TECHNICAL REPORT

Conditional Automaticity and Age-related Modulations of (A)synchrony Effects in a Spatial Stroop Task: An ERP and Behavioral Study

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 indirect 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). This general prediction dovetails in two distinct expectations regarding younger and older participants, as a result of an age-related loss of efficiency in control exertion. Underpinning this loss, larger amounts of resources being assigned to the indirect route while setting up control would be dispersed to the direct route, as function of increasing age: Resources recruited by younger participants for on-peak control exertion would be assigned to the indirect route with minimal dispersion to the direct route, whereas off-peak resource recruitment would trail long enough for significant activation to leak to the direct route, rendering conditional-automatic responses more likely; in contrast, resources recruited by older participants to exert control on-peak would significantly be dispersed into the direct route, resulting in inefficient control deployment, whereas resource recruitment for off-peak control would trail long enough for significant activation to leak to the direct route, rendering conditional-automatic responses more likely and fast than on-peak conditional-automatic responses.

As for the low-level expectancy favoring response alternations, the conditional automaticity hypothesis entails that it should remain constant across on- and off-peak times. Even though

[3] For clarity, we will often use the expression "on- off-peak" to refer to the interaction between chronotype and time-of-day.

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.

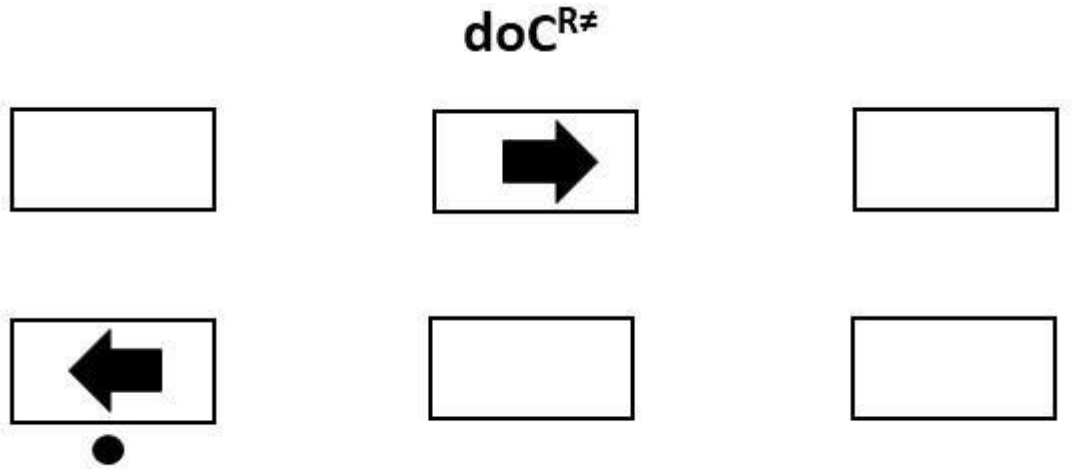

Figure 1. DO - C trial sequence with a correct response for the C trial opposite to the DO trial's. The dot represents the response supported by the alternation bias. The direction-based and position-based plans support the same response.

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.

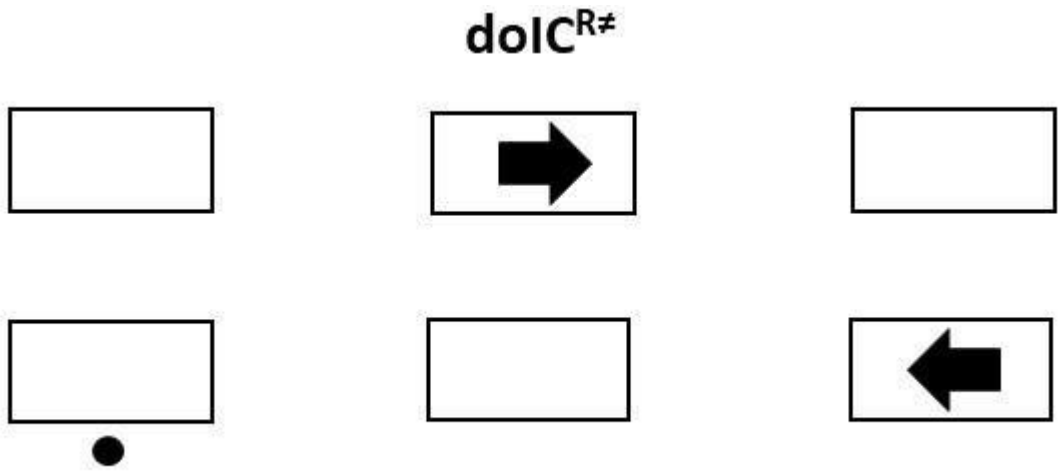

Figure 2. DO - IC trial sequence with a correct response for the IC trial opposite to the DO trial's. The dot represents the response supported by the alternation bias. The direction-based plan supports the same response and the position-based plan its opposite.

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.

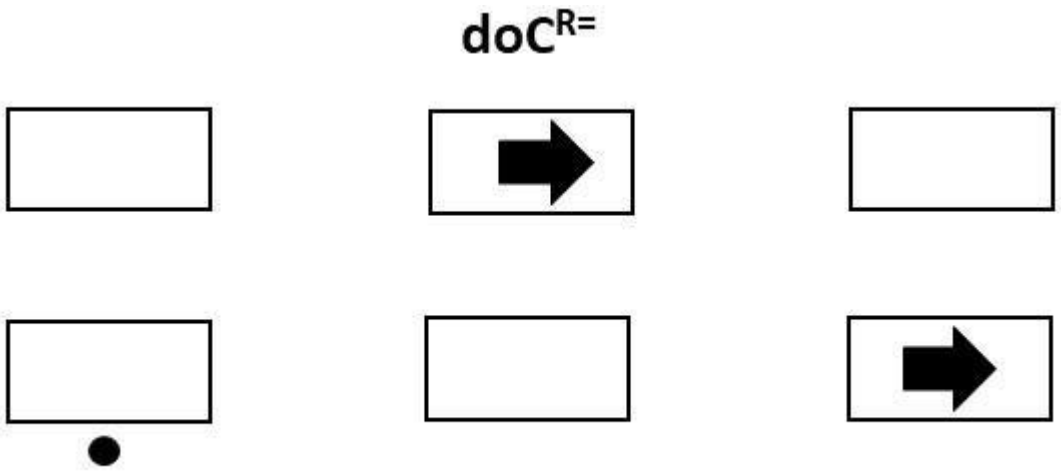

Figure 3. DO - C trial sequence with a correct response for the C trial repeating the DO trial's. The dot represents the response supported by the alternation bias. The opposite response is supported by the direction-based and position-based plans.

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.

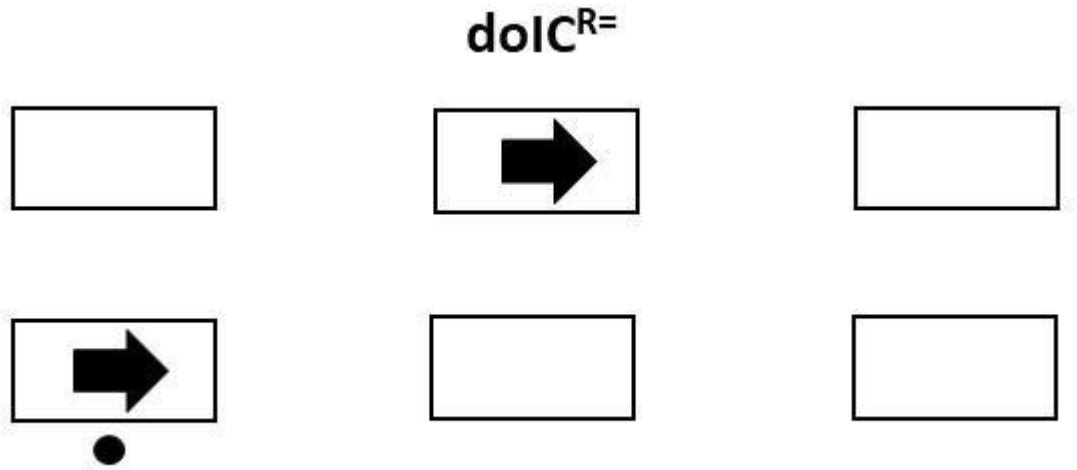

Figure 4. DO - IC trial sequence with a correct response for the IC trial repeating the DO trial's. The dot represents the response supported by the alternation bias action plan. The position-based plan supports the same response and the direction-based plan its opposite.

