Research Report

Aging and sequential modulations of poorer strategy effects: An EEG study in arithmetic problem solving

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Abstract
This study investigated age-related differences in electrophysiological signatures of sequential modulations of poorer strategy effects. Sequential modulations of poorer strategy effects refer to decreased poorer strategy effects (i.e., poorer performance when the cued strategy is not the best) on current problem following poorer strategy problems compared to after better strategy problems. Analyses on electrophysiological (EEG) data revealed important age-related changes in time, frequency, and coherence of brain activities underlying sequential modulations of poorer strategy effects. More specifically, sequential modulations of poorer strategy effects were associated with earlier and later time windows (i.e., between 200- and 550 ms and between 850- and 1250 ms). Event-related potentials (ERPs) also revealed an earlier onset in older adults, together with more anterior and less lateralized activations. Furthermore, sequential modulations of poorer strategy effects were associated with theta and alpha frequencies in young adults while these modulations were found in delta frequency and theta inter-hemispheric coherence in older adults, consistent with qualitatively distinct patterns of brain activity. These findings have important implications to further our understanding of age-related differences and similarities in sequential modulations of cognitive control processes during arithmetic strategy execution.

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1. Introduction

Aging is generally accompanied by declines in a variety of cognitive functions such as episodic memory, working-memory, or inhibitory functions (see Craik and Salthouse, 2007; Salthouse, 2010, for reviews). Previous research on cognitive aging has also showed that both young and older adults use several strategies to accomplish most cognitive tasks (see Lemaire, 2015, for an overview). Moreover, both young and older adults obtain poorer performance when the cued strategy is not the most adapted to characteristics of problems compared to when they had to execute the better strategy (i.e., which yields the best performance) on a given item (e.g., Ardiale et al., 2012; Dunlosky and Hertzog, 2000;
Gey et al., 1993; Hertzog et al., 2012; Lemaire et al., 2004; Lemaire and Leclère, 2014; Uittenhove and Lemaire, 2012, 2013; Uittenhove et al., 2013). Such poorer strategy effects have been accounted for by assuming that, when they are asked to execute a poorer strategy on a given problem, participants have to inhibit the automatically activated strategy and activate the procedures of the required strategy before executing these procedures (e.g., Ardiale et al., 2012; Lemaire and Hinault, 2014). When they are asked to execute the better strategy, participants do not engage inhibition processes and can immediately execute procedures of the automatically activated better strategy. This makes poorer strategy effects interesting to inform how participants engage in cognitive control processes (like inhibition) during strategy execution and how these control processes evolve during aging.

Previous research has also shown that people sequentially modulate cognitive control mechanisms from one trial to the next while executing strategies. This was evidenced by several sequential effects like strategy switch costs (i.e., better performance when participants are asked to repeat the same strategy over two consecutive trials than when they are asked to use two different strategies; Ardiale et al., 2012; Luwel et al., 2009; Schillemans et al., 2009, 2011; Lemaire and Lecacheur, 2010; Lemaire and Leclère, 2014), strategy sequential difficulty effects (i.e., better performance with a strategy after executing an easy strategy compared to after executing a difficult strategy on the preceding item; Uittenhove and Lemaire, 2012, 2013; Uittenhove et al., 2013), and, the focus of this study, sequential modulations of poorer strategy effects (Lemaire and Hinault, 2014; Hinault et al., 2014).

Recently, Lemaire and Hinault (2014) reported that poorer strategy effects on current problem were larger after better strategy problems than following poorer strategy problems. It was proposed that the detection of a conflict on poorer strategy problems led the cognitive system to increase its level of control to more efficiently solve a potential conflict on the next problem, resulting in decreased poorer strategy effects. Conversely, when participants are asked to solve the previous problem with the better strategy, cognitive control processes are not prepared for a potential conflict on the next problem. This results in larger poorer strategy effects on the next problem. Regarding aging effects, Lemaire and Hinault (2014) distinguished two subgroups based on performance in a Simon task (i.e., a conflict task requiring to inhibit a spatial dimension and to focus on a target dimension, for example, the shape; Simon and Small, 1969). They revealed that high- and low-functioning older adults differed in how efficient they were in sequential modulations of cognitive control. Indeed, high-functioning older adults showed the same pattern than young adults in sequential modulations of poorer strategy effects, while lower-functioning older adults did not show such modulations. These findings suggest that efficient control mechanisms (as measured with the Simon task) allow efficient sequential modulations of poorer strategy effects.

EEG is a useful tool to investigate aging effects on cognitive processes and to reveal age-related differences when both age groups do not differ in behavioural measures. For example, in arithmetic processing, El Yagoubi et al. (2005) studied age-related differences in split effects (i.e., better performance in arithmetic verification tasks when false proposed products are far from correct products, like in $8+4=19$, than when splits are small, like in $8+4=13$). Split effects have been explained as reflecting the use of plausibility-checking strategy on large-split problems, and exact-calculation strategy on small-split problems (Allen et al., 1992, 1997, 2005; Ashcraft and Bataglia, 1978; De Rammelaere et al., 2001; Duverne and Lemaire, 2004, 2005; Duverne et al., 2007; El Yagoubi et al., 2003; Pesenti et al., 2000; Zbrodoff and Logan, 1990). El Yagoubi et al. (2005) found that, although both groups did not differ in behavioural split-effects, event-related potentials (ERPs) associated with large and small-split problems were similar in older adults, while a larger positivity for large-split compared to small-split problems occurring 250 ms after problem display was observed in young adults. These results are consistent with the use of a plausibility-checking strategy (i.e., determining that a proposed product cannot be true, without calculating the correct product) on large split problems in young adults, whereas older adults used an exact-calculation strategy (i.e., calculating the correct product) on both small-split and large-split problems. Hence, while behavioural measures could have led to conclude to age-invariance in split effects, ERPs revealed important qualitative differences between young and older adults.

Recently, Hinault et al. (2014) analyzed ERPs to determine the time course of sequential modulations of poorer strategy effects in young adults. They found ERP differences on current poorer strategy problems as a function of previous better or poorer strategy problems. These differences occurred both in early and late time windows, over anterior left sites of the scalp. Larger positive amplitudes on poorer strategy problems when following better strategy problems than after poorer strategy problems were associated with sequential modulations of poorer strategy effects. The first time window (i.e., 200–550 ms after stimulus presentation) suggests that control mechanisms occurred immediately after the encoding of the problem. In this latency, it was proposed that participants focused on the cue to know which strategy is required and to inhibit the automatic activation of the better strategy triggered by units of operands. The second time window (i.e., 850–1250 ms after stimulus display) has been interpreted as participants keeping the activation of the better strategy at its lower level while executing the required poorer strategy. These positive modulations are consistent with P3 (i.e., centro-parietal positive deflection peaking between 350- and 500 ms post-stimulus presentation) and conflict SP (i.e. sustained positivity starting about 500 ms following stimulus presentation) components, previously found in conflict tasks. These components have been associated with response inhibition (i.e., P3) and implementation of attentional control (i.e., conflict SP) during sequential modulations of cognitive control mechanisms (see Larson et al., 2014, for a review).

