executive control: Alternation plan would have yielded correct response

+ speed
Alternation plan induces early set up of response-stimulus spatial match-test , which subsequently triggers supression of position-based action plan, enhancing speed of controlled response

+ accuracy
Deployment of executive control necessary for correct response

Alternation plan prompts response-stimulus spatial match-test, which subsequently comes to supress all support for the incorrect response and singles-out the direction-based plan, enhancing speed and accuracy.
+ speed
+ accuracy

+ speed
Direction and position-based action-plans likely do not encounter an existing setup that suppresses (correct) responses on same-side as stimulus

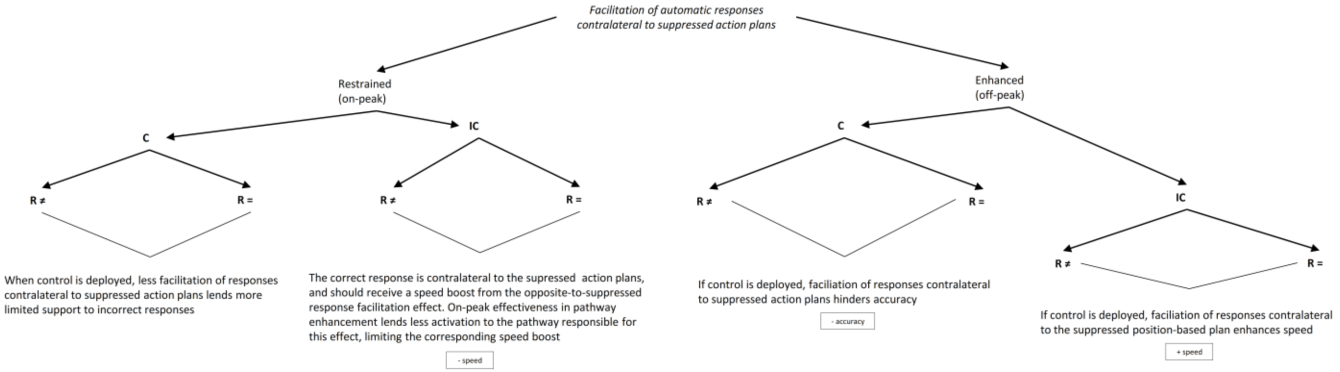
Alternation plan supports the correct response, which starts gathering activation before the stimulus is displayed.
+ speed

Alternation plan does not support the correct response. This response's motor code will not start to receive activation before the stimulus is displayed

The alternation plan offers early support for the same response as the direction-based plan; therefore (i) a correct response can obtain without lengthy control deployment, through incremental activation of the corresponding motor code and (ii) speed is further enhanced by the early presence of the alternation plan
+ speed
+ speed

The alternation plan supports the same (incorrect) response as the position-based plan. Without early control deployment, enactment of the corresponding motor code can result from the process of incremental activation driven by the alternation and position plans
- accuracy

Figure 5. Mapping, onto the four types of experimental trials, of speed/accuracy hindrances and benefits pertaining to the control processes involved in response-outcome prediction for the action plans present in the trial, according to PRO and the conditional automaticity hypothesis.



When control is deployed, less facilitation of responses contralateral to suppressed action plans lends more limited support to incorrect responses

The correct response is contralateral to the supressed action plans, and should receive a speed boost from the opposite-to-suppressed response facilitation effect. On-peak effectiveness in pathway enhancement lends less activation to the pathway responsible for this effect, limiting the corresponding speed boost

If control is deployed, faciliation of responses contralateral to suppressed action plans hinders accuracy

If control is deployed, faciliation of responses contralateral to the suppressed position-based plan enhances speed

Figure 6. Mapping, onto the four types of experimental trials, of speed/accuracy hindrances and benefits pertaining to the process (conditional upon control deployment) of facilitation of automatic responses opposite to those currently under controlled inhibition.

Summary. In table 1 we systematize the predictions above, quantifying for each type of trial the on- and off-peak positive or negative contributions of the two main processes associated with control deployment, namely, the match-test between the spatial code of current predicted responses and that of the stimulus, to assign response-outcome predictions (figure 5), and (conditional) automatic facilitation of responses opposite to those under controlled inhibition (figure 6). We specify the contributions of these processes to on- and off-peak performance in respect to speed, accuracy and to their summation in a combined speed-accuracy measure, to be understood as an estimation of efficiency. Predictions of intensity of the resulting (a)synchrony effects are also specified in table 1. The predictions of (a)synchrony intensity for the combined speed-accuracy measure entail an overall asynchrony effect (Chronotype x ToD interaction, favoring off-peak performance) that should show gradations across the four types of trial, with a breakdown of asynchrony for $\mathrm{doIC}^{R=}$ trials, in which we expect on-peak overall efficiency to surpass off-peak's. Accordingly, a particular ordering of asynchrony intensity is expected: $\mathrm{doC}^{R=} > \mathrm{doIC}^{R\neq} > \mathrm{doC}^{R\neq} >> \mathrm{doIC}^{R=}$. In the statistical analysis of the speed-accuracy measure, support for this gradation corresponds to the combination of three interaction patterns, two of which pertain to the 4-factor interaction Chronotype x Congruency x Response Repetition x ToD, and another pertaining to the 3-factor interaction Chronotype x ToD x Congruency. We expect a 3-factor interaction pattern of lower IC vs C off-peak gains, qualified by two 4-factor interaction patterns (see (a) and (b) below). The combination of the 4-factors' patterns should support the partial order of off- over on-peak benefits $\mathrm{doC}^{R=}$ & $\mathrm{doIC}^{R\neq} > \mathrm{doC}^{R\neq}$ & $\mathrm{doIC}^{R=}$. Taken together with the lower order 3-factors' interaction indicating greater overall asynchrony in C vs IC trials, the partial order yields an expected full ordering $\mathrm{doC}^{R=} > \mathrm{doIC}^{R\neq} > \mathrm{doC}^{R\neq} > \mathrm{doIC}^{R=}$. One of the expected patterns of the 4-factor interaction concerns the relative magnitude of off-peak benefits in response alternation vs repetition trials, within congruent or incongruent trials: a) Within congruent trials, there should be an off-peak gain in efficiency greater for response repetition trials then for response alternation trials, whereas within incongruent trials, off-peak gains should be greater for alternation trials. The other pattern of the 4-factors interaction concerns congruent vs repetition trials within response alternation or repetition trials: b) Within response alternation trials, there should be an off-peak gain in efficiency greater for incongruent then for congruent trials, whereas within response repetition trials, off-peak gains should be greater for congruent trials. As for the contribution of RTs to the patterns observed for efficiency (see table 1), we expect a significant first-order Chronotype x ToD interaction, indicating asynchrony, qualified by a 4-factor interaction, consisting of no modulations of asynchrony by congruency within the response alternation condition, whereas within the repetition condition we anticipate greater asynchrony for C than for IC trials. In respect to the contribution of ACC to efficiency, the first-order Chronotype x ToD interaction is expected to be absent, and a 4-factor interaction pattern is anticipated, consisting of a small synchrony effect for C trials and no effect for IC trials within the response alternation condition, whereas within the repetition condition a small asynchrony should be observed for C trials and a larger synchrony effect for IC trials.

The two main alternatives to conditional automaticity that we have considered entail different orderings of (a)synchrony effects' sizes across the four experimental conditions: Assuming that the top-down character of a process is the determinant of (a)synchrony effects, an off-peak dimming of the alternation bias should occur, and the resulting predictions for each condition entail the asynchrony ordering $doC^{R=} > doC^{R\neq} > doIC^{R=} >>> doIC^{R\neq}$, whereas attributing (a)synchrony to the voluntary/conscious character of a process, entails an off-peak enhancement of the alteration bias, that should be manifest in the ordering $doIC^{R\neq} > doC^{R\neq} > doIC^{R=} >>> doC^{R=}$, in which ">>>" denotes a transition from asynchrony or null ToD effect to a strong synchrony effect. The 4-factor interaction prediction derived from the conditional automaticity hypothesis does not follow from either of the two alternative conjectures. According to these accounts, congruence and response repetition, instead of displaying an interaction embedded within the ToD x Chronotype matrix, should yield only simple effects within that matrix, with congruent and response repetition trials more prone to asynchrony, according to the top-down account, and response alternation and incongruent trials more prone to asynchrony, according to the voluntariness/awareness account.