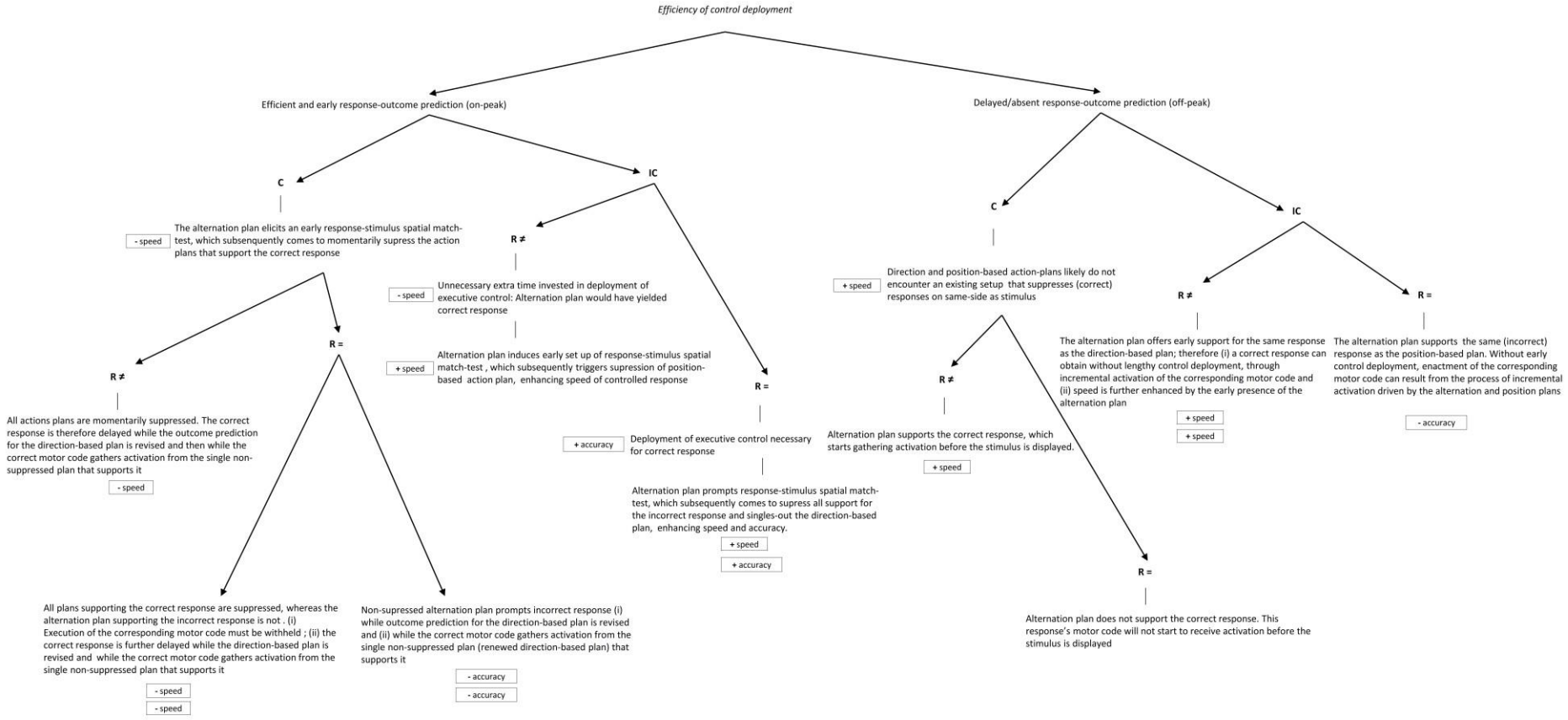

Figure 5. Mapping, onto the four types of experimental trials, of speed/accuracy hindrances and benefits pertaining to the control processes involved in response-outcome prediction for the action plans present in the trial, according to PRO and the conditional automaticity hypothesis.

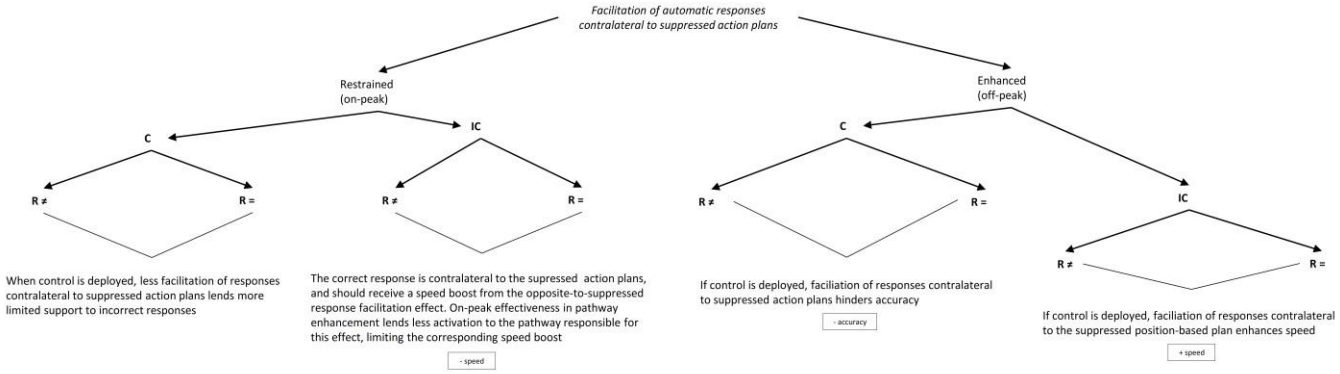

Figure 6. Mapping, onto the four types of experimental trials, of speed/accuracy hindrances and benefits pertaining to the process (conditional upon control deployment) of facilitation of automatic responses opposite to those currently under controlled inhibition.

Our model entails 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 $doIC^{R=}$ trials, in which we expect on-peak overall efficiency to surpass off-peak's. Accordingly, a particular ordering of asynchrony intensity is expected: $doC^{R=}$ > $doIC^{R\neq}$ > $doC^{R\neq}$ >> $doIC^{R=}$, in which ">>" denotes a transition from asynchrony to a a null ToD effect, or an incipient synchrony effect.

Methods

Participants

One hundred and thirty-six students at the University of Coimbra, Portugal, originally participated in data gathering sessions for course credit or payment. Twelve multivariate RT outliers were identified and their data was removed from further analyses, resulting in a pool of 124 participants with viable data. Forty-eight older adults also participated for payment. Data from eight older participants were removed from further analyses either due to their multivariate RT outlier status or poor EEG quality. The final group of older adults comprised 40 participants (18 women; 65-76 years old, *M* = 63.45, *SD* = 6.21; 5-17 years of formal education, *M*=11.35, *SD*=3.31). Forty younger participants were matched with an older counterpart, taking into account gender, degree of morningness and exact time of participation (18 women, 18-28 years old, *M* = 21.04, *SD* = 3.36; 12-17 years of formal education, *M*=13.85, *SD*=2.31).

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 = 38; 19 younger, 19 older) and Evening-types (E-Types; N = 42; 21 younger, 21 older), respectively corresponding to scores above the 80th and below the 20th percentiles of the normative sample. Originally, half of the participants of each chronotype 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, with unequal sizes due to exclusion of participants with corrupted data (multivariate RT outlier status or poor EEG quality, as mentioned above); younger-older participants remained matched in each group: (i) M-Types on-peak (N = 16; 8 women, $M_{younger}$ = 21.13 years old [YO], SD = 3.50; M_{older} = 68.33 YO, SD = 4.70); (ii) M-Types off-peak (N = 22; 9 women, *M younger* = 20.31 YO, SD = 2.71; M_{older} = 67.03 YO, SD = 3.83)); (iii) E-Types on-peak (N = 24; 10 women, $M_{younger}$ = 20.85 YO, SD = 3.37; M_{older} = 70.03 YO, SD = 5.66); and (iv) E-Types off-peak (N = 18; 9 women, $M_{younger}$ = 21.84 YO, SD = 3.84; $M_{younger}$ = 67.84 YO, SD = 5.04).

Materials and procedure

After electrode application, participants sat in a sound-attenuated, dimly lit booth, in front of a 19'' computer screen, at a distance of approximately 100 cm. 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.