Cognitive control mechanisms were also studied by means of frequency and coherence analyses. Indeed, previous studies using these analyses revealed that cognitive and sensory processes induce modulations of electric activity over time, as well as qualitative differences in rhythmic activity (e.g.,
Cavanagh et al., 2012; Hanslmayr et al., 2008; Micheloyannis et al., 2002, 2005). Previous research associated the theta band (4–8 Hz) to conflict detection and enhanced control engagement (e.g., Cavanagh and Shackman, 2015; Nigbur et al., 2011). Moreover, power in the delta band (1–3.5 Hz) and the lower alpha band (8–10 Hz) have been associated with inhibitory control of irrelevant information (see Harmony, 2013; Klimesch et al., 2007, for reviews). Regarding connectivity patterns, higher frontal theta coherence was previously found for conflict trials in a Flanker task (Cavanagh et al., 2009), and was associated with implementation of proactive control during task switching (Cooper et al., 2015). Also, higher delta coherence has been showed in NoGo condition compared to Go condition, suggesting a link with inhibitory processes (e.g., Papenberg et al., 2013).

Frequency and coherence analyses can also reveal qualitative and quantitative differences between young and older adults. Using a 2-back task, Gajewski and Falkenstein (2014) found age-related decreased power in theta, lower and upper alpha band, while the delta band remained unchanged. Moreover, Finnigan and Robertson (2011) found that older adults’ theta power was significantly correlated with higher performance on numerous cognitive tests assessing verbal memory, attention, and cognitive control. Regarding connectivity patterns, decreased efficiency of cognitive control and memory processes with age have been associated with lower theta coherence (Papenberg et al., 2013; Tóth et al., 2014).

Here, of specific interest was whether electrophysiological measures would reveal age-related differences in sequential modulations of poorer strategy effects in higher functioning older adults. Such age-related differences in electrophysiological measures were expected to reveal whether high-functioning older adults are using different or additional mechanisms to be as able as young adults to sequentially modulate cognitive control processes during strategy execution. We collected electrophysiological measures because previous studies (e.g., De Smedt et al., 2009; El Yagoubi et al., 2003, 2005; Gräbner and De Smedt, 2011, 2012; Hinault et al., 2014; Jost et al., 2004; Luo et al., 2009; Núñez-Peña et al., 2006; Peng et al., 2011; Uittenhove et al., 2013) showed that these measures were useful to investigate strategic aspects of cognition, and to characterize cognitive processes during arithmetic problem solving. These measures are also fruitful to investigate executive control processes involved not only in general cognitive tasks but also during arithmetic strategy execution.

The first goal of the present study was to examine age-related differences in the time-course of sequential modulations of poorer strategy effects. Age-related differences in the time course of sequential modulations of poorer strategy effects were expected because of less efficient inhibitory processes with aging (see Diamond, 2013, for a review). Indeed, increased poorer strategy effects with age (e.g., Lemaire and Hinault, 2014) suggests that executing a cued poorer strategy on a problem is more resource demanding in older adults than in young adults. Thus, older participants have fewer resources to prepare themselves on the next problem. We predicted that cognitive control mechanisms would be delayed in older adults, resulting in later time windows for sequential modulations of poorer strategy effects. Alternatively, high-functioning older adults could be as able as young adults to implement cognitive control mechanisms, resulting in early and late time windows of similar latencies in both age groups.

The second goal of this study was to use EEG frequency and coherence analyses to determine changes associated with sequential modulations of poorer strategy effects. Until now, no studies have examined what frequencies are associated with sequential modulations of cognitive control mechanisms during strategy execution. Such analyses have been fruitfully undertaken to understand sequential modulations of control processes when participants perform conflict tasks like Simon, flanker, or Stroop tasks (e.g., Cohen and Cavanagh, 2011; Hanslmayr et al., 2008; Oehrn et al., 2014; Tang et al., 2013; Van Steenbergen et al., 2012). We expected to observe increased delta, theta and/or lower alpha power on current poorer strategy problem when poorer strategies were executed on previous problems compared to following better strategy problems. These frequencies were previously associated with conflict detection and implementation of control processes (e.g., Cavanagh and Shackman, 2015; Klimesch et al., 2007; Nigbur et al., 2011), and could be elicited by strategy conflict detection in previous problems and strategy adjustment on current problem. Moreover, coherence analyses were expected to inform us about functionally interconnected neuronal networks and to determine if sequential modulations of poorer strategy effects were associated with specific patterns of local, distal, or inter-hemispheric connectivity. We expected increased local frontal coherence in both theta and delta bands on poorer strategy problems when a poorer strategy has been executed on the previous problem compared to following a better strategy, consistently with previous research on conflict tasks (e.g., Cavanagh et al., 2009; Papenberg et al., 2013). Thus, we expected that such analyses would bring further insights on sequential modulations of control mechanisms when participants execute strategies to accomplish high-level cognitive tasks like arithmetic problem solving tasks.

Investigating age-related changes in frequency and coherence patterns was the third goal of this study. Consistent with previous findings (e.g., Finnigan and Robertson, 2011; Gajewski and Falkenstein, 2014), we expected decreased power in older adults compared to young adults in both theta and alpha bands on current poorer strategy problem following poorer strategy problems. In addition, sequential modulations of poorer strategy effects could be more associated with delta power in high-control older adults compared to young adults. Alternatively, high-functioning older adults could show larger theta coherence than young adults, as an electrophysiological signature of older adults’ maintaining sequential modulations of poorer strategy effects equivalent to young adults. All in all, these outcomes were expected to document how older adults manage to reach similar sequential modulations of poorer strategy effects to young adults during arithmetic strategy execution.

2. Results

2.1. Behavioural data

Mean solution times, percentages of errors in strategy selection, and percentages of errors in strategy execution on the
contrasts revealed that poorer strategy effects were significant when current problems followed better strategy problems (250 ms, $F(1,39) = 52.87$, $p < .01$, $MSe = 34.36$, $n^2 = .58$), and non-significant after poorer strategy problems (38 ms, $F < 1.5$, $p > .25$). Consistent with the selection criterion described in the Method section, the age $\times$ strategy on the previous problem $\times$ strategy on the current problem interaction was not significant ($F < 1.5$, $p > .71$).