Table 1

Expected positive and negative contributions to on- and off-peak performance of response-outcome prediction processes and of conditional facilitation of automatic non-inhibited responses, specified in respect to speed, accuracy, and to their summation in a speed-accuracy measure, for each of the four types of trial.

	doC$^{R\neq}$			doIC$^{R\neq}$			doC$^{R=}$			doIC$^{R=}$		
	LISAS	SPD	ACC	LISAS	SPD	ACC	LISAS	SPD	ACC	LISAS	SPD	ACC
On-peak												
E-ROPred	--	--	=	=	=	=	-----	---	--	+++	+	++
H-AOIResp	=	=	=	-	-	=	=	=	=	-	-	=
Off-peak												
H-ROPred	++	++	=	++	++	=	+	+	=	-	=	-
E-AOIResp	-	=	-	+	+	=	-	=	-	+	+	=
Overall effect	Asynchrony	Asynchrony	Synchrony	Asynchrony	Asynchrony	_________	Asynchrony	Asynchrony	Asynchrony	Synchrony	Asynchrony	Synchrony
Intensity	+++	++++	+	++++	++++	_________	+++++	++++	+	++	+	+++

*Note.*E = Enhanced. H = Hindered. ROPred = Response-outcome prediction. AOIResp = Automatic opposite-to-inhibited response. LISAS = Linear integrated speed-accuracy scores. SPD = Speed. ACC = Accuracy.

Methods

Participants

One hundred and thirty-six students at the University of Coimbra, Portugal, participated in this study for course credit. Twelve multivariate outliers were identified and their data was removed from further analyses, resulting in a final sample of 124 participants (60.48% women, 18-31 years old, *M* = 21.04, *SD* = 3.36). All participants provided written informed consent in accordance with institutional guidelines. Exclusion criteria comprised current or previous diagnosis of a psychiatric and/or neurologic disorder (self-declared); intake of psychotropic medication; history of traumatic brain injury; impaired visual acuity (uncorrected); a score of 14 or above in the Basic Scale on Insomnia complaints and Quality of Sleep (Miller-Mendes, Gomes, Ruivo Marques, Clemente, & Azevedo, 2019), indicating poor sleep quality; a score of 20 points or above in the Beck Depression Inventory II (Beck, Steer, & Brown, 1996), indicating moderate depressive symptoms. Participants were selected from a large pool of voluntaries who completed the Portuguese version of the Composite Scale of Morningness (CSM; Smith, Reilly, & Midkiff, 1989), Questionário Compósito de Matutinidade (QCM; Silva, Azevedo, & Dias, 1995). Age-appropriate QCM norms (Gomes, 2005) were used to identify and select Morning-Types (M-Types; *N* = 59) and Evening-types (E-Types; *N* = 65), respectively corresponding to scores above the 80th and below the 20th percentiles of the normative sample. Half of the participants took part in the experiment at their optimal time-of-day (on-peak) and the other half at their non-optimal time-of-day (off-peak). Four groups resulted from this assignment: (i) M-Types on-peak (*N* = 30; 18 women, *M* = 21.13 years old [YO], *SD* = 3.50; *M* = 14.53 years of formal education [YFE], *SD* = 2.18); (ii) M-Types off-peak (*N* = 29; 18 women, *M* = 20.31 YO, *SD* = 2.71; *M* = 13.72 YFE, *SD* = 2.15); (iii) E-Types on-peak (*N* = 34; 20 women, *M* = 20.85 YO, *SD* = 3.37; *M* = 13.76 YFE, *SD* = 2.02); and (iv)

E-Types off-peak (*N* = 31; 19 women, *M* = 21.84 YO, *SD* = 3.84; *M* = 14.74 YFE, *SD* = 2.31). No significant differences were found between groups in respect to age, *F*(3, 120) = 1.104, *p* = .350, gender, $\chi^2(3, N = 124) = 0.081$, *p* = .994, and YFE, *F*(3, 120) = 1.812, *p* = .149.

Materials and procedure

Participants sat comfortably in front of a 17″ computer screen at approximately 100 cm in a dimly lit room. They were instructed to make left/right button presses using two switches, one held in each hand, in response to the left/right direction of an arrow, while ignoring its on-screen position (see Figure 5). The arrow's direction and position were either congruent (C trials), incongruent (IC trials) or neutral (DO trials). Two DO trials preceded (*n*-2 and *n*-1) each of the C or IC trials (*n*) that yielded data for analyses. The correct response in a *n*-1 trial was always the alternation of the correct response in the *n*-2 trial. Correct responses to *n* trials were alternations of responses to *n*-1 trials ($^{R\neq}$) in half of the sequences and were repetitions ($^{R=}$) in the other half. Each trial began with a fixation cross appearing in a white box in the center of the screen, and two lateral boxes filled with masks (figure 5). Mask presentation was used to overcome afterimage effect issues (Breitmeyer & Öğmen, 2006). In addition to the C and IC trials in the critical sequences described above, in non-critical sequences we included position-only (PO) trials. In PO trials, participants had to press the left/right response button that directly corresponded to the left/right position of a circle (intrinsically devoid of direction information), displayed on-screen instead of an arrow in these trials. PO trials were introduced to minimize the possibility of development and automatization of facilitating strategies by some participants (e.g., focusing attention on the head of the arrow and systematically suppressing position information). Such facilitating strategies are likely to reduce the spatial Stroop effect (Lu & Proctor, 1995). The proportion of PO trials was kept low (11% of the total trials) in order to preserve the nature of the task. The task comprised 1600 trials (386 C trials; 386 IC trials; 640 DO trials and 194 PO trials) that were presented in prearranged sequences of which participants were unaware, the succession of different trial types being perceived as random. The proportion of response types (Left/Right x Repetition/Alternation) was the same throughout the task.

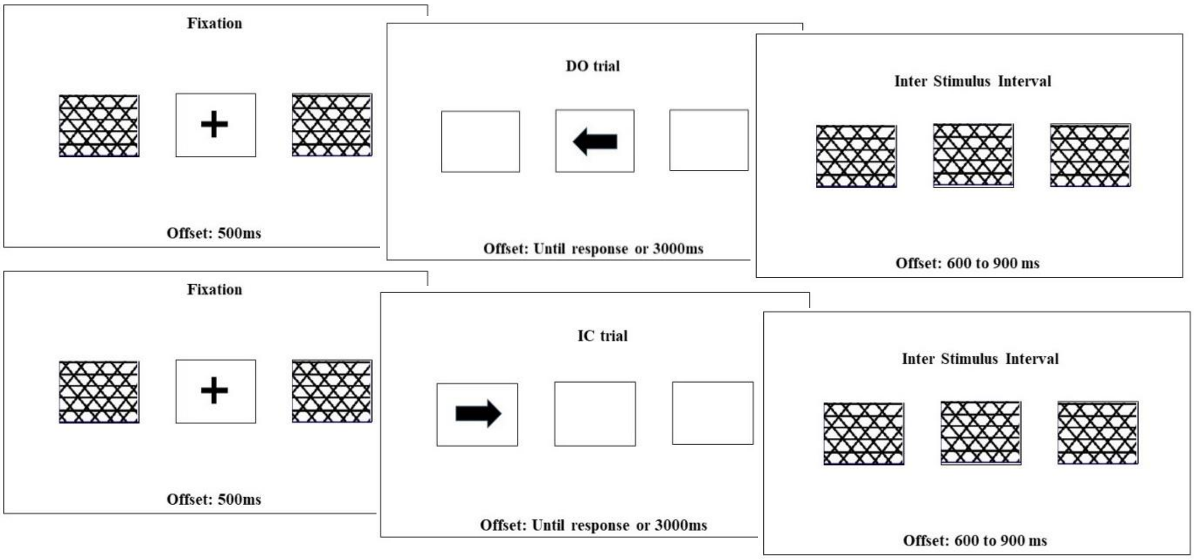


Figure 7. Examples of a DO and IC trials. Each trial begins with a fixation cross, after which the stimulus is displayed. The stimulus remains visible until a response is produced or a time limit of 3000 ms is reached. The response is followed by an interval of randomly variable length, after which a new trial begins.