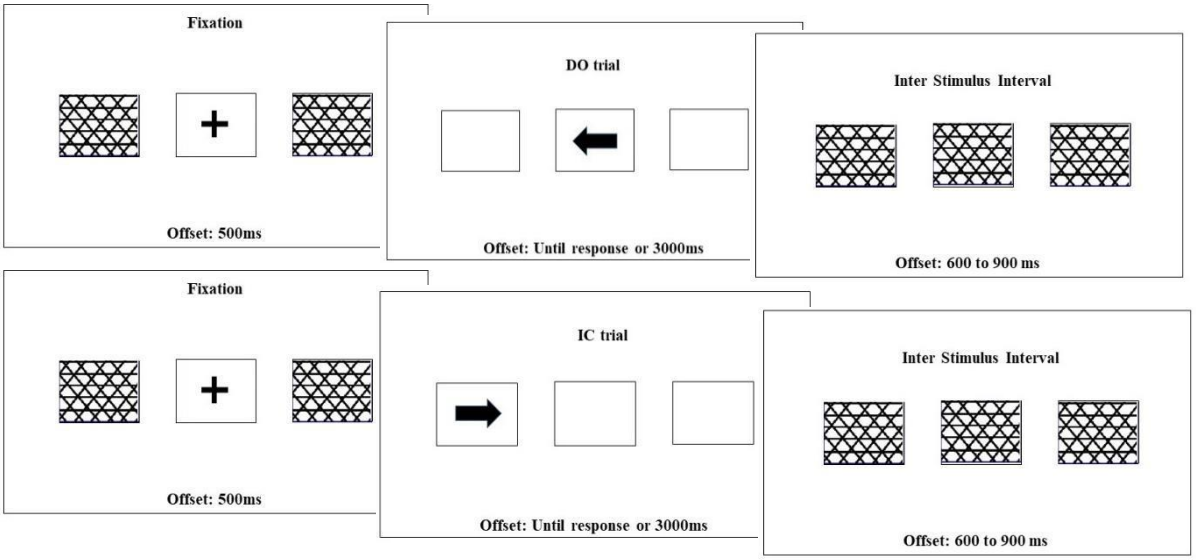

Figure 7. Examples of a DO and IC trials. Each trial begins with a fixation cross, after which the stimulus is displayed. The stimulus remains visible until a response is produced or a time limit of 3000 ms is reached. The response is followed by an interval of randomly variable length, after which a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

EEG Recording

Continuous electroencephalogram recordings (EEG) were collected from 64 Ag/AgCl scalp active electrodes mounted in an electrode cap conforming to the extended 10-20 system for electrode positioning (Biosemi Active Two system and Biosemi electrode caps). Vertical eye movements and blinks were monitored via a supra- to sub-orbital bipolar montage. A right-to-left canthal bipolar montage was used to monitor for horizontal eye movements. EEG was also recorded over the left and right mastoid sites. Electrode offsets were kept within the interval 25 μv to -25 μv. The signals were recorded continuously with a digitization rate of 512 Hz, referenced to the average of all electrodes, and re-referenced off-line to the mean of the left and right mastoids.

Results

Performance 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. Two 2x2x2x2x2 mixed ANOVAs were conducted using the Statistical Package for the Social Sciences (SPSS, version 25; IBM Corporation), one on RT data, another on ACC data. In each ANOVA, between-subjects factors were age group (younger vs older adults), chronotype (M-type vs E-type) and on- off-peak time of day (time of day congruous vs incongruous with chronotype), and within-subjects factors were congruency (C vs IC) and response repetition ($R^{\neq}$ or $R^{=}$).

Response Times (RTs)

A 2x2x2x2x2 mixed ANOVA was conducted, with age group (younger vs older adults), chronotype (morning vs evening types) and on- off-peak time-of-day (time of day congruous with chronotype vs uncongruous) as between-groups factors, and congruency (congruent vs incongruent) and response repetition (response repetition vs response alternation) as within-participants' factors. A main effect of congruency was unveiled, with RTs on incongruent trials (M = 483.68, SD = 75.08) longer than on congruent trials (M = 391.22, SD = 64.91), F(1, 76) = 430.02 , p = .003 , η^2_p = .66, and a main effect of response repetition, with RTs significantly longer on response repetition trials (M = 432.33, SD = 63.47) than on response alternation trials (M = 398.94, SD = 60.62), F(1, 76) = 139.51 , p = .008 , η^2_p = .57. The Age Group x On- Off Time-of-Day interaction was significant, F(1, 76) = 6.55 , p = .039 , η^2_p = .043. Follow-up analyses of simple effects revealed an asynchrony effect for younger participants, with RTs significantly faster off-peak (M = 437.34, SD = 46.18) than on-peak (M = 466.02, SD = 71.35), F(1, 76) = 15.83 , p = .012 , η^2_p = .35, whereas for older participants the mean RT was only marginally smaller off-peak (M = 440.61, SD = 68.23) than on-peak (M = 451.09, SD = 72.01), F(1, 76) = 2.33, p = .091 , η^2_p = .033. The Chronotype x On- Off Time-of-Day interaction was marginally significant, F(1, 76) = 2.55, p = .061 , η^2_p = .03. Follow-up analyses of simple effects revealed an asynchrony effect for morning chronotypes, with RTs significantly faster off-peak (M = 436.34, SD = 56.18) than on-peak (M = 477.12, SD = 61.31), F(1, 76) = 12.83 , p = .031 , η^2_p = .32, whereas for evening chronotypes the mean RT was also smaller off-peak (M = 458.64, SD = 58.11), but only marginally different from that observed on-peak (M = 478.52, SD = 66.34), F(1, 76) = 2.83 , p = .081 , η^2_p = .02. The 4-factor interaction between age group, on- off-peak time of day, response repetition and congruency was significant, F(1, 76) = 4.85, p = .030, η^2_p = .04. Analyses of simple effects resolved this interaction to two contrasting second-order interactions, namely, the interaction

Congruency x Response Repetition x On- Off-Peak, as observed for younger adults, and the interaction between these factors as observed for older participants. For younger participants, RTs in response alternation conditions were faster off-peak, indicating a significant asynchrony in incongruent trials (on-peak: *M* = 488.92, *SD* = 74.02; off-peak: *M* = 459.10, *SD* = 49.08), *F*(1, 76) = 5.92, *p* = .030, η_p^2 = .05, and a non-significant asynchrony in congruent trials (on-peak: *M* = 402.15, *SD* = 71.16; off-peak: *M* = 372.76, *SD* = 47.33), *F*(1, 76) = 2.83, *p* = .112, η_p^2 = .03, whereas in response repetition trials the off-peak advantage was significant and larger for congruent trials (off-peak: *M* = 418.83, *SD* = 67.04; PM: *M* = 388.19, *SD* = 49.29), *F*(1, 76) = 3.58, *p* = .044, η_p^2 = .03, in comparison to a smaller asynchrony effect, marginally significant, for incongruent trials (on-peak: *M* = 498.18, *SD* = 64.63; off-peak: *M* = 460.28, *SD* = 51.34), *F*(1, 76) = 3.02 , *p* = .088, η_p^2 = .02. In contrast, for older participants, RT differences favoring off-peak presented a reversal of the pattern of asynchrony observed in younger participants' in response alternation trials, this effect now being marginally significant for congruent trials (on-peak: *M* = 383.39, *SD* = 67.34; off-peak: *M* = 357.52, *SD* = 49.46), *F*(1, 76) = 2.46, *p* = .097, η_p^2 = 0.22, and non-significant for incongruent trials (on-peak: *M* = 457.33, *SD* = 63.14; off-peak: *M* = 450.28, *SD* = 61.33), *F*(1, 76) = 0.38, *ns*, whereas in response repetition trials the effect of time-of-day became irrelevant for both congruent trials (off-peak: *M* = 411.24, *SD* = 59.50; on-peak: *M* = 420.96, *SD* = 69.13), *F*(1, 76) = 0.79, *ns*, and incongruent trials (on-peak: *M* = 478.35, *SD* = 71.31; off-peak: *M* = 485.48, *SD* = 62.07), *F*(1, 76) = 0.08, *ns*.

Accuracy (ACC)

The Age Group x Chronotype x On- Off-Peak x Congruency x Response Repetition ANOVA revealed a main effect of congruency, with ACC on incongruent trials (*M* = .85, *SD* = .11) lower than on congruent trials (*M* = .97, *SD* = .07), *F*(1, 76) = 192.03 , *p* =.006 , η_p^2 = .61, and a main effect of response repetition, with lower ACC on response repetition trials

(*M* = .88, *SD* = .08) than on alternation trials (*M* = .95, *SD* = .07), *F*(1, 76) = 104.74 , *p* = .008 , η_p^2 = .49. The Congruency x Response Repetition interaction was significant, *F*(1, 76) = 68.80, *p* = .022, 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* = .80 , *DP* = .15) vs. alternations (*M* = .92, *SD* = .08), *F*(1, 76) = 139.10, *p* = .003 , η_p^2 = .49, was 4.5-fold larger than that same effect in congruous trials (Repetitions: *M* = .97 , *SD* = .02; Alternations: *M* = .96, *SD* = .04), *F*(1, 72) = 18.95, *p* =.008 , η_p^2 = .11. The 4-factor interaction between age group, on- off-peak time-of-day, response repetition and congruency was also significant, *F*(1, 76) = 10.32, *p* = .011 , η_p^2 = .05 and was resolved to two contrasting second-order interactions, namely, the interaction Congruency x Response Repetition x On- Off-peak Time-of-Day as observed for younger participants, and as observed for older participants. For younger participants the simple time-of-day effects within response alternation trials were an off-peak advantage, marginally significant, in congruent trials (on-peak: *M* = .95, *SD* = .06; off-peak: *M* = .98, *SD* = .08), *F*(1, 76) = 7.53, *p* = .086, η_p^2 = .03, and a non-significant off-peak advantage in incongruent trials (on-peak: *M* = .92, *SD* = .13; off-peak: *M* = 0.94, *SD* = .12), *F*(1, 76) = 2.98, *p* = .286, η_p^2 = .01, whereas in response repetition trials no on/off-peak advantage was observed in both congruent (on-peak: *M* = .97, *SD* = .08; off-peak: *M* = 0.97, *SD* = .07), *F*(1, 76) = 0.43, *ns*, and incongruent trials (AM: *M* = 0.98, *SD* = .07; PM: *M* = 0.98, *SD* = .06), *F*(1, 76) = 0.33, *ns*. In contrast, for older participants, in response alternation trials, no on/off-peak advantage was observed in congruent (on-peak: *M* = .95, *SD* = .10; off-peak: *M* = .96, *SD* = .09), *F*(1, 76) = 0.21, *ns*, nor in incongruent trials (on-peak: *M* = .90, *SD* = .14; off-peak: *M* = .92, *SD* = .12), *F*(1, 76) = 0.86, *ns*, whereas in response repetition trials no on- off-peak effect was observed in congruent trials (on-peak: *M* = .93, *SD* = .09; off-peak: *M* = .94, *SD* = .10), *F*(1, 76) = 0.88, *ns*, but a

significant on-peak advantage emerged in incongruent trials (on-peak: *M* = .85, *SD* = .21; off-peak: *M* = .80, *SD* = .19), $F(1, 76) = 4.12$, $p = .041$, $\eta_p^2 = .04$.

