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Effects of Aging on Arithmetic Problem-Solving: An Event-related Brain Potential Study

Radouane El Yagoubi¹, Patrick Lemaire², and Mireille Besson³

Abstract

■ Younger and older participants were asked to indicate if 240 complex two-digit addition problems were smaller than 100 or not. Half of the problems were small-split problems (i.e., the proposed sums were 2% or 5% away from 100; e.g., $53 + 49$) and half were large-split problems (i.e., proposed sums were 10% or 15% away from 100; $46 + 39$). Behavioral and event-related potential (ERP) data revealed that (a) both groups showed a split effect on both reaction times and percent errors, (b) split effects were smaller for older than for

younger adults in ERPs, and (c) the hemispheric asymmetry (left hemisphere advantage) reported for younger adults was reduced in older adults (age-related hemispheric asymmetry reduction). These results suggest that older adults tend to use only one strategy to solve all problems, whereas younger adults flexibly and adaptively use different strategies for small- and large-split problems. Implications of these findings for our understanding of age-related similarities and differences in arithmetic problem-solving are discussed. ■

INTRODUCTION

One type of brain dysfunction that will affect all of us if we live long enough is normal aging. Previous studies have shown that normal aging is accompanied by a variety of cognitive declines in working memory, episodic memory, attention, and executive processes (see Craik & Salthouse, 2000; Perfect & Maylor, 2000, for recent reviews). In this article, we report an investigation of changes in the neurophysiological activity and behavioral performance that are associated with cognitive aging in an arithmetic problem-solving task.

Arithmetic and Aging

Arithmetic processing is of particular interest because the effects of aging on number processing differ from other findings about cognitive aging in general, mainly in that the deleterious effects of age may be counteracted by experience or initial formal training. For instance, when participants are asked to solve simple arithmetic problems (e.g., $8 \times 4 = ?$), older people are as good as, or even better, than younger people (Duverne, Lemaire, & Michel, 2003; Allen, Smith, Jerge, & Vires-Collins, 1997; Geary, Frensch, & Wiley, 1993; Geary & Wiley, 1991). As discussed by Geary and his collaborators, this presumably occurs because older people may compensate po-

tential aging effects by practice and good formal training at elementary school. However, in more complex arithmetic tasks (e.g., verifying equations such as $5 + 3 - 1 + 4 - 1 = 6$ or $72 - 9 = 63$), younger adults performed better than older adults (Lemaire, & Lecacheur, 2001; Salthouse & Coon, 1994).

A number of studies have examined age-related differences in arithmetic performance (i.e., % errors, solution times). Following previous works in younger adults, two types of arithmetic tasks have been used: production and problem verification tasks. In production tasks, participants are presented with a series of problems (e.g., $8 \times 3 = ?$; $26 - 7 = ?$) and are asked to provide an answer for each problem. In problem verification tasks, participants have to verify whether proposed arithmetic equations (e.g., $7 + 4 = 13$) are true or false. Interestingly, participants can use multiple strategies to accomplish production and verification tasks (Kirk & Ashcraft, 2001; Campbell & Timm, 2000; Siegler & Lemaire, 1997; LeFevre, Sadesky, & Bisanz, 1996). A strategy can be defined as “a procedure or set of procedures to achieve a higher-level goal or task; these procedures do not require conscious awareness to be called a strategy” (Lemaire & Reder, 1999, p. 365). For example, to solve problems such as “ 8×7 ,” an individual can directly retrieve the correct solution from memory (using a retrieval strategy), or add the first multiplicand the number of times indicated by the second multiplicand (using a repeated addition strategy).

Regarding problem verification tasks, different strategies can also be used depending upon the characteristics

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of the problems. For example, performance on equations such as “ $8 + 4 = 13$ ” have been compared to “ $8 + 4 = 19$.” Typically, results show that participants are slower to verify the former than the latter. This phenomenon, which has been largely replicated in the arithmetic literature, has been called “split effect” because results depend upon the distance between the proposed and exact solutions (Duverne & Lemaire, in press; Duverne, Lemaire, & Michel, 2003; El Yagoubi, Lemaire, & Besson, 2003; De Rammelaere, Stuyven, & Vandierendonck, 2001; Pesenti, Thioux, Seron, & De Volder, 2000; Stanescu-Cosson et al., 2000; Zbrodoff & Logan, 1990; Ashcraft & Battaglia, 1978). One suggested explanation of split effects is that two different strategies may be used to solve the two types of problems. When the proposed solution is close to the correct solution, participants may use an exhaustive verification strategy (exact calculation), which includes encoding the numbers, retrieving answers from memory, comparing proposed and retrieved answers and making true/false decisions, before they respond. By contrast, when the proposed solution is too far from the correct solution to be plausible, as in “ $8 + 4 = 19$,” participants do not need to use such an exhaustive verification strategy. Rather, they can use an approximate calculation strategy to give their answers.