The exact time of participation was individually defined according to each participant's sleep habits, previously assessed by a short questionnaire. Participants assigned to morning sessions took part in the experiment 1.5 hours after waking-up; those assigned to afternoon sessions, 8 hours after waking-up. Morning sessions started between 8:00 am and 11.30 am and afternoon sessions between 3:00 pm and 6:30 pm. Time-on-task was about 75 minutes. All sessions took place from Tuesday to Friday. Participants were instructed to respond quickly, while avoiding errors. Instructions were followed by a block of 96 practice trials, after which the main task began. The task comprised seven rest breaks lasting about two minutes each. Time-on-task was therefore split in eight periods lasting approximately seven to eight minutes.

Data Analysis

We analyzed data from four critical conditions (doC$^{R\neq}$; doIC$^{R\neq}$; doC$^{R=}$; and doIC$^{R=}$). Error and post-error trials were excluded from the analysis. Anticipations (RTs ≤100 ms and RTs 3 SD lower than the participant's mean for a given experimental condition) and lapses of attention (RTs more than 3 SD longer than the participant's experimental condition mean) were also removed. The arcsine square root transformation was applied to ACC proportion-correct data, to minimize mean-variance relationships. Three 2x2x2x2 mixed ANOVAs were conducted using the Statistical Package for the Social Sciences (SPSS, version 25; IBM Corporation), one for each of the following measures: Linear Integrated Speed Accuracy Scores (LISAS; Vandierendonck, 2017, 2018), RT data, and ACC data. In each ANOVA, between-subjects factors were chronotype (M-type vs E-type) and ToD (morning vs afternoon), and within-subjects factors were congruency (C vs IC) and response repetition (R$^{\neq}$ or R$^{=}$). LISAS are a linear combination of speed and accuracy data points, designed to reflect in a principled manner the dynamic relation between these two parameters. LISAS are defined as:

$$\text{LISAS} = \text{RT}_j + S_{\text{RT}}/S_{\text{PE}} \times \text{PE}_j$$

where RT_j is the participant’s mean RT in condition j, PE_j is the participant’s proportion of error in condition j, S_{RT} is the overall RT standard deviation in condition j in the participant’s group, and S_{PE} is the overall PE standard deviation in condition j in the participant’s group (Vandierendonck, 2018). LISAS formula combines speed and accuracy by entering error information as a RT penalty. This penalty is weighted by the dispersion of RT and ACC measures in condition j within the participant’s group: Less dispersion in ACC than in RT amplifies the error penalty, whereas comparatively less dispersion in RT reduces the penalty’s weight.

Results

We include for each of the three ANOVAs a bar chart of effect sizes (Cohen’s *d*), to facilitate the identification and comparison of the synchrony and asynchrony effects that subtend the third-order interaction Chronotype x ToD x Congruency x Response Repetition, which was significant in all ANOVAs. We conventionally charted asynchrony as a negative *d* value, and synchrony as a positive value. The charted values correspond to the size of the ToD effect for each chronotype (i.e., the effect of performing on- vs off-peak considered separately for M-types and E-types) and to the size of the chronotype effect for each ToD (i.e., in the morning, effect of performing on- [M-types] vs off-peak [E-types], and, in the afternoon, effect of performing on- [E-types] vs off-peak [M-types]). Synchrony/asynchrony is thus charted in two complementary manners, one corresponding to an intra-chronotype contrast (performing on- vs. off-peak, considering the same chronotype at the two corresponding alternative ToDs), the other to an inter-chronotype contrast (performing on-/off-peak, considering the two chronoptypes at the same time-of-day). This information is charted in four clusters, one for each Congruency x Response Repetition condition.

We report follow-up analyses of simple effects for significant third-order interactions and for the second-order interaction ToD x Chronotype x Congruency which, taken together with the third-order interaction involving all factors, bears upon our predictions pertaining to the ordering of (a)synchrony effects across the Congruency x Response Repetition conditions. In respect to third-order interactions, we will inspect the modulations of intra and inter-chronotypes (a)synchrony effects by the interactions of congruency and response repetition. We will extract from these modulations the orderings of (a)synchrony effect sizes that are licensed for the four Congruency x Response Repetition conditions. Effect sizes pertaining to (a)synchronies for which $F \leq 1$ will not be ordered in respect to each other. As to first-order interactions, we will only report follow-up analyses for the interaction between chronotype and ToD, which pertains to overall (a)synchrony effects, and that between congruency and response repetition, which informs the interpretation of stimulus-bound effects.

Linear Integrated Speed Accuracy Scores (LISAS)