ERP Data Analysis

Data were band-pass filtered offline to 0.5 - 100 Hz and screened for eye-movements, muscle artifacts, and electrode drifting. A total of 18% trials were rejected due to artifact contamination. Blink artifacts were removed using an independent component analysis filter algorithm. ERPs were time-locked to the onset of the stimulus, and epochs ranging from 150 ms pre stimulus to 1500 ms post stimulus were extracted, baseline corrected by subtraction using the pre stimulus period, and averaged per participant and condition. Data from 61 electrodes were analyzed. ERPs were quantified as mean amplitudes within four consecutive time windows, defined by visual inspection around the peaks of main ERP components: P200 (100-250 ms), P300 (250-450 ms), N400/N450 (350-550 ms) and Late Positivity Complex (LPC) (500-750 ms)). Medial and lateral scalp regions were examined separately for each time window by means of mixed model analyses of variance. The lateral ANOVAs were conducted with the topographical factors Gradient (7 levels) and Hemisphere (2 levels), defining 14 regions. The medial ANOVAs were conducted with the factor Gradient, defining 7 additional regions. Thus, 21 scalp regions were considered in the analyses, represented by the averaged data of their corresponding electrodes (figure 8): Anterior-Frontal (Left: Fp1 AF7 AF3; Medial: Fpz AFz; Right: Fp2 AF8 AF4), Frontal (Left: F7 F5 F3; Medial: F1 Fz F2; Right: F8 F6 F4), Fronto-Temporal (Left: FT7 FC5 FC3; Right: FT8 FC6 FC4), Mid Fronto-Central (FC1 FCz FC2), Mid Central (C1 Cz C2), Centro-Temporal (Left: T7 C5 C3; Right: T8 C6 C4), Mid Centro-Parietal (CP1 CPz CP2), Temporo-Parietal (Left: TP7 CP5 CP3; Right: TP8 CP6 CP4), Parietal (Left: P7 P5 P3; Medial: P1 Pz P2; Right: P8 P6 P4), and Parieto-Occipital (Left: PO7 PO3 O1; Medial: POz Oz; Right: PO8 PO4 O2). All of the ANOVAs further included the between participants' factors age group (younger vs older adults), and synchrony (on- vs off-

peak). Four iterations of this set of medial and lateral ANOVAs were performed, each of which pertained to one experimental condition, namely, doCR$^{=}$, doICR$^{=}$, doCR$^{\neq}$, and doICR$^{\neq}$. The Greenhouse-Geisser (1959) correction was used for univariate F-tests with more than one degree of freedom in the numerator.

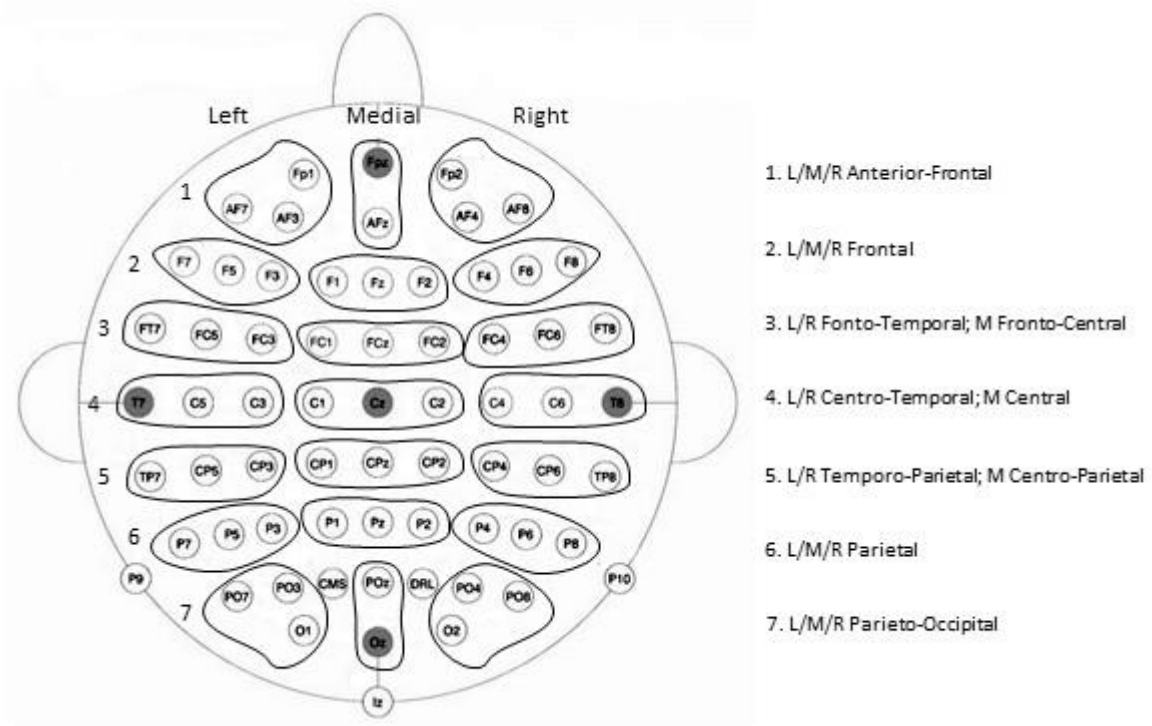

Figure 8. The 21 scalp regions and the electrodes contained therein, corresponding to the topographical factors Gradient (7 levels) and Hemisphere (2 levels), defining 14 regions, plus 7 additional gradient levels in the medial region.