Analyses of errors in strategy selection only revealed a significant main effect of strategy on the current problem, $F(1,38) = 8.78$, $p < .01$, $MSe = 2.49$, $n^2 = .19$. Participants made more errors on current poorer strategy problems than on current better strategy problems (4.9% vs. 3.3%). Analyses of errors in strategy execution revealed no significant main or interaction effects ($Fs < 2.7$, $ps > .11$). We also arcsine corrected the error rates to normalize the data. Analyses yielded the same results as analyses on untransformed data.

### 2.2. Electrophysiological data

Significant interactions involving the age factor were followed by planned contrasts and pairwise comparisons to further describe age-related changes. Following previous works on sequential modulations of control processes (Clayson and Larson, 2011a, 2011b; Larson et al., 2012; Tang et al., 2013b), pairwise comparisons (Sidak corrected) were undertaken to analyze poorer strategy effects after poorer strategy problems and after better strategy problems. In case of similar main effects or interactions between lateral and midline electrodes, only results for lateral electrodes were reported. Significant interactions involving the age factor were followed by separate analyses in young and older adults. Unless otherwise noted, only effects significant to at least $p < .05$ were reported.

#### 2.2.1. Event-related potentials

We conducted mixed-design ANOVAs on mean amplitudes of electrophysiological activities in successive time windows. ANOVAs were conducted separately for midline and lateral electrodes. Design was 2 (Age: young, older adults) $\times$ 2 (Anteroposterior: anterior, posterior) $\times$ 2 (Hemisphere: left, right) $\times$ 2 (Strategy on the previous problem: poorer, better) $\times$ 2 (Strategy on the current problem: poorer, better) for lateral electrodes, and 2 (Age: young, older adults) $\times$ 2 (Region: front, back, right, left) $\times$ 2 (Strategy on the previous problem: poorer, better) $\times$ 2 (Strategy on the current problem: poorer, better) for midline electrodes. Age was the only between-participants factor.

In the 0–200 ms window, results showed a main effect of age ($F(1,38) = 8.15$, $p < .01$, $MSe = 3.12$, $n^2 = .18$), with a larger negativity in young adults ($–1.07 \mu V$) than in older adults ($–0.21 \mu V$). Also, overall, brain potentials were more negative at posterior sites ($–0.87 \mu V$) relative to anterior sites ($–0.41 \mu V$), as revealed by the main effect of anteroposterior, $F(1,38) = 7.30$, $p < .02$, $MSe = .87$, $n^2 = .16$. Most importantly, the Age $\times$ Hemisphere $\times$ Strategy on the previous problem $\times$ Strategy on the current problem interaction was significant, $F(1,38) = 10.02$, $p < .01$, $MSe = .03$, $n^2 = .21$. Separate analyses in young and older adults revealed that this interaction was significant in older adults ($F(1,19) = 6.14$, $p < .01$, $MSe = .02$,

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**Table 1 – Young and older adults’ mean solution times (in ms), percentages of errors (with SEM) in strategy selection on current problems for better-strategy and poorer-strategy items when previous problems were better-strategy or poorer-strategy items.**

<table>
<thead>
<tr>
<th>Strategy on current problems</th>
<th>Young adults</th>
<th>Older adults</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strategy on previous problems</td>
<td>Poorer strategy</td>
<td>Better strategy</td>
</tr>
<tr>
<td>Poorer strategy</td>
<td>4667 (368)</td>
<td>4163 (178)</td>
</tr>
<tr>
<td>Better strategy</td>
<td>4796 (377)</td>
<td>4307 (202)</td>
</tr>
</tbody>
</table>

<table>
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<tr>
<th>Poorer-strategy effects</th>
<th>Mean solution times (in ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poorer strategy</td>
<td>177*</td>
</tr>
<tr>
<td>Better strategy</td>
<td>4.0 (0.9)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Poorer-strategy effects</th>
<th>Mean percentages of errors in strategy selection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poorer strategy</td>
<td>–0.3</td>
</tr>
<tr>
<td>Better strategy</td>
<td>3.2 (0.9)</td>
</tr>
</tbody>
</table>

Notes. Poorer-strategy effects = poorer strategy – better strategy. Mean percentages of errors in strategy selection: mean percentages of problems on which participants used another strategy than the cued strategy. Mean percentages of errors in strategy execution: mean percentages of problems for which estimates were different from expected estimates given the strategies that were used on problems for which participants used the cued strategies.

*p < .05.

**p < .01. ***p < .001.
Contrasts revealed that older adults showed larger negativity for better-poorer trials compared to poorer-poorer trials in the left hemisphere, $F(1,19)=6.81$, $p<.02$, MSe=.03, $n^2=.26$ (see Figs. 1a and 2). There was also a significant difference between better-better and poorer-better trials, with larger negativity for better-better trials compared to poorer-better trials in anterior sites of the scalp while older adults had larger activities. Moreover, the Anteroposterior/C2 trials in anterior sites of the brain, $F(1,19)=5.74$, $p<.03$, MSe=.04, $n^2=.23$.

In the 200–550 ms window, the Age $\times$ Anteroposterior interaction revealed larger amplitudes in posterior sites of the scalp in young adults, while older adults had larger activities in frontal sites ($F(1,19)=30.39$, $p<.01$, MSe=1.02, $n^2=.44$). Moreover, the Anteroposterior $\times$ Hemisphere $\times$ Strategy on the previous problem ($F(1,19)=9.22$, $p<.01$, MSe=.01, $n^2=.20$), and Age $\times$ Anteroposterior $\times$ Hemisphere $\times$ Strategy on the previous problem ($F(1,19)=8.02$, $p<.01$, MSe=.01, $n^2=.17$) interactions were significant. Larger positivity after executing the better strategy on previous problems relative to following the poorer strategy was more important in anterior left sites of the scalp, and this effect was larger in young adults than in older adults. Most importantly, the Age $\times$ Hemisphere $\times$ Strategy on the previous problem $\times$ Strategy on the current problem interaction was significant, $F(1,19)=6.89$, $p<.01$, MSe=.01, $n^2=.15$. Separate analyses in young and older adults revealed that this interaction was significant in young adults ($F(1,19)=9.68$, $p<.01$, MSe=.03, $n^2=.34$) but not in older adults ($F<1.0$, $p>.42$). Contrasts in young adults revealed larger positive amplitudes for better-poorer trials compared to poorer-poorer trials, $F(1,19)=5.61$, $p<.02$, MSe=.16, $n^2=.23$, in anterior left regions of the scalp (see Figs. 1b and 3); no differences were found between better-better and poorer-better trials, $F<2.5$ and $p>.11$.