A 2x2x2x2 mixed ANOVA was conducted, with chronotype (M-type vs E-type) and ToD (morning vs afternoon) as between-groups factors, and congruency (congruent vs incongruent) and response repetition (response repetition vs response alternation) as within-participants' factors. Efficiency in incongruent trials (*M* = 548.81, *SD* = 62.50), as expressed by LISAS, with higher scores signifying lower efficiency, was inferior to that in congruent trials (*M* = 461.27, *SD* = 60.83), $F(1, 120) = 286.15$, $p < .001$, $\eta_p^2 = .70$. Efficiency was also significantly hindered in response repetition trials (*M* = 527.39, *SD* = 56.17) relative to response alternation trials (*M* = 482.69, *SD* = 62.44), $F(1, 120) = 112.02$, $p < .001$, $\eta_p^2 = .48$. The interaction between chronotype and ToD was significant, $F(1, 120) = 20.73$, $p < .001$, $\eta_p^2 = .15$. Follow-up analyses unveiled simple intra-chronotype asynchrony effects, with M-types' efficiency significantly enhanced in the afternoon (*M* = 476.89, *SD* = 31.94) relative to the morning (*M* = 524.02, *SD* = 66.78), $F(1, 120) = 11.05$, $p = .001$, $\eta_p^2 = .08$, $d = -0.90$, whereas for E-types a significant efficiency enhancement was observed in the morning (*M* = 488.61, *SD* = 64.19), relative to the afternoon (*M* = 530.66, *SD* = 47.40), $F(1, 120) = 9.66$, $p = .002$, $\eta_p^2 = .08$, $d = -0.75$. Inter-chronotype contrasts showed similar results, with significant advantages of the off-peak chronotype in the morning $F(1, 120) = 6.45$, $p = .012$, $\eta_p^2 = .05$, $d = 0.54$, and in the afternoon $F(1, 120) = 15.27$, $p < .001$, $\eta_p^2 = .11$, $d = -1.33$. Another significant first-order interaction was found between factors congruency and ToD, $F(1, 120) = 11.17$, $p = .001$, $\eta_p^2 = .09$, and a second-order interaction was observed between factors chronotype, congruency, and ToD, $F(1, 120) = 11.54$, $p = .001$, $\eta_p^2 = .09$. Follow-up analyses of simple effects resolved this interaction to two first-order interactions bearing contrasting patterns, namely, the interaction Congruency x ToD, as observed for M-types, and the interaction between those factors for E-types. For E-types, the differences in efficiency significantly favored the morning in congruent trials (AM: *M* = 430.65, *SD* = 73.50; PM: *M* = 507.58, *SD* = 61.00), $F(1, 120) = 26.02$, $p < .001$, $\eta_p^2 = .18$, $d = -1.14$, whereas in incongruent trials the asynchrony effect was not significant, (AM: *M* = 546.56, *SD* = 65.41; PM: *M* = 553.73, *SD* = 57.32), *F*(1, 120) = 0.22, *ns*. In contrast, for M-types, significant differences favoring the afternoon were found for both congruent (AM: *M* = 477.13, *SD* = 63.54; PM: *M* = 429.72, *SD* = 38.09), *F*(1, 120) = 8.99, *p* = .003, η_p^2 = .07, *d* = -0.91, and incongruent trials (AM: *M* = 570.90, *SD* = 80.01; PM: *M* = 524.05, *SD* = 40.00), *F*(1, 120) = 8.31, *p* = .005, η_p^2 = .07, *d* = -0.74. A similar resolution of the Chronotype x Congruency x ToD interaction was unveiled by follow-up analyses of simple inter-chronotype effects, with differences in efficiency significantly favoring E-types in the morning for congruent trials (M-types: *M* = 477.13, *SD* = 63.54; E-types: *M* = 430.65, *SD* = 73.50), *F*(1, 120) = 8.93, *p* = .003, η_p^2 = .07, *d* = -0.68, but without reaching statistical significance for incongruent trials (M-types: *M* = 570.90, *SD* = 80.01; E-types: *M* = 546.56, *SD* = 65.41), *F*(1, 120) = 2.32, *p* = .130, η_p^2 = .02, *d* = -0.33, whereas in the afternoon efficiency was significantly favored for M-types in congruent trials (M-types: *M* = 429.72, *SD* = 38.09; E-types: *M* = 507.58, *SD* = 61.00), *F*(1, 120) = 25.73, *p* < .001 , η_p^2 = .18, *d* = -1.53, and trended towards significance in incongruent trials (M-types: *M* = 524.05, *SD* = 40.00; E-types: *M* = 553.73, *SD* = 57.32), *F*(1, 120) = 3.54, *p* = .062, η_p^2 = .03, *d* = -0.60. The third-order interaction involving all factors was also significant, *F*(1, 120) = 12.26 , *p* = .001 , η_p^2 = .09. Follow-up analyses resolved this interaction to two second-level interactions bearing contrasting patterns, namely, the interaction Congruency x Response Repetition x ToD, as observed for M-types, and the interaction between these factors for E-types: For M-types, the ToD asynchrony effect in response alternation trials was larger for incongruent trials (AM: *M* = 559.42, *SD* = 92.79; PM: *M* = 491.76, *SD* = 42.54), *F*(1, 120) = 13.54 , *p* < .001 , η_p^2 = .10, *d* = -0.94, than for congruent trials (AM: *M* = 454.73, *SD* = 77.76; PM: *M* = 411.22, *SD* = 43.67), *F*(1, 120) = 5.4, *p* = .022 , η_p^2= .04, *d* = -0.69, whereas in response repetition trials asynchrony was larger for congruent trials (AM: *M* = 499.53, *SD* = 66.79; PM: *M* = 448.22, *SD* = 48.22), *F*(1, 120) = 9.354 , *p* = .003 , η_p^2 = .07, *d* = -0.88, than for incongruent trials, in which asynchrony was not significant (AM: *M* = 582.38, *SD* = 79.47; PM: *M* = 556.33, *SD* = 54.09), *F*(1, 120) = 2.12 , *p* =.142, η_p^2 = .02, *d* = -0.38. Overall, for M-types, the pattern of asynchrony effects' relative sizes for C vs IC trials within response alternation and within response repetition conditions was: $\text{doIC}^{\text{R}\neq}$ (*d* = -0.94) > $\text{doC}^{\text{R}\neq}$ (*d* = -0.69) & $\text{doC}^{\text{R=}}$ (*d* = -0.88) > $\text{doIC}^{\text{R=}}$ (*d* = -0.38). Rearranging these results to foreground the comparison of response alternation vs repetition asynchrony effects within C and IC trial, we observed that: $\text{doC}^{\text{R=}}$ (*d* = -0.88) > $\text{doC}^{\text{R}\neq}$ (*d* = -0.69) & $\text{doIC}^{\text{R}\neq}$ (*d* = -0.94) > $\text{doIC}^{\text{R=}}$ (*d* = -0.38). These two patterns combine to yield the following partial order of asynchrony effect sizes: $\text{doC}^{\text{R=}}$ & $\text{doIC}^{\text{R}\neq}$ > $\text{doC}^{\text{R}\neq}$ & $\text{doIC}^{\text{R=}}$. In contrast, for E-types, the differences in efficiency favored the morning in three of the Congruency x Response Repetition conditions, and the afternoon in the incongruent trials with response repetition. The pattern of ToD effect sizes across conditions was also in contrast to that observed for M-types, with the ToD asynchrony effect in response alternation trials larger for congruent trials (AM: *M* = 411.43, *SD* = 72.48; PM: *M* = 484.23, *SD* = 84.13), *F*(1, 120) = 16.63, *p* < 0.001, η_p^2 = .12, *d* = -0.93, than for incongruent trials, in which asynchrony was not significant (AM: *M* = 510.54, *SD* = 72.42; PM: *M* = 538.20, *SD* = 65.21), *F*(1, 120) = 2.49, *p* = .117, η_p^2 = .02, *d* = -0.20, and, in response repetition trials, with an asynchrony effect also larger for congruent trials (AM: *M* = 449.87, *SD* = 78.42 PM: *M* = 530.93, *SD* = 60.81), *F*(1, 120) = 25.52, *p* < .001, η_p^2 = .18, *d* = -1.16, than for incongruent trials, in which a non-significant synchrony occurred (AM: *M* = 582.57, *SD* = 72.25; PM: *M* = 569.26, *SD* = 62.07), *F*(1, 120) = 0.63, *ns*. Overall, in E-types, the pattern of (a)synchrony effects' relative sizes for C vs IC trials within response alternation and within response repetition conditions was: $\text{doC}^{\text{R}\neq}$ (*d* = -0.93) > $\text{doIC}^{\text{R}\neq}$ (*d* = -0.20) & $\text{doC}^{\text{R=}}$ (*d* = -1.16) > $\text{doIC}^{\text{R=}}$ (F < 1). Rearranging these results to foreground the comparison of response alternation vs repetition (a)synchrony effects within C and IC trials, we observed that: $\text{doC}^{\text{R=}}$ (*d* = -1.16-) > $\text{doC}^{\text{R}\neq}$ (*d* = -0.93) & $\text{doIC}^{\text{R}\neq}$ (*d* = -0.20) > $\text{doIC}^{\text{R=}}$ (F < 1). These two sequences combine to yield the full order doC$^{R=}$ > doC$^{R\neq}$ > doIC$^{R\neq}$ > doIC$^{R=}$. When we examined this interaction considering inter-chronotype contrasts at the same ToD, a similar pattern emerged: In the morning, within response alternation trials, the size of the chronotype asynchrony effect was larger for incongruent trials (M-types: *M* = 559.42, *SD* = 92.79; E-types: *M* = 510.54, *SD* = 72.42), *F*(1, 120) = 7.31, *p* = .008, η_p^2 = .06, *d* = -0.59, than for congruent trials (M-types: *M* = 454.73, *SD* = 77.76; E-types: *M* = 411.43, *SD* = 72.48), *F*(1, 120) = 5.53, *p* = .020, η_p^2 = .04, *d* = -0.58, whereas within response repetition trials chronotype asynchrony was larger for congruent trials (M-types: *M* = 499.53, *SD* = 66.79; E-types: *M* = 449.87, *SD* = 78.42), *F*(1, 120) = 9.00, *p* = .003, η_p^2= .07, *d* = -0.68, than for incongruent trials, in which a non-significant synchrony occurred (M-types: *M* = 582.38, *SD* = 79.47; E-types: *M* = 582.57, *SD* = 72.25), *F*(1, 120) < 0.01, *ns*. Overall, in the morning, the pattern of (a)synchrony effects' relative sizes for C vs IC trials within response alternation and within response repetition conditions was: doIC$^{R\neq}$ (*d* = -0.59) > doC$^{R\neq}$ (*d* = -0.58) & doC$^{R=}$ (*d* = -0.68) > doIC$^{R=}$ (F < 1). Rearranging these results to foreground the comparison of response alternation vs repetition (a)synchrony effects within C and IC trials, we observe that: doC$^{R=}$ (*d* = -0.68) > doC$^{R\neq}$ (*d* = -0.58) & doIC$^{R\neq}$ (*d* = -0.59) > doIC$^{R=}$ (F < 1). These two sequences combine to yield the partial order for asynchrony doC$^{R=}$ & doIC$^{R\neq}$ > doC$^{R\neq}$ & doIC$^{R=}$. In contrast, in the afternoon, within the response alternation condition, we observed a larger chronotype asynchrony effect for congruent trials (M-types: *M* = 411.22, *SD* = 43.70; E-types: *M* = 484.23, *SD* = 84.13), *F*(1, 120) = 16.15, *p* < .001, η_p^2 = .12, *d* = -1.09, than for incongruent trials (M-types: *M* = 491.78, *SD* = 42.54; E-types: *M* = 538.20, *SD* = 65.21), *F*(1, 120) = 6.77, *p* = .010, η_p^2 = .05, *d* = -0.84. Within the response repetition condition, larger chronotype asynchrony effects also occurred for congruent trials (M-types: *M* = 448.22, *SD* = 48.22; E-types: *M* = 530.93, *SD* = 60.81), *F*(1, 120) = 25.65, *p* < .001, η_p^2 = .18, *d* = -1.51 than for incongruent trials, for which asynchrony was not significant (M-types: *M* = 556.33, *SD* = 54.09; E-types: *M* = 569.26, *SD* = 62.07), *F*(1, 120) = 0.57, *ns*.