Congruent repetition trials

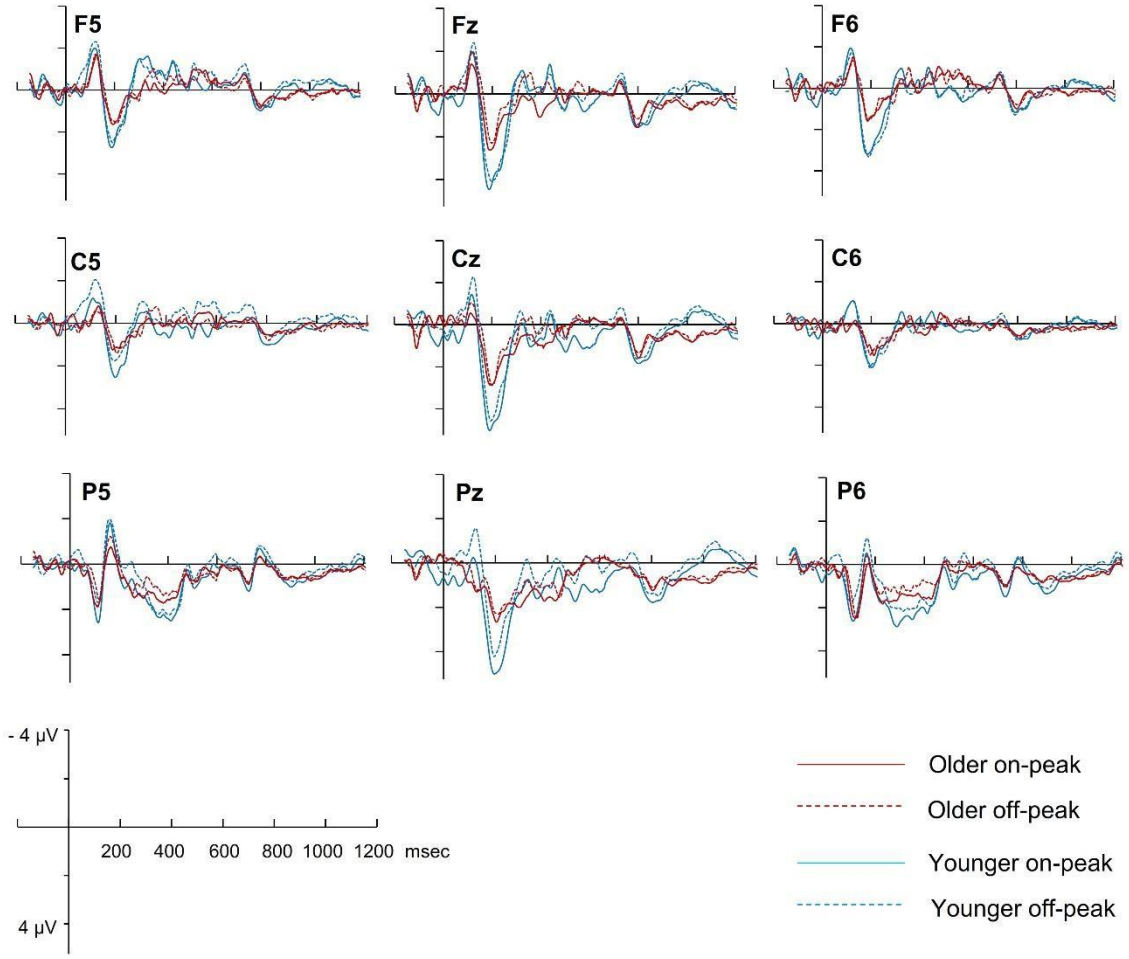

Figure 9. ERP waveforms, time-locked to stimulus' onset, elicited during the congruent with response repetition condition of the spatial Stroop task, for selected electrodes within the left/medial/right frontal, medial central and left/right centro-temporal and left/medial/right parietal scalp regions.

100-250 ms. The medial ANOVA for the 100-250 ms window showed a significant main effect of age group ($F(1, 76) = 8.75$, $p = .015$, $\eta_p^2 = .05$), consisting in a more pronounced positivity for younger than for older participants. This effect was also present in the lateral ANOVA ($F(1, 76) = 9.00$, $p = .012$, $\eta_p^2 = .05$). The main effect of synchrony was also significant for the medial ($F(1, 76) = 5.75$, $p = .025$, $\eta_p^2 = .04$), and lateral ($F(1, 76) = 6.00$, $p =$

.022, η_p^2 = .03) ANOVAs, indicating a larger on-peak positivity. Significant Age Group x Synchrony interactions were found in both the medial ANOVA (F(1, 76) = 3.46, p = .048, η_p^2 = .02) and lateral ANOVAs (F(1, 76) = 3.86, p = .041, η_p^2 = .02). Follow-up pairwise comparisons for these interactions revealed that the positivity elicited on-peak was significantly larger than that observed off-peak only in younger adults. The medial ANOVA yielded an Age Group x Synchrony x Gradient interaction (F(1, 76) = 6.83, p = .03, η_p^2 = .04). Follow-up comparisons indicated that the younger adults' enhanced on-peak positivity was significant only at posterior scalp regions (viz. Mid Centro-Parietal, Mid Parietal and Mid Parieto-Occipital). The lateral ANOVA further revealed an Age Group x Synchrony x Hemisphere interaction (F(1, 76) = 5.77, p = .042, η_p^2 = .02). Follow-up comparisons revealed a left lateralization of the younger adults' enhanced on-peak positivity.

250-450 ms. The main effect of synchrony in the 250-450 ms window was significant for the medial (F(1, 76) = 4.75, p = .045, η_p^2 = .03), and lateral (F(1, 76) = 5.00, p = .032, η_p^2 = .04) ANOVAs, indicating an on-peak positive deflection relative to off-peak's measurements. Significant Age Group x Synchrony interactions were found in both the medial ANOVA (F(1, 76) = 4.16, p = .041, η_p^2 = .04) and lateral ANOVA (F(1, 76) = 4.03, p = .038, η_p^2 = .04). Follow-up pairwise comparisons for these interactions revealed that the on-peak positive deflection was significant only in older adults. The lateral ANOVA further revealed an Age Group x Synchrony x Hemisphere interaction (F(1, 76) = 5.77, p = .042, η_p^2 = .03). Follow-up comparisons indicated that the older adults' on-peak positivity was significant only over left scalp regions. The medial ANOVA unveiled an Age Group x Synchrony x Gradient interaction (F(1, 76) = 5.96, p = .037, η_p^2 = .03). Follow-up comparisons indicated that the older adults' on-peak positivity was significantly larger than that observed for younger adults only at frontal and central scalp regions (viz. Mid Anterior-Frontal, Mid Frontal, Mid Fronto-Central, Mid Central).

350-550 ms. The main effect of synchrony in the 350-550 ms window was significant for the medial ($F(1, 76) = 3.99$, $p = .048$, $\eta_p^2 = .02$), and lateral ($F(1, 76) = 4.76$, $p = .041$, $\eta_p^2 = .03$) ANOVAs, indicating an on-peak positive deflection relative to off-peak's measurements. The medial ANOVA revealed an Age Group x Synchrony x Gradient interaction ($F(1, 76) = 5.96$, $p = .037$, $\eta_p^2 = .04$). Follow-up comparisons indicated that older adults' on-peak positivity was significantly larger than that observed for younger adults only over frontal scalp regions (viz. Mid Anterior-Frontal and Mid Frontal), and a reversal of this pattern over more posterior regions (viz. Mid Central, Mid Centro-Parietal, and Mid Parietal), in which younger adults' on-peak positivity was significantly larger than that observed for older adults.

500-750 ms. Significant Age Group x Synchrony interactions in the 500-750 ms window were found in both the medial ANOVA ($F(1, 76) = 6.46$, $p = .028$, $\eta_p^2 = .04$) and lateral ANOVAs ($F(1, 76) = 5.86$, $p = .021$, $\eta_p^2 = .04$). Follow-up pairwise comparisons for these interactions revealed an on-peak positivity, relative do off-peak measurements, that was significant only in younger adults. The medial ANOVA yielded an Age Group x Synchrony x Gradient interaction ($F(1, 76) = 5.53$, $p = .038$, $\eta_p^2 = .04$). Follow-up comparisons indicated that the younger adults' enhanced on-peak positivity was significant only at central and posterior scalp regions (viz. Mid Fronto-Central, Mid Central, Mid Centro-Parietal, Mid Parietal and Mid Parieto-Occipital). The lateral ANOVA further revealed an Age Group x Synchrony x Hemisphere x Gradient interaction ($F(1, 76) = 6.77$, $p = .039$, $\eta_p^2 = .04$). Follow-up comparisons revealed a left lateralization of the younger adults' enhanced on-peak positivity, which was significant only over the central and some posterior scalp regions (viz. Left Fronto-Temporal, Left Centro-Temporal, Left Centro-Parietal, Left Parietal).