In the 550–850 ms window, a main effect of age ($F(1,19)=5.69$, $p<.03$, MSe=1.27, $n^2=.13$) revealed that signal was negative in young adults ($–.033 \mu V$) while it was positive in older adults ($0.22 \mu V$). Most importantly, the Age $\times$ Anteroposterior $\times$ Strategy on the previous problem $\times$ Strategy on the current problem interaction was significant, $F(1,19)=5.47$, $p<.03$, MSe=.03, $n^2=.13$. Separate analyses in young and older adults revealed that this interaction was significant in older adults ($F(1,19)=6.14$, $p<.03$, MSe=.05, $n^2=.24$) but not in young adults ($F<1.5$, $p>.94$). Contrasts in older adults revealed larger negative amplitudes for better-poorer trials compared to poorer-poorer trials in left hemisphere of the scalp, $F(1,19)=5.87$, $p<.02$, MSe=.06, $n^2=.24$. No differences were found between better-better and poorer-better trials, $F<2.0$ and $p>.18$.

In the 850–1250 ms window, the Age $\times$ Anteroposterior interaction revealed that young adults displayed a larger positivity in posterior sites of the scalp while older adults showed larger positivity in anterior sites, $F(1,19)=10.15$, $p<.01$, MSe=.41, $n^2=.21$). Moreover, the Age $\times$ Anteroposterior $\times$ Hemisphere $\times$ Strategy on the previous problem interaction ($F(1,19)=4.49$, $p<.05$, MSe=.01, $n^2=.11$) revealed larger negativity following poorer strategy problems than after better strategy problems in anterior left sites, only in young adults. Most importantly, the Age $\times$ Hemisphere $\times$ Strategy on the previous problem $\times$ Strategy on the current problem interaction ($F(1,19)=

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Fig. 1 – Scalp maps of the difference wave between better-poorer and poorer-poorer trials, (a) in older adults in the 0–200- and 550–850 ms windows, and (b) in young adults in the 200–550- and 850–1250 ms windows.

Fig. 2 – Wave amplitudes of right and left anterior and posterior electrodes, and midline electrodes, in older adults in better-poorer trials (dashed lines) and in poorer-poorer trials (solid lines) during the first 1500 ms post-stimulus display.
Fig. 3 – Wave amplitudes of right and left anterior and posterior electrodes, and midline electrodes in young adults in better-poorer trials (dashed lines) and in poorer-poorer trials (solid lines) during the first 1500 ms post-stimulus display.

15.14, p < .01, MSe = .02, np² = .29) was significant. Separate analyses in young and older adults revealed that this interaction was significant in young adults (F(1,19) = 13.17, p < .01, MSe = .04, np² = .41) and not in older adults (F(1,38) = 1.39, p > .54). Contrasts in young adults revealed that amplitudes were significantly more positive for better-poorer trials compared to poorer-poorer trials, F(1,19) = 7.04, p < .03, MSe = .16, np² = .27, in anterior left regions of the scalp. No differences were found between better–better and poorer–better trials, F(1,15) and p > .25.

In the 1250–1500 ms window, main effect of age showed that young adults exhibited negativity while older adults had positive amplitudes (−.15 μV and 0.31 μV, respectively; F(1,38) = 4.91, p < .05, MSe = .90, np² = .11). Moreover, a main effect of anteroposterior was significant, as amplitudes were larger in anterior relative to posterior sites of the scalp (F(1,36) = 6.30, p < .02, MSe = .27, np² = .14). The Age × Strategy on the previous problem interaction (F(1,38) = 5.02, p < .04, MSe = .14, np² = .12) revealed that young adults exhibited larger negativity when previous problem was solved with the poorer strategy compared to following better strategy problem, while older adults showed larger negativity. This difference was, overall, larger in anterior left sites of the scalp, as revealed by the Anteroposterior × Hemisphere × Strategy on the previous problem interaction, F(1,38) = 7.29, p < .02, MSe = .01, np² = .16.

In sum, both age groups exhibited early and late sequential modulations of poorer strategy effects. Interestingly, these modulations occurred earlier in older adults (0–200- and 550–850-ms windows) than in young adults (200–550- and 850–1250-ms windows). In young adults, sequential modulations were characterized by larger positivity on better-poorer trials compared to poorer-poorer trials in anterior left regions of the scalp. In contrast, older adults showed larger negativity on better-poorer trials in left hemisphere of the scalp.

2.2.2. Frequency analyses
We conducted mixed-design ANOVAs separately on each frequency bands. ANOVAs were conducted separately for midline and lateral electrodes. Design was 2 (Age: young, older adults) × 2 (Anteroposterior: anterior, posterior) × 2 (Hemisphere: left, right) × 2 (Strategy on the previous problem: poorer, better) × 2 (Strategy on the current problem: poorer, better) for lateral electrodes, and 2 (Age: young, older adults) × 2 (Region: front, back, right, left) × 2 (Strategy on the previous problem: poorer, better) × 2 (Strategy on the current problem: poorer, better) for midline electrodes. Age was the only between-participants factor.

In the delta band (1–3.5 Hz), the Age × Anteroposterior interaction revealed larger power in posterior areas in young adults (1.16 μV²) while larger power was found in anterior areas in older adults (1.07 μV²), F(1,38) = 4.59, p < .04, MSe = .09, np² = .11. Moreover, at midline electrodes, the Age × Region × Strategy on the previous problem × Strategy on the current problem interaction was significant, F(3,114) = 2.97, p < .04, MSe = .21, np² = .07. Separate analyses in young and older adults revealed that this interaction was significant in older adults (F(1,19) = 9.75, p < .01, MSe = .21, np² = .34), but not in young adults (F(1,19) = 1.0, p > .75). Contrasts in older adults showed that better-poorer trials elicited larger power than poorer-poorer trials in frontal sites of the scalp, F(1,19) = 5.58, p < .03, MSe = .05, np² = .13 (see Fig. 4a). There were no power differences between better–better and poorer–better trials (F < 1.0, p > .95).