Overall, in the afternoon, the pattern of (a)synchrony effects' relative sizes for C vs IC trials within response alternation and within response repetition conditions was: doC$^{R\neq}$ (d = -1.09) > doIC$^{R\neq}$ (d = -0.84) & doC$^{R=}$ (d = -1.51) > doIC$^{R=}$ (F < 1). Rearranging these results to foreground the comparison of response alternation vs repetition (a)synchrony effects within C and IC trials: doC$^{R=}$ (d = -1.51) > doC$^{R\neq}$ (d = -1.09) & doIC$^{R\neq}$ (d = -0.84) > doIC$^{R=}$ (F < 1). These two sequences combine to yield the full order for asynchrony doC$^{R=}$ > doC$^{R\neq}$ > doIC$^{R\neq}$ > doIC$^{R=}$.

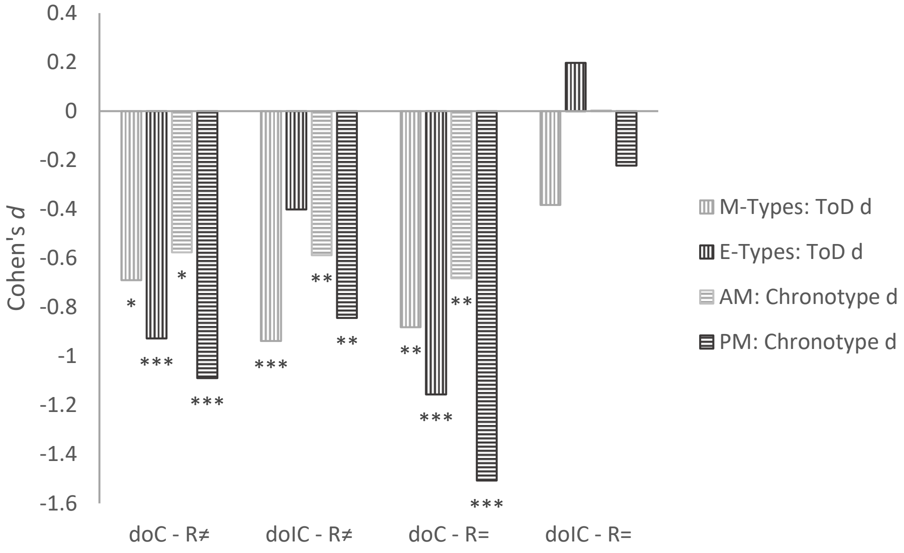


Figure 8. Cohen's *d* for on/off-peak effects on LISAS by chronotype and for chronotype effects on LISAS by time-of-day. * denotes p < .05, ** p < .01, and *** p < .001

Response Times (RTs)

The Chronotype x ToD x Congruency x Response Repetition ANOVA revealed a main effect of congruency, with RTs on incongruent trials (M = 469.68, SD = 65.05) longer than on congruent trials (M = 389.15, SD = 54.92), F(1, 120) = 730.02 , p < .001 , η_p^2 = .86, and a main effect of response repetition, with RTs significantly longer on response repetition trials (M = 450.45, SD = 58.46) than on response alternation trials (M = 418.14, SD = 60.62), F(1, 120) = 239.51 , p < .001 , η_p^2 = .67. The Chronotype x Time-of-Day interaction was significant, F(1, 120) = 4.25 , p = .042 , η_p^2 = .034. Follow-up analyses of simple effects revealed an asynchrony effect for M-types, with RTs significantly faster in the afternoon (*M* = 416.37, *SD* = 36.18) than in the morning (*M* = 450.12, *SD* = 70.15), *F*(1, 120) = 4.94 , *p* = .028 , η_p^2 = .04, *d* = -0.60, whereas for E-types the mean RT was smaller in the morning (*M* = 430.61, *SD* = 58.22), but not significantly different from that observed in the afternoon (*M* = 440.09, *SD* = 62.01), *F*(1, 120) = 0.429, *ns*. The interaction between the four factors also proved to be significant, *F*(1, 120) = 4.85, *p* = .030, η_p^2 = .04. Inspection of the simple effects' pattern resolved this interaction to two contrasting second-level interactions, namely, the interaction Congruency x Response Repetition x ToD, as observed for M-types, and the interaction between these factors as observed for E-types. For M-types, RTs in response alternation conditions were faster in the afternoon, indicating asynchrony, significantly so and with greater ToD effect in incongruent trials (AM: *M* = 474.82, *SD* = 94.02; PM: *M* = 429.10, *SD* = 39.08), *F*(1, 120) = 6.82, *p* = .010, η_p^2 = .05, *d* = -0.64, than in congruent trials, with a lower sized, marginally significant asynchrony (AM: *M* = 396.25, *SD* = 68.26; PM: *M* = 366.60, *SD* = 37.32), *F*(1, 120) = 3.91, *p* = .051, η_p^2 = .03, *d* = -0.54, whereas in response repetition trials the afternoon advantage was significant and larger for congruent trials (AM: *M* = 429.23, *SD* = 57.01; PM: *M* = 398.79, *SD* = 39.89), *F*(1, 120) = 4.58, *p* = .034, η_p^2 = .04, *d* = -0.62, in comparison to a smaller effect, marginally significant, for incongruent trials (AM: *M* = 500.17, *SD* = 74.63; PM: *M* = 470.98, *SD* = 45.44), *F*(1, 120) = 2.92 , *p* = .090, η_p^2 = .02, *d* = -0.47. In contrast, for E-types, all RT differences favored the morning and were non-significant, with a reversal of M-types' pattern of ToD effect size in response alternation trials, where the ToD effect was larger for congruent trials (AM: *M* = 377.32, *SD* = 51.36; PM: *M* = 393.39, *SD* = 66.33), *F*(1, 120) = 1.26, *p* = .264, η_p^2 = 0.10, *d* = -0.27, than for incongruent trials (AM: *M* = 450.23, *SD* = 62.14; PM: *M* = 457.38, *SD* = 62.23), *F*(1, 120) = 0.18, *ns*, and, in response repetition trials, with a ToD effect irrelevant for both congruent trials (AM: *M* = 408.46, *SD* = 58.33; PM: *M* = 421.24, *SD* = 59.50), *F*(1, 120) = 0.89, *ns*, and incongruent trials (AM: *M* = 486.41, *SD* = 68.07; PM: *M* = 488.35, *SD* =