Incongruent repetition trials

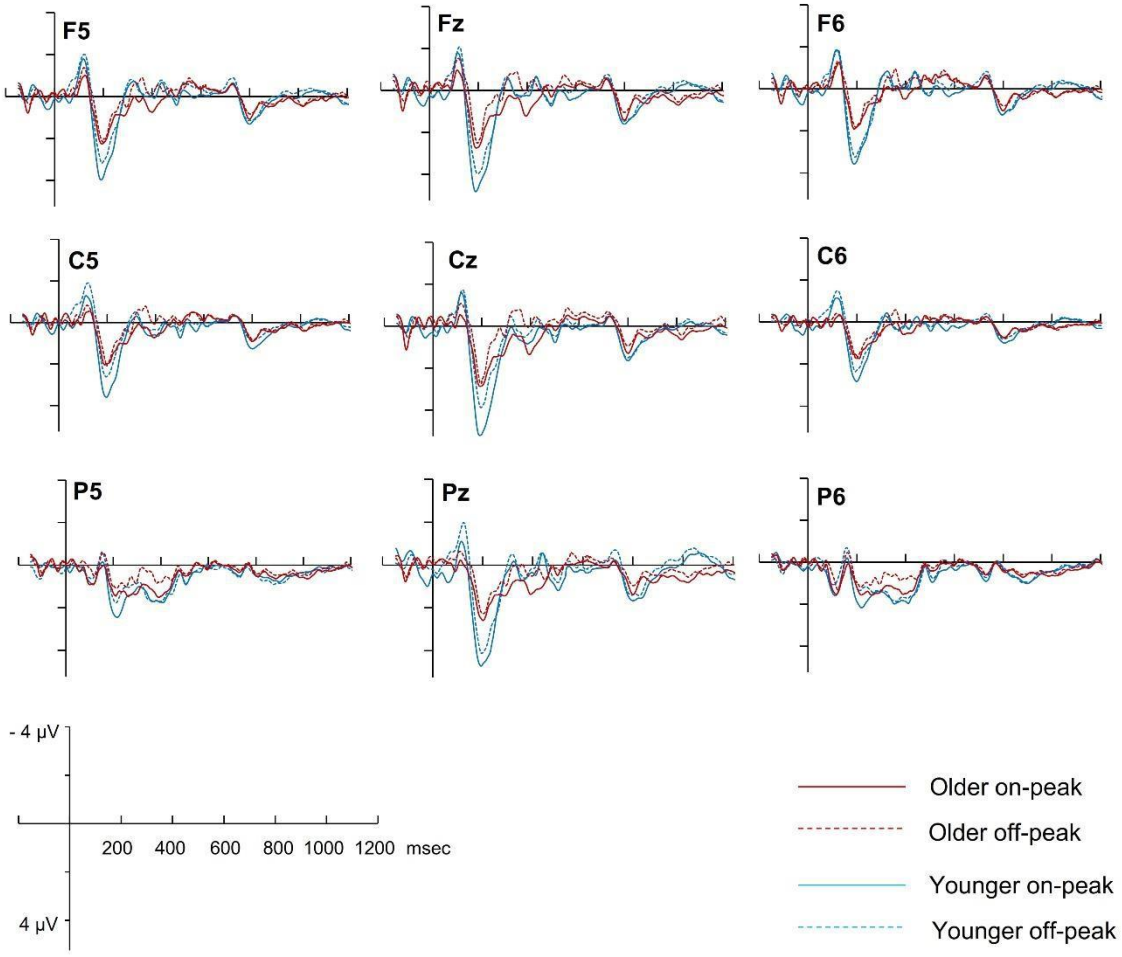

Figure 10. ERP waveforms, time-locked to stimulus' onset, elicited during the incongruent with response repetition condition of the spatial Stroop task, for selected electrodes within the left/medial/right frontal, medial central and left/right centro-temporal and left/medial/right parietal scalp regions.

100-250 ms. The medial ANOVA for the 100-250 ms window showed a significant main effect of age group ($F(1, 76) = 9.55$, $p = .015$, $\eta_p^2 = .05$), consisting in a more pronounced positivity for younger than for older participants. This effect was also present in the lateral ANOVA ($F(1, 76) = 8.10$, $p = .011$, $\eta_p^2 = .05$). The main effect of synchrony was also significant for the medial ($F(1, 76) = 4.75$, $p = .044$, $\eta_p^2 = .03$), and lateral ($F(1, 76) = 5.11$, $p =$

.032, η_p^2 = .04) ANOVAs, indicating a larger on-peak positivity. Significant Age Group x Synchrony interactions were found in both the medial ANOVA (F(1, 76) = 4.46, p = .036, η_p^2 = .03) and lateral ANOVA (F(1, 76) = 5.86, p = .031, η_p^2 = .04). Follow-up pairwise comparisons for these interactions revealed that the positivity elicited on-peak was significantly larger than that observed off-peak only in younger adults. The lateral ANOVA further revealed an Age Group x Synchrony x Hemisphere interaction (F(1, 76) = 4.01, p = .048, η_p^2 = .02). Follow-up comparisons suggest a more left lateralized on-peak positivity enhancement, indicated by a larger effect size of synchrony over left scalp regions that over their right counterparts.

250-450 ms. The main effect of synchrony in the 250-450 ms window was significant for the medial (F(1, 76) = 3.75, p = .047, η_p^2 = .02), and lateral (F(1, 76) = 4.12, p = .039, η_p^2 = .03) ANOVAs, indicating an on-peak positive deflection relative to off-peak's measurements. Significant Age Group x Synchrony interactions were found in both the medial ANOVA (F(1, 76) = 5.18, p = .031, η_p^2 = .04) and lateral ANOVA (F(1, 76) = 5.03, p = .044, η_p^2 = .03). Follow-up pairwise comparisons for these interactions revealed that the on-peak positive deflection was significant only in older adults. The lateral ANOVA further revealed an Age Group x Synchrony x Hemisphere interaction (F(1, 76) = 6.57, p = .032, η_p^2 = .04). Follow-up comparisons indicated that the older adults' on-peak positivity more pronounced over left scalp regions, whereas the synchrony effect size over right scalp regions was markedly smaller.

350-550 ms. In the 350-550 ms window significant Age Group x Synchrony interactions were found in both the medial ANOVA (F(1, 76) = 4.16, p = .038, η_p^2 = .04) and lateral ANOVA (F(1, 76) = 4.93, p = .033, η_p^2 = .04). Follow-up pairwise comparisons for these interactions revealed an on-peak positive deflection, relative to off-peak measurements, that was significant only in older adults. The lateral ANOVA further revealed an Age Group x Synchrony x Hemisphere interaction (F(1, 76) = 6.07, p = .04, η_p^2 = .04). Follow-up

comparisons indicated that the older adults' on-peak positivity more pronounced over left scalp regions, whereas the synchrony effect size over right scalp regions was markedly smaller.

500-750 ms. The medial ANOVA for the 500-750 window yielded an Age Group x Gradient interaction ($F(1, 76) = 4.53$, $p = .048$, $\eta_p^2 = .02$). Follow-up comparisons indicated that younger adults' potentials were more positive relative to older adults' over frontal and central scalp regions (viz. Mid-Frontal, Mid Fronto-Central, and Mid Central).

Congruent alternation trials

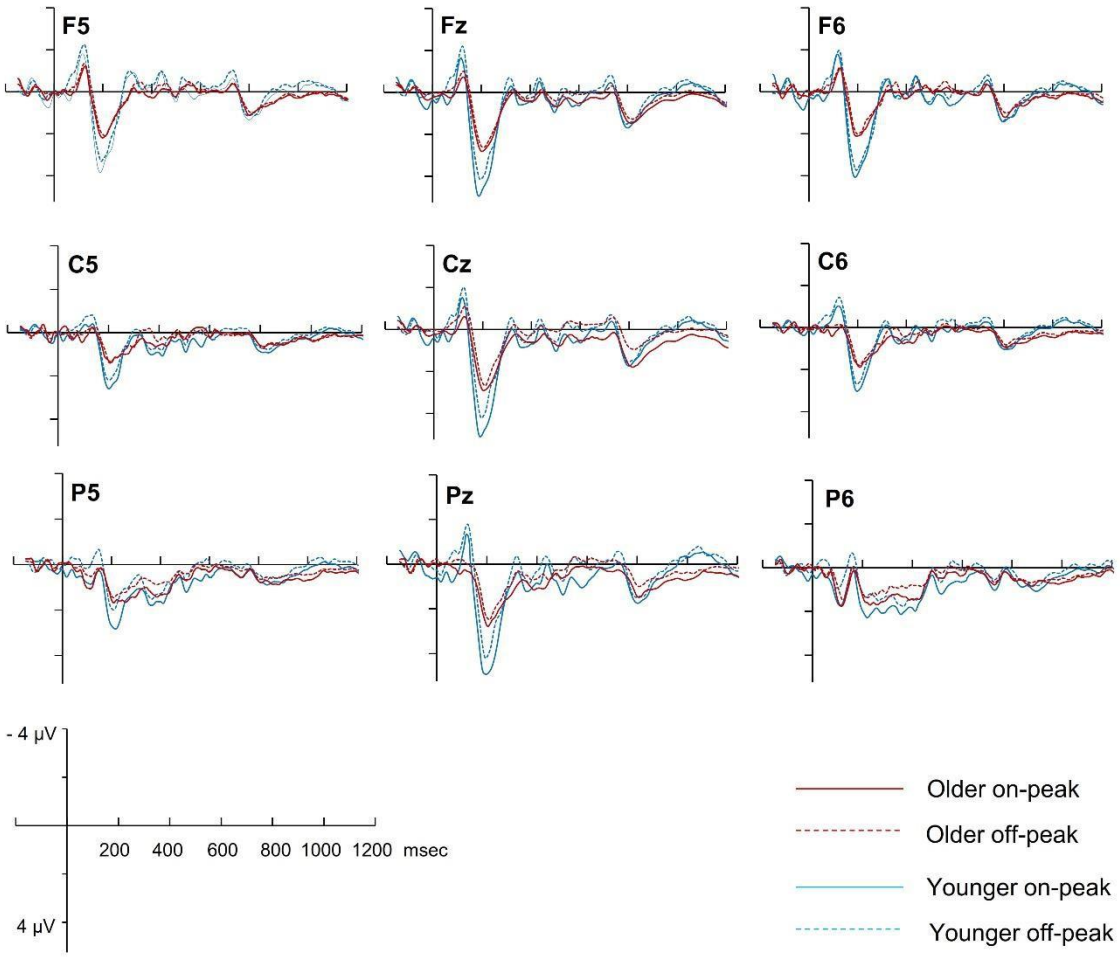

Figure 11. ERP waveforms, time-locked to stimulus' onset, elicited during the congruent with response alternation condition of the spatial Stroop task, for selected electrodes within the left/medial/right frontal, medial central and left/right centro-temporal and left/medial/right parietal scalp regions.