In the theta band (4–8 Hz), a main effect of age showed that power was larger in young adults compared to older adults, (0.54 μV² vs. 0.32 μV²), F(1,38) = 13.94, p < .01, MSe = .21, np² = .27. Most importantly, the Age × Strategy on the previous problem × Strategy on the current problem interaction interaction (F(1,38) = 5.64, p < .03, MSe = .395, np² = .13) was significant. Separate analyses in young and older adults showed that the Strategy on the previous problem × Strategy on the current problem interaction was marginally significant in young adults (F(1,19) = 4.10, p < .06, MSe = .526, np² = .18) and not in older adults (F < 1.0, p > .45). Contrasts in young adults revealed that power was larger for poorer-poorer trials compared to better-poorer trials in anterior right sites of the scalp (F(1,19) = 5.00, p < .04, MSe = .01, np² = .21). There were no power differences between better–better and poorer–better trials (F < 1.0, p > .36), see Fig. 4b.

In the lower alpha band (8–10 Hz), there was a main effect of age, as young adults had larger power in posterior areas of
In sum, while young adults exhibited larger power in lower alpha and theta bands for poorer–poorer trials compared to better–poorer trials, older adults had larger power in the delta band for better–poorer trials than for poorer–poorer trials.

2.2.3. Coherence analyses
We conducted mixed-design ANOVAs separately on each frequency bands. ANOVAs were conducted separately for local, distant, and inter-hemispheric coherence analyses. Design was 2 (Age: young, older adults) × 2 (Region: frontal, temporal, central, parietal) × 2 (Hemisphere: left, right) × 2 (Strategy on the previous problem: poorer, better) × 2 (Strategy on the current problem: poorer, better) for local coherence analyses. Distant coherence analyses did not include region factor, while inter-hemispheric coherence analyses did not include hemisphere factor. Age was the only between-participants factor.

In the delta band, local coherence was higher when the current problem was solved with the poorer strategy, as revealed by main effect of strategy on the current problem (F(1,19)=4.57, p<.04, MSe=9.47, np²=.11). Also, a main effect of age revealed higher distant coherence in young adults that in older adults (0.465² vs. 0.405², respectively; F(1,19)=5.24, p<.03, MSe=.01, np²=.12). Moreover, larger local coherence for current poorer strategy problems than for current better strategy problems was more important in left hemisphere of the scalp (0.017γ) relative to right hemisphere (0.004γ), as shown by the Hemisphere × Strategy on the current problem interaction F(1,19)=4.81, p<.04, MSe=3.68, np²=.11.

In the theta band, a main effect of age revealed that distant coherence was higher in young adults that in older adults (0.417² vs. 0.357², respectively; F(1,19)=7.33, p<.02, MSe=0.01, np²=.16). Moreover, local coherence increases when previous problems were solved with the poorer strategy (0.65γ), as revealed by the Age × Strategy on the previous problem interaction, F(1,19)=5.70, p<.03, MSe=7.11, np²=.13. Separate analyses revealed a main effect of strategy on the previous problem in young adults (F(1,19)=4.88, p<.05, MSe=.01, np²=.20) but not in older adults (F<1.5, p>.27). Separate analyses also revealed a significant Hemisphere × Strategy on the previous problem × Strategy on the current problem interaction in older adults, F(1,19)=6.74, p<.02, MSe=5.26, np²=.26. Contrasts in older adults showed that local coherence was larger for better–poorer trials compared to poorer–poorer trials in temporal right sites, F(1,19)=7.08, p<.02, MSe=.02, np²=.27 (see Fig. 5a). There were no differences between better–better and poorer–better trials (F<2.2,
3. Discussion

The aim of the present study was to investigate age-related differences in electrophysiological signatures of sequential modulations of poorer strategy effects. Both young and older adults were matched on behavioural sequential modulations of poorer strategy effects. Preliminary analyses did not showed any effects of strategy repetitions, ruling out an explanation of the present findings in terms of switch costs. Rather, sequential modulations of poorer strategy effects more likely originate from modulations of interference processing following poorer strategy problems. We discuss behavioural sequential modulations of poorer strategy effects before addressing ERPs. Moreover, we discuss how age-related differences in ERP, frequency, and coherence analyses further our understanding of aging effects on sequential modulations of poorer strategy effects. More generally, the present findings help to better understand modulations of cognitive control processes during strategy execution, as well as age-related differences in these processes.

Modulations of poorer strategy effects as a function of the previously executed strategy share similarities with congruency sequence effects found in the general cognitive control literature (Craton et al., 1992). Following theories of cognitive control (Botvinick et al., 2001; De Pisapia and Braver, 2006; see Duthoo et al.; 2014; Scherbaum et al., 2012, for alternative views), solving a conflict on a given problem increases the level of top-down control and enables participants to more efficiently monitor strategy conflict on the subsequent problem. That is, Hinault et al. (2014) proposed that top-down control increases selectivity of strategy-relevant information on a given problem and decreases activation of the strategy-irrelevant information. When the previous problem was solved with the better strategy, significant poorer strategy effects result from the lack of preparation for the subsequent poorer strategy problem and less efficient inhibition of irrelevant information (e.g., size of unit digits). As previously discussed by Hinault et al. (2014), ERPs in young adults suggest that sequential modulations of poorer strategy effects involve two sets of processes. A first, early modulation occurred between 200- and 550-ms after stimulus display, when participants had to focus on the cue to know which strategy is required on the current problem, and to inhibit processing of unit digits of operands. A second, later modulation occurred between 850- and 1250 ms after stimulus display, when participants had to keep the activation of the better strategy at its lower level in order to execute the procedures of the required, poorer strategy on poorer strategy problems.

Our results suggest that, like young adults, older adults used earlier and later sets of cognitive control processes for sequential modulations of poorer strategy effects. However, our results also revealed that timing of these processes differed in each age group, as they occurred earlier in older adults. Given that we studied high-functioning older adults, it is possible that earlier modulations (0–200 ms vs. 200–550 ms in young adults) enabled this subpopulation of older adults to maintain similar behavioural performance to young adults during sequential modulations of poorer strategy effects. Early modulations in the 0–200 ms windows suggest preparation to efficiently detect the poorer strategy during the encoding of the problem (e.g., Dehaene et al., 1999). Indeed, cognitive control processes have been observed as early as 100-ms after stimulus onset (e.g., Shedden et al., 2013). Furthermore, proactive preparation of control processes was found to result in ERPs modulations along with, and even before, stimulus onset (e.g., Schmid et al., 2015). On
poorer–poorer trials, solving conflict on a previous problem could have led high-functioning older adults to proactively prepare themselves to a greater extent than young adults to process a potential conflict (i.e., between the most available strategy and the cued strategy) on the following problem. Larger positivity on poorer–better trials relative to better–better trials is also consistent with better preparation following poorer strategy execution on previous problem. Speculatively, it could be envisaged that such pre-trial preparation may have acted as compensation for a subgroup of older adults to circumvent well-known age-related decline in inhibition mechanisms (e.g., Mayas et al., 2012; West and Alain, 2000) and strategic processing (Lemaire, 2010). Eye-movements studies could improve our knowledge about how older adults encode problems by determining if older adults focus earlier and more efficiently on the cue during the encoding phase. Indeed, pre-trial preparation for potential subsequent conflict on poorer–poorer trials suggests increased attention to strategy-relevant information (e.g., the cued strategy) and decreased attention to strategy-irrelevant information (e.g., the unit digits).