69.31), *F*(1, 120) = 0.01, *ns*. Examining this interaction as a pattern of inter-chronotype differences at the same ToD, we observed shorter RTs for the off-peak chronotype in all of the Congruency x Time-of-Day conditions. In the afternoon, we noted the sole inter-chronotype asynchrony effects that approached statistical significance, namely, in response alternation trials, with a larger asynchrony in incongruent trials (M-types: *M* = 429.10, *SD* = 39.08; E-types: *M* = 457.38, *SD* = 62.22), *F*(1, 120) = 2.77, *p* = .099, η_p^2 = .02, *d* = -0.54, than in congruent trials (M-types: *M* = 366.60, *SD* = 37.32; E-types: *M* = 393.39, *SD* = 66.33), *F*(1, 120) = 3.38, *p* = .068, η_p^2 = .03, *d* = -0.50. The pattern of asynchrony in response repetition trials in the afternoon's consisted in larger, albeit not significant, inter-chronotype differences in congruent trials (M-types: *M* = 398.79, *SD* = 39.89; E-types: *M* = 421.24, *SD* = 59.50), *F*(1, 120) = 2.65, *p* = .106, η_p^2 = .02, *d* = -0.44 than in incongruent trials (M-types: *M* = 470.98, *SD* = 45.44; E-types: *M* = 488.35, *SD* = 69.31), *F*(1, 120) = 1.10, *p* = .297, η_p^2 < .01, *d* = -0.3. In the morning, a non-significant benefit for E-types was observed within the response alternation condition, with the same size for congruent (M-types: *M* = 396.25, *SD* = 68.26; E-types: *M* = 377.32, *SD* = 51.36), *F*(1, 120) = 1.65, *p* = .202, η_p^2 = .01, *d* = -0.31, and incongruent trials (M-types: *M* = 474.82, *SD* = 94.02; E-types: *M* = 450.23, *SD* = 62.14), *F*(1, 120) = 2.04, *p* = .156, η_p^2 =.02, *d* = -0.31; in response repetition trials, the morning inter-chronotype asynchrony was again not significant, with the size of the E-type's advantage larger in congruent (M-types: *M* = 429.22, *SD* = 57.01; E-types: *M* = 408.46, *SD* = 74.63, *F*(1, 120) = 2.21, *p* = .140, η_p^2 < .02, *d* = -0.36 than in incongruent trials (M-types: *M* = 500.17, *SD* = 74.63; E-types: *M* = 486.41, *SD* = 68.07), *F*(1, 120) = 0.67, *ns*.

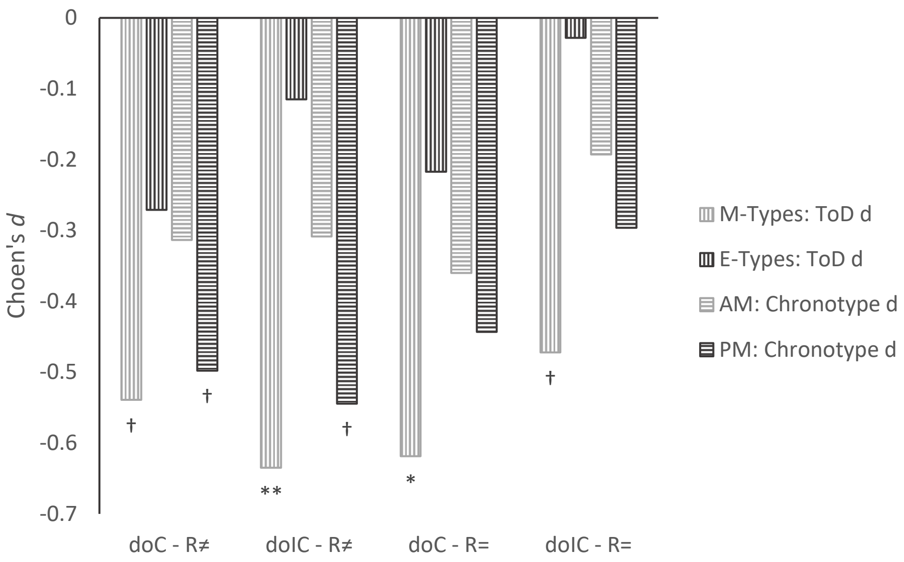


Figure 9. Cohen's *d* for on/off-peak effects on RTs by chronotype and for chronotype effects on RTs by time-of-day. * denotes p < .05, ** p < .01, and † .05 ≤ p < .10

Accuracy (ACC)

The Chronotype x ToD x Congruency x Response Repetition ANOVA revealed a main effect of congruency, with ACC on incongruent trials (*M* = .88, *SD* = .09) lower than on congruent trials (*M* = .97, *SD* = .03), *F*(1, 120) = 292.03 , *p* < .001 , η_p^2 = .71, and a main effect of response repetition, with lower ACC on response repetition trials (*M* = .89, *SD* = .07) than on alternation trials (*M* = .95, *SD* = .04), *F*(1, 120) = 174.44 , *p* < .001 , η_p^2 = .59. The Chronotype x ToD interaction was not significant, F < 1. The Congruency x Response Repetition interaction was significant, *F*(1, 120) = 88.80, *p* < .001, η_p^2 = .43. Follow-up analyses resolved the interaction to a differential effect of response repetition within congruency conditions: for incongruent trials, the deleterious effect of response repetitions (*M* = .83 , *DP* = .12) vs. alternations (*M* = .93, *SD* = .07), *F*(1, 120) = 169.10, *p* < .001 , η_p^2 = .59, was 4.1-fold larger than that same effect in congruous trials (Repetitions: *M* = .98 , *SD* = .02; Alternations: *M* = .97, *SD* = .03), *F*(1, 120) = 20.05, *p* < .001 , η_p^2 = .14. The interaction between the four factors was also significant, $F(1, 120) = 7.32$, $p = .008$, $\eta_p^2 = .06$ and was resolved to two contrasting second-order interactions, namely, the interaction Congruency x Response Repetition x ToD as observed for M-types, and as observed for E-types. For M-types the simple ToD effects patterned within response alternation trials as an on-peak advantage, below statistical significance, in congruent trials (AM: *M* = .98, *SD* = .06; PM: *M* = .97, *SD* = .06), $F(1, 120) = 2.52$, $p = .115$, $\eta_p^2 = .02$, $d = 0.52$, and identical on- off-peak results in incongruent trials (AM: *M* = .93, *SD* = .12; PM: *M* = 0.94, *SD* = .13), $F(1, 120) = 0.98$, *ns*, whereas in response repetition trials no on/off-peak advantage was observed in both congruent (AM: *M* = .97, *SD* = .07; PM: *M* = 0.97, *SD* = .07), $F(1, 120) = 0.233$, *ns*, and incongruent trials (AM: *M* = 0.98, *SD* = .06; PM: *M* = 0.98, *SD* = .06), $F(1, 120) = 0.03$, *ns*. In contrast, for E-types, in response alternation trials, no on/off-peak advantage was observed in congruent (AM: *M* = .97, *SD* = .06; PM: *M* = .97, *SD* = .06), $F(1, 120) = 0.15$, *ns*, nor in incongruent trials (AM: *M* = .91, *SD* = .12; PM: *M* = .93, *SD* = .12), $F(1, 120) = 0.56$, *ns*, whereas in response repetition trials no ToD effect was observed in congruent trials (AM: *M* = .96, *SD* = .07; PM: *M* = .96, *SD* = .07), $F(1, 120) = 0.58$, *ns*, but a significant on-peak advantage emerged for incongruent trials (AM: *M* = .80, *SD* = .24; PM: *M* = .85, *SD* = .23), $F(1, 120) = 3.99$, $p = .048$, $\eta_p^2 = .03$, $d = 0.45$. When we examined this interaction considering inter-chronotype differences at the same ToD, we observed, in the morning, benefits for the on-peak chronotype across all conditions: For response alternations, the largest benefit for M-types occurred in congruent trials and was statistically significant (M-types: *M* = .98, *SD* = .01; E-types: *M* = .97, *SD* = .05), $F(1, 120) = 5.20$, $p = .024$, $\eta_p^2 = .04$, $d = 0.53$, whereas in the response repetition condition the largest benefit for M-types occurred in incongruent trials and was not significant (M-types: *M* = .83, *SD* = .11; E-types: *M* = .80, *SD* = .14), $F(1, 120) = 0.625$, *ns*. Contrastingly, in the afternoon, benefits for the off-peak chronotype, albeit non-significant, were observed in three conditions, whereas an on-peak advantage, also not significant, emerged in incongruent trials with response repetition: For the response alternation condition chronotype effects were irrelevant, of which the nominally largest benefit occurred for M-types in incongruent trials (M-types: *M* = .94, *SD* = .04; E-types: *M* = .93, *SD* = .06), *F*(1, 120) = 0.78, *ns*, whereas in the response repetition condition the largest benefit was observed for the on-peak chronotype (E-types) in incongruent trials, without approaching statistical significance (M-types: *M* =.83, *SD* = .09; E-types: *M* = .85, *SD* = .13), *F*(1, 120) = 1.78, *p* = .185, η_p^2 = .02, *d* = 0.35.