100-250 ms. The medial ANOVA for the 100-250 ms window showed a significant main effect of age group ($F(1, 76) = 7.75$, $p = .014$, $\eta_p^2 = .05$), consisting in a more pronounced positivity for younger than for older participants. This effect was also present in the lateral ANOVA ($F(1, 76) = 8.15$, $p = .018$, $\eta_p^2 = .05$). Significant Age Group x Synchrony interactions were found in both the medial ANOVA ($F(1, 76) = 4.36$, $p = .039$, $\eta_p^2 = .03$) and lateral ANOVAs ($F(1, 76) = 4.06$, $p = .041$, $\eta_p^2 = .03$). Follow-up pairwise comparisons for these interactions revealed that the positivity elicited on-peak was significantly larger than that observed off-peak only in younger adults. The lateral ANOVA revealed an Age Group x Synchrony x Hemisphere interaction x Gradient interaction ($F(1, 76) = 4.77$, $p = .043$, $\eta_p^2 = .02$). Follow-up comparisons revealed a significant left lateralization of the younger adults' enhanced on-peak positivity, that emerged over frontal and central scalp regions, viz. Left Anterior-Frontal, Left Frontal, and Left Fronto-Temporal.

250-450 ms. The main effect of synchrony in the 250-450 ms window was significant for the medial ($F(1, 76) = 4.05$, $p = .043$, $\eta_p^2 = .03$), and lateral ($F(1, 76) = 4.79$, $p = .038$, $\eta_p^2 = .04$) ANOVAs, indicating an on-peak positive deflection relative to off-peak's measurements. Significant Synchrony x Gradient interactions were found in both the medial ANOVA ($F(1, 76) = 4.76$, $p = .043$, $\eta_p^2 = .03$) and lateral ANOVA ($F(1, 76) = 5.03$, $p = .039$, $\eta_p^2 = .03$). Follow-up pairwise comparisons for these interactions revealed that the on-peak positive deflection was significant only over central and posterior scalp regions, viz. Mid Fronto-Central, Mid Central, Mid Centro-Parietal, Mid Parietal and, bilaterally, Fronto-Temporal, Centro- Temporal, Temporo-Parietal, and Parietal.

350-550 ms. Significant Synchrony x Gradient interactions were found in the 350-450 window, in both the medial ANOVA ($F(1, 76) = 3.76$, $p = .044$, $\eta_p^2 = .03$) and lateral ANOVA ($F(1, 76) = 4.03$, $p = .041$, $\eta_p^2 = .03$). Follow-up pairwise comparisons for these interactions

revealed that the on-peak positive deflection was significant only over central and posterior scalp regions, viz. Mid Fronto-Central, Mid Central, Mid Centro-Parietal, Mid Parietal and, bilaterally, Fronto-Temporal , Centro-Temporal, Temporo-Parietal, and Parietal.

500-750 ms. The main effect of synchrony in the 500-750 ms window was significant for the medial ($F(1, 76) = 4.15$, $p = .044$, $\eta_p^2 = .03$), and lateral ($F(1, 76) = 5.03$, $p = .039$, $\eta_p^2 = .04$) ANOVAs, indicating an on-peak positive deflection relative to off-peak's measurements. Significant Age Group x Synchrony x Gradient interactions were found in both the medial ANOVA ($F(1, 76) = 3.97$, $p = .047$, $\eta_p^2 = .02$) and lateral ANOVA ($F(1, 76) = 4.63$, $p = .043$, $\eta_p^2 = .03$). Follow-up pairwise comparisons for these interactions revealed that the effect of synchrony was larger, as attested by more marked on-peak positive deflections, for younger participants over posterior scalp regions, viz. Mid Parietal and, bilaterally, Temporo-Parietal, and Parietal.

Incongruent alternation trials

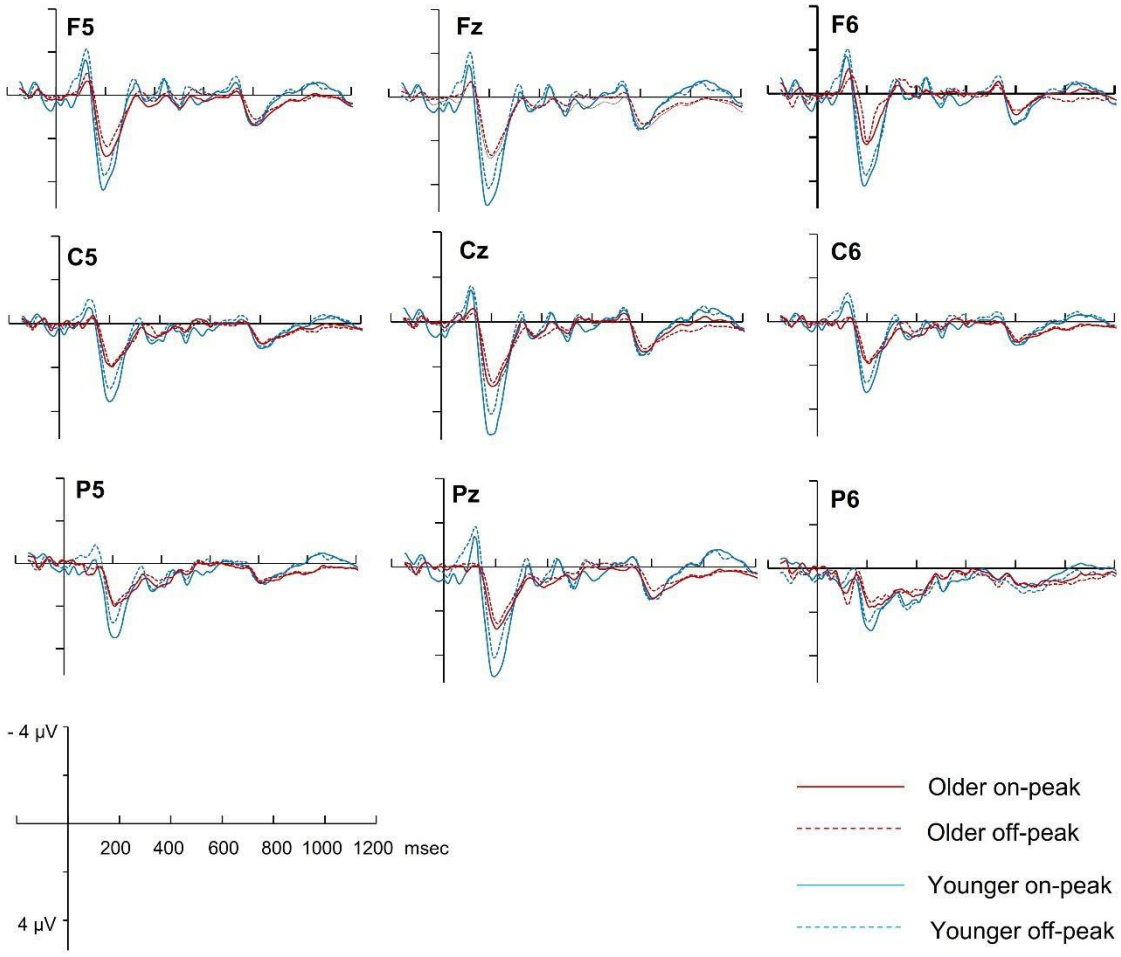

Figure 12. ERP waveforms, time-locked to stimulus' onset, elicited during the incongruent with response alternation condition of the spatial Stroop task, for selected electrodes within the left/medial/right frontal, medial central and left/right centro-temporal and left/medial/right parietal scalp regions.

100-250 ms. The medial ANOVA for the 100-250 ms window showed a significant main effect of age group ($F(1, 76) = 8.05$, $p = .021$, $\eta_p^2 = .04$), consisting in a more pronounced positivity for younger than for older participants. This effect was also present in the lateral ANOVA ($F(1, 76) = 8.63$, $p = .03$, $\eta_p^2 = .03$). Significant Age Group x Synchrony interactions were found in both the medial ANOVA ($F(1, 76) = 5.06$, $p = .031$, $\eta_p^2 = .03$) and lateral

ANOVAs (F(1, 76) = 5.08, p = .043, η_p^2 = .02). Follow-up pairwise comparisons for these interactions revealed that the positivity elicited on-peak was significantly larger than that observed off-peak only in younger adults.

250-450 ms. No significant main effects nor interactions involving the factors age group and synchrony were found.

350-550 ms. No significant main effects nor interactions involving the factors age group and synchrony were found.

500-750 ms. A significant Age Group x Synchrony x Gradient interaction was found in the medial ANOVA (F(1, 76) = 3.76, p = .048, η_p^2 = .02). Follow-up pairwise comparisons revealed an on-peak positive deflection, relative do off-peak measures, that was significant only for younger participants, and over central and posterior scalp regions, viz. Mid Central, Mid Centro-Parietal, Mid Parietal, and Mid Parieto-Occipital. A significant Age Group x Synchrony x Hemisphere x Gradient interaction was unveiled in the lateral ANOVA (F(1, 76) = 3.96, p = .047, η_p^2 = .02). Follow-up comparisons revealed an on-peak positive deflection that was significant only for younger participants, and over left central and left posterior scalp regions, viz. Left Centro-Temporal, Left Temporo-Parietal, Left Mid Parietal, and Left Parieto-Occipital.