The second, later set of control processes also occurred earlier in older adults than in young adults (550–850 ms vs. 850–1250 ms). These later processes are likely involved in increased control during the execution of strategy procedures. Noteworthy, contrary to the ERPs of young adults, who exhibited larger positivity for better–poorer trials compared to poorer–poorer trials, this difference consisted in larger negativity in older adults. This polarity difference could originate from changes in neuronal recruitment (e.g., Wolk et al., 2009), due to a need for additional or different control processes on better–poorer trials. Later negative modulations are consistent with the N450 (i.e., fronto-central negative deflection elicited about 400–550 ms following stimulus presentation) component, associated with cognitive control mechanisms and interpreted as an index of conflict (e.g., Larson et al., 2014). This result suggests that older adults rely on different control mechanisms from young adults during sequential modulations of poorer strategy effects.

Furthermore, in addition to findings in line with general decrease in ERP amplitudes and frequency power with aging (e.g., Bellis et al., 2000; Dustman et al., 1999; Golob and Starr, 2000; Iragui et al., 1993), our results also showed reduced variability in ERP activities in older adults compared to young adults. These findings stand in contrast with the neural noise hypothesis (Cremer and Zeef, 1987), according to which the signal to noise ratio of neural communication decreases with aging. Note however that we selected a specific subgroup of older adults who showed similar behavioural sequential modulations of poorer strategy effects to young adults. This is consistent with recent work finding reduced neural noise in older participants who undergo successful aging and who obtained better working-memory performance (e.g., Voytek et al., 2015).

Another original set of findings in this study concerns changes revealed by frequency and coherence analyses. Although coherence results could have been inflated by volume-conduction, the fact that results showed the same frequency bands as in conflict tasks (e.g., Tang et al., 2013) suggests that an important part of connectivity is genuine and not artifactual. In young adults, theta power as well as theta local coherence on current poorer strategy problems were increased when previous problems were solved with the poorer strategy compared to better-poorer trials. These findings are consistent with higher level of control when the poorer strategy has just been executed (e.g., Cohen and Cavanagh, 2011; Hanslmayr et al., 2008; Tang et al., 2013). Indeed, several studies interpreted increased theta power as reflecting enhanced focus on the relevant characteristics and decreased activation of irrelevant dimensions in the subsequent trial (e.g., Nibgur et al., 2011; Van Steenbergen et al., 2012). Moreover, several studies linked the alpha band with inhibitory processes (e.g., Tang et al., 2013; for reviews see Klimesch et al., 2007; Mathewson et al., 2011). This frequency band, more specifically the lower alpha band power and distant lower alpha coherence, could contribute, together with the theta band, to the monitoring of irrelevant information during task processing (e.g., Hanslmayr et al., 2008). As a matter of fact, several studies showed alpha involvement in optimal performance with increased power in task-irrelevant regions while power decreased in regions engaged by the task (e.g., Jokisch and Jensen, 2007; Jensen and Mazaheri, 2010). Here, lower alpha power and upper alpha distant coherence were larger over posterior regions and right hemisphere, while ERPs associated with sequential modulations of poorer strategy effects were found in anterior left regions of the scalp.

Previous studies revealed a general decrease in all frequency bands with aging (e.g., Gajewski and Falkenstein, 2014; Kolev et al., 2005; Shigeta et al., 1995; see Dustman et al., 1999 for a review). Moreover, inter-hemispheric coherence at rest was also found to decline with aging (e.g., Duffy et al., 1995, 1996; Knott and Harr, 1997; Kikuchi et al., 2000). Noteworthy, our results in older adults showed increased delta power and inter-hemispheric theta coherence for better–poorer trials compared to poorer–poorer trials, while young adults did not show changes in delta band in association with sequential modulations of poorer strategy effects. The delta band has been interpreted as reflecting inhibitory control of irrelevant information (e.g., Prada et al., 2014) and context updating (e.g., Harper et al., 2014). Likewise, increased inter-hemispheric theta coherence in older adults suggests the involvement of additional neural networks and the need for enhanced control engagement (e.g., Nibgur et al., 2011). We can hypothesize that changes in the delta band and in theta coherence reflect the recruitment of additional cognitive control mechanisms on current poorer strategy problems when the better strategy was executed on previous problems, compared to poorer–poorer trials. Indeed, on better–poorer trials, cognitive control processes are not prepared for a potential conflict on the current problem, and additional mechanisms are needed in older adults to maintain similar level of behavioural performance to young adults.

Our results are consistent with qualitatively distinct processes involved in young and older adults. Indeed, sequential modulations of poorer strategy effects resulted in (a) larger power in theta and lower alpha bands as well as greater local theta coherence in young adults, while larger power in the delta band and inter-hemispheric theta coherence were observed in older adults, and (b) larger power/coherence for
poorer–poorer trials compared to better–poorer trials in young adults, while the reverse was observed in older adults. It appears that older adults manage to be as efficient as young adults in sequential modulations of poorer strategy effects by relying on different frequency bands and by recruiting additional neuronal networks when conflict is the highest (i.e., on better–poorer trials). In line with studies linking high theta power with healthy cognitive aging (e.g., Finnigan and Robertson, 2011), this suggests that delta power and theta coherence could be considered as neurophysiological markers of high-performing older adults.

In sum, ERP results revealed age-related differences in time course of sequential modulations of poorer strategy effects, resulting in earlier modulations in older adults than in young adults. Furthermore, these modulations consisted, in older adults, in larger negativity on better–poorer trials than on poorer–poorer trials, while young adults exhibited larger positivity on better–poorer trials than on poorer–poorer trials. Moreover, frequency and coherence analyses revealed larger theta and lower alpha power on poorer–poorer trials than on better–poorer trials in young adults, while older adults exhibited larger delta power and theta coherence on better–poorer trials than on poorer–poorer trials. These findings demonstrate the usefulness of EEG to detect age-related changes in cognition even when both groups were selected to be similar in behavioural measures. Combining ERPs, frequency, and coherence analyses allows to highlight how high-performing older adults manage to exhibit similar behavioural performance to young adults. These findings further our understanding of aging effects on sequential modulations of cognitive control mechanisms involved during strategy execution.