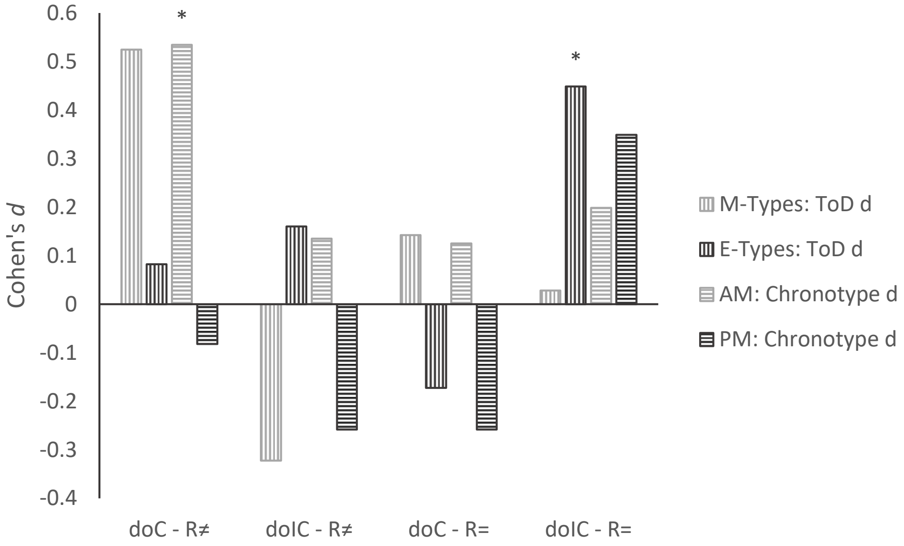


Figure 10. Cohen's *d* for on/off-peak effects on accuracy by chronotype and for chronotype effects on accuracy by time-of-day. * denotes p < .05.

Discussion

The expected overall asynchrony has emerged in the LISAS data, fully supported by the Chronotype x ToD interaction, both as an intra- and inter-chronotype pattern. The same interaction is significant for the RT data, and supports intra-chronotype asynchrony, also as expected, albeit with a non-significant off-peak benefit for E-types. Again in line with our predictions, there were no overall significant (a)synchrony effects for ACC. As anticipated, off-peak benefits were modulated by congruency in the LISAS data, in which both intra-chronotype and inter-chronotype asynchrony is greater for C than for IC trials. The pattern is not significant in RT data, for which no clear modulation of asynchrony by congruency was expected, nor in ACC data, for which no definite overall (a)synchrony effects were expected. In the LISAS data, modulation of asynchrony by congruency is further compounded by response repetition, which partakes in an anticipated 4-factor interaction. The patterns of this interaction for both M-types' intra-chronotype asynchrony and morning inter-chronotype asynchrony yield the expected partial order $doC^{R=}$ & $doIC^{R\neq}$ > $doC^{R\neq}$ & $doIC^{R=}$, which, taken together with the result of the lower level Chronotype x ToD x Congruency interaction, indicating overall greater asynchrony for C trials, supports the predicted ordering of asynchrony effects, $doC^{R=} > doIC^{R\neq} > doC^{R\neq} > doIC^{R=}$. For E-types' intra-chronotype asynchrony and afternoon's inter-chronotype asynchrony, another order of asynchrony sizes emerged, $doC^{R=} > doC^{R\neq} > doIC^{R\neq} > doIC^{R=}$, in which the position of the two mid-range asynchronies is reversed relative to our prediction.

The 4-factor interaction was significant for RT and ACC data, also in line with expected results. The follow-up pairwise contrasts pertaining to (a)synchrony effects within each of the four experimental conditions, for LISAS, RT and ACC data, are summarized, along with the predicted results, in table 2 in respect to both intra- and inter-chronotype effects.

Table 2

Predicted and observed intra- and inter-chronotype (a)synchrony effects and instances of irrelevant intra- and inter-chronotype variance ($F \leq 1$), specified in respect to LISAS, speed, and accuracy, for each of the four types of trial.

	doC$^{R\neq}$			doIC$^{R\neq}$			doC$^{R=}$			doIC$^{R=}$		
	LISAS	SPD	ACC	LISAS	SPD	ACC	LISAS	SPD	ACC	LISAS	SPD	ACC
Predicted	Asynchrony	Asynchrony	Synchrony	Asynchrony	Asynchrony	____	Asynchrony	Asynchrony	Asynchrony	Synchrony	Asynchrony	Synchrony
Intensity	+++	++++	+	++++	++++	___	+++++	++++	+	++	+	+++
Observed												
Asynchrony-Intra	M-tp*; E-tp*	M-tp†; E-tp	_; _	M-tp*; E-tp	M-tp*; _	_; _	M-tp*; E-tp*	M-tp*; _	_; _	M-tp; _	M-tp†; _	_; _
Asynchrony-Inter	AM*; PM*	AM; PM†	_; _	AM*; PM*	AM; PM†	_; _	AM*; PM*	AM; PM	_; _	_; _	_; PM	_; _
Synchrony-Intra	_; _	_; _	M-tp; _	_; _	_; _	_; _	_; _	_; _	_; _	_; _	_; _	_; E-tp*
Synchrony-Inter	_; _	_; _	AM*; _	_; _	_; _	_; _	_; _	_; _	_; _	_; _	_; _	_; PM
$F \leq 1$ Intra	_; _	_; _	_; E-tp	_; _	_; E-tp	M-tp; E-tp	_; _	_; E-tp	M-tp; E-tp	_; E-tp	_; E-tp	M-tp; _
$F \leq 1$ Inter	_; _	_; _	_; PM	_; _	_; _	AM; PM	_; _	_; _	AM; PM	AM; PM	AM;_	AM;_
Mean Cohen's *d*	-0.73	-0.41	0.26	-0.64	-0.37	0	-1.06	-0.36	0	-0.09	-0.19	0.20