Discussion

Our theoretical model entails a particular overall ordering of asynchrony effects across experimental conditions, $doC^{R=} > doIC^{R\neq} > doC^{R\neq} > doIC^{R=}$. More specifically, the conditional automaticity hypothesis suggests that at off-peak times controlled inhibition will be less effective due to activation leaking to the pathways implicated in automatic production of responses opposite to those targeted by controlled inhibition, and that for older participants this effect should be present on-peak and enhanced off-peak. Our results were generally in agreement with these predictions. For the condition predicted to benefit the most from off-

peak times-of-day, doC$^{R=}$ (figure 3), younger participants are not impaired in their on-peak accuracy, but preservation of on-peak accuracy was obtained at the expense of longer RTs, thus configuring an asynchrony effect for these trials. Older adults do not show (a)synchrony effects in doC$^{R=}$ trials, suggesting that the mechanism recruited by younger participants on-peak, responsible for the RT penalty observed at that time of day, is less effective in older participants, thus protecting their on-peak performance from the negative impact it has in younger individuals. We deem this mechanism to be the initial step of controlled inhibition in the spatial Stroop task, aimed at flagging the action plan on the same side of the stimulus, the one liable to yield an incorrect response. In our interpretation of the ERP data, recruitment of this mechanism by younger participants is firstly indexed by the significant positivity within the P200 window, that is not present for their older counterparts. We speculate that this positivity indexes the setting up of the 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. Preparation of the match-test is prompted by the early presence of the alternation plan, preceding that of the actual stimulus. Older participants on-peak are likely to be less efficient than their younger counterparts in responding to this early alternation plan by setting up the spatial match-test, and, in their on-peak responses, they are therefore less impaired than younger participants by the ensuing transient suppression of all appropriate action plans. The positivity within the P300 window that was observed for older, but not for younger, participants, likely indexes the mechanism by which older participants' setting up of the spatial match-test is rendered less efficient on-peak than that of their younger counterparts. We propose that this loss of efficiency is a consequence of an age-related augmentation of conditional automaticity, i.e., of activation leakage to the pathway that supports automatic production of responses contralateral to those currently targeted by controlled inhibition. Thus, the greater on-peak incidence of controlled suppression of action-plans yielding same-

side-as-stimulus responses is diluted by the leakage to the response supported by the alternation plan. We suggest that this less resource-efficient controlled inhibition, that occurs for older participants, is indexed by their larger on-peak P300. Even though the conditional automaticity created by this leakage supports an incorrect response, there are still two action plans, inefficiently inhibited, supporting the appropriate response, that thus minimize the performance impact of the leakage. We interpret the late positivity observed on-peak for younger participants as indexing the process of correction of the initial inhibition of all action-plans supporting the correct response, that also accounts for their longer on-peak RTs without losses in accuracy. In our model, inappropriate suppression of the plans supporting the correct response must be corrected by a later controlled renewal of the direction-based plan, and we deem this renewal to be indexed by the younger participants' on-peak late positivity, which, as expected, is absent for older participants.

Also predicted to yield an asynchrony effect, the second largest, $doIC^{R\neq}$ (figure 2) trials do prompt asynchrony wrt younger participants' RTs, but not wrt accuracy, suggesting that their longer on-peak RTs derive from optimal on-peak control efficiency, that, for $doIC^{R\neq}$ trials, taxes RTs without creating a meaningful accuracy benefit. As with $doC^{R=}$ trials, the P200 on-peak effect that we observe for younger participants likely indexes the setting up of the match-test between the spatial code of current predicted responses and that of the stimulus, prompted by the early presence of the alternation plan, and resulting in the suppression of the action plan based on the arrow's positon. However, and unlike in $doC^{R=}$ trials, the direction-based plan, supporting the appropriate response, remains active, and that same response is supported by the alternation plan. Accordingly, and in line with our expectation, the late positivity that was significant for younger participants in $doC^{R=}$ trials is now absent, since the direction-based plan remains available and therefore does not require regeneration. Off-peak, faster correct responses may be obtained dispensing with time-consuming controlled

suppression of the position-base plan, being generated by the conjoint support of the direction- and alternation-based plans before the less efficient off-peak controlled processing intervenes. Older adults, unlike their younger counterparts, do not show (a)synchrony effects in $doIC^{R\neq}$ trials, again suggesting that the mechanism recruited by younger participants that underpins on-peak's additional demands in respect to response preparation is less efficiently recruited by older participants. However, older participants do not show the P300 on-peak effect that was present for $doC^{R=}$ trials. In $doIC^{R\neq}$ trials, there should also occur greater recruitment of control, in order to suppress the position-based action plan, with a corresponding activation leakage to the pathway that supports automatic production of responses contralateral to those currently targeted by controlled inhibition. Crucially, and unlike in $doC^{R=}$ trials, in which this leakage was supporting the response opposite to the correct one (linked to the position and direction-based plans), in $doIC^{R\neq}$ trials, leakage from the control pathway directly enhances the correct response supported by the alternation-based plan, converging with the direction-based plan. In such circumstances, we deem the leakage to be rapidly subsumed within the production of an appropriate response, without yielding a significant P300 effect.

$doC^{R\neq}$ trials (figure 1) were expected to show the smallest asynchrony effect, whereas $doIC^{R=}$ trials (figure 4) should show a small synchrony effect. In fact, $doC^{R\neq}$ trials in younger participants show a marginally significant asynchrony in respect to accuracy, that is not coupled with RT asynchrony, suggesting that a mechanism deployed optimally on-peak hinders accuracy in these trials, and is not paired with an elicitation of longer RTs that might compensate for that hindrance, unlike what seems to be the case for younger participants in $doC^{R=}$ and $doIC^{R\neq}$ trials. The presence of a P200 effect in younger participants is congruent with our prediction of an on-peak setting up of the match-test between the spatial code of current predicted responses and that of the stimulus, prompted by the early presence of the alternation plan, and resulting in an unnecessary transient inhibition of all action plans. In

doC$^{R\neq}$ trials, crucially, controlled inhibition is particularly resource-intensive, as it momentarily suppresses all available action plans, to the point that, even in younger participants, leakage to the direct pathway becomes significant. This is congruent with the presence in all participants, younger and older, of a P300, which we take to index an accrued leakage of activation to the pathway that supports automatic production of responses contralateral to those currently targeted by controlled inhibition. These are incorrect responses, which we deem responsible for to the asynchrony effect restricted to accuracy observed in younger participants. Since on-peak deployment of controlled inhibition may result both in incorrect responses, if the conditional-automatic production of opposite-to-inhibited responses prevails, and correct responses, if regeneration of the direction-based plan comes to be enacted (indexed by the significant late positivity observed for younger participants), the additional time invested in control deployment does not result in a net gain, and thus the younger participants' marginally significant asynchrony emerges for accuracy but not for RTs. In older participants, an asynchrony trending towards significance emerges in doC$^{R\neq}$ trials in respect to RTs, coupled with absent (a)synchrony effects for accuracy. We predicted that older participants would have a greater leakage of activation to the automatic pathway supporting automatic production of opposite-to-inhibited responses. Therefore, in contrast with their younger counterparts, for older participants lengthier RTs would be more likely to indicate the presence of the regeneration and enactment of the direction-based plan. doC$^{R\neq}$ trials are also the only ones for which an on-peak late positivity is present for older participants, likely indicating that the suppression on-peak of all available action plans is particularly conductive to the regeneration of the direction-based plan. As for doIC$^{R=}$ trials, younger participants show a trend towards asynchrony in respect to their response times, paired with no (a)synchrony effects in accuracy. This likely results from the suppression of all action plans that support the incorrect response, allowing a straightforward

execution of the direction-based plan, dispensing with the regeneration process, as attested by the absence of any late positivities. The setting up of the match-test between the spatial code of current predicted responses and that of the stimulus, prompted by the early presence of the alternation plan, is indexed by a P200 effect, as in other trials in which this event was predicted for younger participants. During off-peak control deployment, a greater activation leakage to the conditional automaticity pathway primes an opposite-to-inhibited response, which converges with the direction-based response, speeding up off-peak production of the direction-based plan, as indicated by the trend toward asynchrony for RTs. In accordance with the prediction that this leakage is augmented in older participants when control is invoked on- peak, we observed for this age group the P300 on-peak effect. This on-peak accrued leakage of activation to the pathway that supports automatic production of opposite-to-inhibited responses, on one hand compensates the speed cost of controlled responses, but, as it implies a less efficient suppression of the action plans supporting the incorrect response, allows for an accrued production of such responses. In accordance with this understanding, older participants did not manifest (a)synchrony effects in their response times, but showed a significant synchrony effect in accuracy.

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