4. Experimental procedure

4.1. Participants

Thirty-one older adults participated in this experiment. In order to study high-control older adults, we matched older participants with the 20 young adults tested by Hinault et al. (2014). Testing in older adults continued until we had two groups of 20 participants each who, on average, showed similar behavioural sequential modulations of poorer strategy effects (i.e., significant sequential modulations of poorer strategy effects, without interaction that involves the age factor). All participants reported normal or corrected-to-normal vision (see participants’ characteristics in Table 2). An informed consent was obtained prior to participation. Participants were paid 15 euros; they were not informed of the purpose of the experiment.

4.2. Stimuli

A computational estimation task was used, and participant were asked to estimate products of multiplication problems. Each of the 208 trials was made of two consecutive two-digit multiplication problems (e.g., 48 × 72). Following previous findings in arithmetic (see Geary, 1994; Campbell, 2005, for reviews), we controlled the following factors: (a) no operands had a zero unit digit, (b) no operands had a five unit digit, (c) no digits were repeated within operands, (d) no reverse orders of operands were used, (e) the first operand was larger than the second in half the problems, and vice versa, (f) no operands had its closest decade equal to 0, 10, or 100, (g) differences between correct products and estimates were matched across strategies (i.e., mean percent deviations were equal when participants used the mixed-rounding up-down or the mixed-rounding down-up strategy on all problems), and (h) rounded operands were never the same across the two problems of a given trial. Trials were followed by a series of five letters (e.g., sevbc). Half the five-letter series included only consonants or only vowels, and half included both types of letters.

Half the problems were so-called mixed-rounding up-down problems, and half were mixed-rounding down-up problems. The unit digit of the first operand was smaller than five and that of the second operand larger than five in the mixed-rounding down-up problems (e.g., 54 × 36). The reverse was true for the mixed-rounding up-down problems (e.g., 46 × 72). There were two types of items, better strategy and poorer strategy items. The better strategy was cued on the better strategy items such that half the mixed-rounding down-up problems were cued with the mixed-rounding down-up strategy (e.g., doing 50 × 40 to estimate 54 × 36), and half the mixed-rounding down-up problems were cued with the mixed-rounding up-down strategy (e.g., doing 50 × 70 to estimate 46 × 72). The poorer strategy was cued on the poorer strategy problems such that the mixed-rounding down-up problems were cued with the mixed-rounding down-up strategy (e.g., doing 50 × 40 to estimate 54 × 36), and the mixed-rounding up-down problems were cued with the mixed-rounding down-up strategy. Poorer strategy and better strategy problems were matched on correct products and mean percent deviations between correct products and estimates.

<p>| Table 2 – Participants characteristics. |</p>
<table>
<thead>
<tr>
<th>Variables</th>
<th>Young adults</th>
<th>Older adults</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>20</td>
<td>20</td>
<td>–</td>
</tr>
<tr>
<td>Age in years and months</td>
<td>21.9 (3.1)</td>
<td>72.6 (3.5)</td>
<td>–</td>
</tr>
<tr>
<td>Years of education</td>
<td>15 (1.9)</td>
<td>16 (3.1)</td>
<td>2.39</td>
</tr>
<tr>
<td>MHVS</td>
<td>24 (3.7)</td>
<td>27 (3.9)</td>
<td>11.21***</td>
</tr>
<tr>
<td>Arithmetic fluency</td>
<td>60 (29.9)</td>
<td>88 (16.6)</td>
<td>22.16**</td>
</tr>
<tr>
<td>MMSE</td>
<td>–</td>
<td>29 (6.6)</td>
<td>–</td>
</tr>
</tbody>
</table>

Note. MHVS = French version of the Mill-Hill Vocabulary Scale (Deltour, 1993; Raven, 1951). MHVS consists of 33 items distributed across three pages. Each item was a target word followed by six proposed words, and the task consisted in identifying which word was the closest to the target. Arithmetic fluency = Score obtained in a paper-and-pencil arithmetic test (French Kit; French et al., 1963) in which participants have to solve as many basic arithmetic problems (e.g., 53-18) as possible in 8 min; MMSE = Mini Mental-State Examination (Folstein et al., 1975). None of the older adults obtained MMSE score lower than 27; therefore, none were excluded. Participants took the MHVS and then the arithmetic fluency tests after the computational estimation task.

“p<.05, “p<.01, ““p<.001.
Four types of trials were tested: better–better trials (i.e., both current and previous problems were solved with the better strategy), better–poorer trials (i.e., current problem was solved with the poorer strategy and previous problem with the better strategy), poorer–better trials (i.e., current problem was solved with the better strategy and previous problem with the poorer strategy), and poorer–poorer trials (i.e., both current and previous problems were solved with the poorer strategy). The strategy to be used was the same on both problems in half the trials and different in the other trials.

4.3. Procedure and design

We used the same procedure as Lemaire and Hinault (2014). Participants were comfortably seated in a quiet and dimly lit room. Participants were individually tested in one session that lasted approximately 60–90 min. Stimuli were presented on a 800 × 600 resolution screen in a 48-point Bold courier font (black colour). When multiplication problems were displayed, participants had to estimate the response as fast and accurately as possible using the cued strategy. Only the two mixed-rounding strategies were allowed. Mixed-rounding down-up was described as rounding the first operand down to the nearest decade and the second up to the nearest decade, for instance, doing 40 × 70 to estimate 43 × 68. Mixed-rounding up-down was described as rounding the first operand up to the nearest decade and the second operand down to nearest decade, for instance, doing 40 × 60 to estimate 38 × 64. Instructions were given verbally. First, participants performed an initial practice period including eight problems (four with each strategy). Then, participants practiced the experimental task on eight trials (i.e., each involving two multiplication problems and a series of five letters). Following previous works (Ardiale et al., 2012; Lemaire and Hinault, 2014; Lemaire and Lecacheur, 2010; Uittenhove and Lemaire, 2012, 2013) this letter-judgement task was used to prevent interference between the last problem of a trial and the first problem of the next trial. The experiment included four blocks. The order of presentation was counterbalanced across participants. Participants had five minutes breaks in-between each block of 52 trials. For each trial, the procedure is illustrated in Fig. 6.