Note. Whenever an instance of $F \leq 1$ occurred, $d = 0$ was used in the computation of the mean Cohen's *d*. M-tp = morning types; E-tp = evening types; intra = intra-chronotype effects; inter = inter-chronotype effects; LISAS = linear integrated speed-accuracy scores; SPD = speed; ACC = accuracy; * $p < .05$; † $.05 \leq p < .10$

Follow-up analyses of the 4-factor interaction in RT data, taking into account the overall intra- and inter-chronotype results, confirmed an expected stronger modulation of asynchrony by congruency within response repetition than within response alternation trials, with a marked slump in asynchrony for doC$^{R=}$ vs doC$^{R=}$ trials, while only a discreet variation in the opposite direction was present within response alternation trials. This pattern is partly attenuated by E-types performance in doIC$^{R\neq}$ and doC$^{R=}$ trials, in which they do not show the expected off-peak benefits. The pattern predicted to subsume ACC 4-factor interaction was partly present, with synchrony for doC$^{R\neq}$ trials paired with absent (a)synchrony for doIC$^{R\neq}$ trials, and synchrony for doIC$^{R=}$ paired with absent (a)synchrony for doIC$^{R=}$ trials, albeit our prediction for doIC$^{R=}$ trials had been of a small asynchrony. Interestingly, ACC synchrony in doC$^{R\neq}$ trials seems to be mostly driven by M-types' on-peak advantages, whereas synchrony in doIC$^{R=}$ trials mainly reflects E-types' on-peak advantages.

Considering the mean Cohen's *d* for LISAS' intra- and inter-chronotype contrasts for both chronotypes and ToDsthe positions of doIC$^{R\neq}$ and doC$^{R\neq}$ conditions are reversed in respect to the predicted sequence of asynchrony sizes doC$^{R=}$ > doIC$^{R\neq}$ > doC$^{R\neq}$ > doIC$^{R=}$. This is because of E-types' absent accuracy synchrony and speed asynchrony in doC$^{R\neq}$ and doIC$^{R\neq}$ trials, respectively. However, all intra- and inter-chronotype LISAS' contrasts converge in singling out doC$^{R=}$ trials as those yielding the strongest asynchrony and doIC$^{R=}$ as those for which asynchrony breaks down. The processing underpinnings of the large off-peak benefit in doC$^{R=}$ trials should be, according to PRO theory and the conditional automaticity model of (a)synchrony, a major on-peak hindrance due to the prompt deployment of the control setup at that ToD: Only in this type of trial does the interaction of the alternation plan with on-peak's efficient control onset result in a double impediment, namely, a transient suppression of both action plans that support the correct response and the presence of the active alternation plan, that yields an incorrect response, the. Execution of this plan must be withheld while the direction-based is renewed, overcoming its previous negative outcome prediction, and eventually providing enough activation for the enactment of its motor code. This strong on-peak speed penalty should be the main contribution to asynchrony in overall efficiency, given that some loss in accuracy was expected both on- and off-peak. The observed results comply with this prediction, lending support to the hypothesized processing mechanism. As for the breakdown of asynchrony effects in efficiency in $doIC^{R=}$ trials, it should mainly reflect variations in accuracy, enhanced on-peak and hampered off-peak. This should result from the same processes responsible for asynchrony in $doC^{R=}$ trials, whose interaction bears quite different outcomes in $doIC^{R=}$ trials. As in $doC^{R=}$ trials, the presence of the alternation plan before stimulus' onset prompts the deployment of the response-stimulus spatial match-test, which, in an IC trial, will have the opposite consequence of that it had in a C trial. In $doIC^{R=}$ trials, all plans that support the incorrect response, namely, the alternation and the position-based plans, will be suppressed, leaving only the direction-based plan, that yields the correct response. This will foster fast correct responses on-peak. Off-peak, the coupling of the early presence of the alternation plan with a delayed deployment of the response-stimulus spatial match-test will provide a primed motor program for the incorrect response. When the position-based plan, supporting that same incorrect response, comes online, it will likely bring the corresponding motor program past threshold. Alternatively, if control happens to be deployed off-peak and the plans supporting the incorrect response are thereby suppressed, an enhanced facilitation of automatic opposite-to-inhibited responses should foster the speed of correct responses, thus reducing the contrast with on-peak performance in respect to speed. Again, the observed results comply with this prediction, lending support to the hypothesized processing mechanism. As for $doIC^{R\neq}$ trials, they were expected to show the second largest asynchrony in efficiency, closely followed by $doC^{R\neq}$ trials' asynchrony. This difference was expected to derive from a small synchrony effect in $\text{doC}^{R\neq}$ trials' accuracy that should not be present in $\text{doIC}^{R\neq}$ trials. The mechanism underpinning these differential ToD effects should be off-peak's facilitation of automatic opposite-to-inhibited responses: In $\text{doC}^{R\neq}$ trials, if control does come to be deployed off-peak, a momentary suppression of all action plans, induced by the alternation bias, should interact with facilitated automatic responses contralateral to those supported by the suppressed plans, hampering off-peak accuracy. In contrast, the same mechanism in $\text{doIC}^{R\neq}$ trials was expected to enhance the speed of correct responses, which are opposite to those that might be inhibited if control is deployed off-peak. This expected off-peak loss in accuracy in $\text{doC}^{R\neq}$ trials is partly supported by our observations, lending credibility to the hypothesized processing mechanism underpinning the effect, but E-types' off-peak performance was seemingly not affected by the control-dependent facilitation of opposite-to-inhibited responses. In fact, other effects dependent upon the same mechanism, namely, speed asynchrony in $\text{doIC}^{R\neq}$, $\text{doC}^{R=}$, and $\text{doIC}^{R=}$ trials, are selectively absent in E-types' intra-chronotype contrasts, suggesting that E-types, unexpectedly, are less likely than M-types to deploy inhibitory control mechanisms off-peak. This observation suggests that (a)synchrony effects may have quite different manifestations in M-types and E-types, particularly in respect to the negative impact of off-peak ToDs upon the ability to compute response-outcome predictions and/or the efficiency of inhibitory feed-back derived from predicted negative outcomes. Specific studies contrasting M- and E-types in this respect would be necessary to duly characterize their differences and ascertain whether or not (a)synchrony effects are distinct phenomena for each of the two chronotypes.

As for the two alternative construals of (a)synchrony that we have considered, the top-down and the voluntariness/awareness accounts, both orderings of asynchrony sizes in efficiency derived thereof, respectively $\text{doC}^{R=} > \text{doC}^{R\neq} > \text{doIC}^{R=} >>> \text{doIC}^{R\neq}$ and $\text{doIC}^{R\neq} > \text{doC}^{R\neq} > \text{doIC}^{R=} >>> \text{doC}^{R=}$, mismatch the results in respect to the prediction of strong synchrony effects, doIC$^{R\neq}$ in one account, doC$^{R=}$ in the other. In fact, doIC$^{R\neq}$ trials have yielded the second largest efficiency asynchrony for M-types and the third largest for E-types, whereas doC$^{R=}$ trials showed the largest asynchrony in M- and E-types. Also, both accounts predict an asynchrony effect in doIC$^{R=}$ trials, again contrary to the observed results. The top-down account does agree with E-types' observed efficiency data in respect to the two largest asynchronies and their ordering, doIC$^{R\neq}$ > doC$^{R\neq}$, but, as the voluntariness/awareness account, cannot not provide a congruous explanation of the full observed orderings. The conditional automaticity hypothesis, coupled with PRO theory, does provide a set of predictions that closely match the observed results, therefore making this hypothesis worth pursuing in future research on (a)synchrony. Of particular interest in such future research would be the use of methods that allow probing the processes underlying overt responses as they unfold in real-time. Event Related Brain Potentials, for instance, would provide data closely matching the grain-size of the conditional automaticity processing model, and thus enable more precise and meaningful testing.

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