The experiment was controlled by the E-Prime software (Psychology Software Tools, 1999). Each trial began with a blank screen for 500 ms, followed by a warning signal (‘*’) presented for 400 ms in the center of the screen. Then, the problem and the cue were simultaneously displayed on the computer screen. The cue appeared 2 cm above the problem and, together with the problem, remained on the screen until participants’ response. The letters “BH” (standing for “Down-Up” in French) cued participants to use mixed-rounding down-up strategy, and the letters “HB” (“Up-Down”) prompted participants to use mixed-rounding up-down strategy. Participants provided their response aloud. This enabled us to control that they used the cued strategy, and to determine which type of error they made. Errors in strategy selection were defined as participants using another strategy than the cued strategy. Errors in strategy execution were defined as participants failing to correctly execute the procedures of the cued strategy. To reduce electrical noise due to speech, participants were allowed to say their final answers only. After participants’ response, a blank screen was presented for 500 ms followed by a ‘*’ warning signal for 400 ms. The second problem of a trial and the cue were then presented. A blank screen followed participant’s response for 500 ms. Then, after a 500-ms blank screen, ‘*’ appeared for 400 ms, followed by five letters (e.g., aeiou). Participants had to press the ‘L’ key on an AZERTY keyboard if all letters were either vowels or consonants or the ‘S’ key if letters included both vowels and consonants. A blank screen for 1000 ms was finally displayed before the next trial starts. Participants were instructed to blink only during inter-trial intervals.

4.4. Electrophysiological recording and analyses

Electrophysiological activity was continuously recorded by a “Biosemi Active 2” system with 64 active electrodes positioned on an elastic cap (Electro-cap Inc) following the 10–10 international system (see Fig. 7). Six additional external electrodes were used: two on the left and right mastoids for the offline reference, and four electrodes placed on the left and right temples and below the eyes, to identify eye blinks and horizontal eye movements. The signal was continuously recorded at a frequency of 256 Hz and processed off line using EEGLAB software (Delorme and Makeig, 2004). All electrodes were re-referenced off line using the algebraic average of the left and right mastoid electrodes (Luck, 2005). Data analysis was similar to the procedure described in previous event-related potentials works in strategy execution (e.g., El Yagoubi et al., 2003, 2005; Galfano et al., 2004; Herron and Rugg, 2003; Johnson and Rugg, 2006; Uittenhove et al., 2013). Signal was filtered ([1–20] Hz bandpass filter), epoched (−200, 1500] stimulus based). Finally, the 200 ms pre-stimulus period served as baseline. Only event-related potentials corresponding to correct answers were analyzed. Event-related potentials containing horizontal eye movements or activity exceeding ±50 μV were rejected. Also, any epoch with a channel containing amplitudes of more than five standard deviations from the epoch mean was rejected. Eye movement and blink artifacts were corrected using least median of

![Fig. 6 – Sequence of events within a trial. The letters “BH” (i.e., standing for “Down-Up” in French) cued participants to use mixed-rounding down-up strategy, and the letters “HB” (i.e., standing for “Up-Down” in French) prompted participants to use mixed-rounding up-down strategy.](image-url)
square algorithm (Klados et al., 2009) based on electrooculogram electrodes. The averages ± standard deviations of better–better, better–poorer, poorer–better, and poorer–poorer trials retained for analyses were respectively 37 ± 6, 39 ± 6, 39 ± 7, and 38 ± 7 in young adults, and 36 ± 9, 35 ± 7, 36 ± 9, 36 ± 8, in older adults. For ERPs analyses, we calculated mean amplitudes of time windows determined by a combination of visual inspection and previous analyses of ERPs in strategy execution (e.g., El Yagoubi et al., 2003, 2005; Uittenhove et al., 2013). Following West and Moore (2005)’s study on sequential modulations of cognitive control processes, we used permutation tests (500 replications, Bonferroni correction, alpha = 0.0001). We defined five windows of interest (0–200; 200–550; 550–850; 850–1250; 1250–1500 ms), and conducted ANOVAs in each window, on the data from 44 lateral and 16 midline electrodes. Indeed, given differences between durations of computational estimation tasks and of conflict tasks, as well as differences in topography between Hinault et al. (2014)’s ERPs results and canonical ERP components (e.g., P3, conflict SP), a time course study was favoured over component analyses. In order to reduce degrees of freedom in the parametric analyses, data from adjacent electrode sites were averaged together (Fig. 2). Note that, to decrease the possibility of Type I error given the number of analyses performed on the ERP data, we used the same approach as in previous works (e.g., El Yagoubi et al., 2003, 2005; Uittenhove et al., 2013) and applied corrections for multiple comparisons associated with individual statistical tests.

Frequency and coherence analyses were conducted using Brain Vision Analyzer software (v.2.0, Brain Products, GmbH, Munich, Germany). EEG power (μV²) as well as coherence in the delta (1–3.5 Hz), theta (4–8 Hz), alpha low (8–10 Hz), and alpha high (10–13 Hz) bands were computed on the whole epoch. We examined two alpha bands separately as they provide complementary information (Fink et al., 2005; Klimesch et al., 2007). Baseline and artefact-free EEG data were submitted to Fast Fourier analysis (0.5 Hz resolution, window length: 10%, window variance correction), with application of a Hanning window to avoid edge effects. Data were subsequently computed for each EEG frequency band. Coherence values (Cross spectrum/Autospectrum), defined as the spectral cross-correlation between two signals normalised by their power spectra (Sauseng et al., 2005), were extracted between groups of electrodes, according to Micheloyannis et al. (2005): Frontal (FP1-F7, FP1-F3, F7-F3, FP1-FT7, FP1-FC3, or FP2-FC4), Temporal (FT7-FT8, T7-T8, TP7-TP8), Central (C3-C4, CP3-CP4, or P3-P4), and Parietal (P3-O1, P7-P8, O1-O2) representing local coherence measures, and Fron-to-Parietal (FP1-CP3, FP1-P3, or CP3-P3) and Parieto-frontal (FP1-P3, or FC3-FC4) representing distant coherence (see Fig. 8a). Inter-hemispheric coherence was measured between the following pairs (see Fig. 8b): Frontal (FP1-F2, F3-F4, F7-F8, FT7-FT8, FC3-FC4), Temporal (T7-T8, TP7-TP8), Central (C3-C4, CP3-CP4, P3-P4, TP7-TP8), and Parietal (P3-P4, P7-P8, O1-O2). EOG and reference
channels were removed before coherence calculation. We did not surface Laplacian because, due to excessive spatial filtering, it has been found that this can lead to poor estimates of lower frequency, which are the focus of this study (e.g., Serrien et al., 2003). Coherence values were Fisher-z transformed. Local, distant, and inter-hemispheric coherence were analyzed separately because local coherence values can be more accurate than other values (e.g., Micheloyannis et al., 2005). To correct for multiple comparisons, Sidak correction was applied.

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References