The present experiment was specifically aimed at tracking the changes in cognitive flexibility that may occur with age in the use of these two arithmetic strategies (i.e., exact calculation and approximate calculation) during an inequality verification task. To achieve this end, we compared current behavioral and event-related potential (ERP) data obtained from older adults with data previously obtained from younger adults performing the same task of verifying small- and large-split problems (El Yagoubi et al., 2003). The aim of this comparison was to determine whether younger and older adults are equally able to choose strategies adaptively to solve small- and large-split problems.

Evoked Potentials and Aging

Using the ERP method to analyze changes in brain electrical activity associated with aging has led to interesting and important findings (see Friedman, Kazmerski, & Fabiani, 1997; Polich, 1996, for reviews). ERPs are useful in that they provide a direct and multidimensional measure (i.e., differences in amplitude, latency, and scalp distribution) of the processes necessary to perform a specific task or analyze the characteristics of specific stimuli. For instance, several studies have shown age-related changes in the N1–P2 complex, which is generally thought to reflect early perceptual processing (Golob & Starr, 2000; Iragui, Kutas, Mitchiner, & Hillyard, 1993; Merrill & Kobus, 1993). Related to language processing, Bellis, Nicol, and Krauss (2000) have shown that although the N1 component associated with

the auditory processing of syllables was strongly left-lateralized in children and young adults, it was bilaterally distributed in older adults. Of most interest to the present research, results of previous experiments have revealed clear changes in the amplitude, latency, and scalp distribution of later cognitive ERP components, such as the P300 and N400.

The P300 is a positive component that typically shows a centro-parietal scalp distribution with maximum amplitude around 300 msec poststimulus onset. It is thought to reflect “context updating” processes; that is, the processes by which information in working memory is updated as a function of incoming relevant contextual information (Donchin & Coles, 1988). A number of factors are known to influence P300 amplitude, such as stimulus novelty and probability, relevance of the stimulus to the task at hand, and the amount of attentional resources necessary to perform a task (see Kok, 2001; Bashore & Van der Molen, 1991; Johnson, 1988, for reviews). P300 latency is generally considered to be a good measure of the time needed to process and categorize a given stimulus, independently of response-related processes, such as response selection or execution (Duncan-Johnson & Donchin, 1982; Kutas, McCarthy, & Donchin, 1977). Insofar as cognitive slowing is a consequence of aging (e.g., Salthouse, 1996), it has been of interest to examine whether P300 latency changes with age. Results of many studies, reviewed by Polich (1996), showed that this is indeed the case: The latency of P300’s maximum amplitude clearly increases with age (see also Iragui et al., 1993). Finally, it is also important to note that changes in the scalp distribution of the P300 component have been shown to occur with age. Typically, the classic centro-parietal distribution of the P300 found in younger subjects shifts toward a more equipotential or frontal distribution in older subjects, which has been related to age-related changes in frontal lobe function (see Friedman, 2003; Cabeza, 2002, Fabiani & Wee, 2001; Friedman, Kazmerski, & Fabiani, 1997, for an overview).

The N400 is a negative component with maximum amplitude around 400 msec poststimulus onset. It typically shows a centro-parietal scalp distribution in the visual modality and a more frontal or equipotential distribution in the auditory modality. It is thought to reflect semantic integration processes; N400 amplitude is especially large for words that are difficult to integrate within a sentence context because they are semantically unexpected or incongruous (Kutas & Hillyard, 1980; see Besson, Magne, & Regnault, 2004, for review). Although few studies have been aimed at studying age-related changes in the spatio-temporal characteristics of the N400 component, results overall have shown both a reduction in N400 amplitude and an increase in N400 latency (Ford et al., 1996; Iragui, Kutas, & Salmon, 1996; Günter, Jackson, & Mulder, 1995; Harbin et al., 1984). Finally, the scalp distribution of the N400 component does

not seem to vary strongly with age. However, as noted for the P300, the distribution of the N400 effect (i.e., the difference between incongruous/unexpected and congruous/expected words) seems to become more equipotential across scalp sites (e.g., Kutas & Iragui, 1998).

Interestingly, this brief review of ERP findings indicates that changes in scalp topography can potentially reveal important modifications in structural and functional brain organization that may occur with aging. Moreover, such findings are in line with a model recently proposed by Cabeza (2002): the Hemispheric Asymmetry Reduction in Older adults (HAROLD Model). This model states that, under similar circumstances, prefrontal cortex (PFC) activity during cognitive performance tends to be less lateralized in older than in younger adults. Furthermore, Grady et al. (2000) showed that this age-related asymmetry reduction seems to occur not only in the PFC, but also in the temporal and parietal regions. Thus, one aim of our experiment was to determine whether such hemispheric asymmetry reduction would be found in older adult's arithmetic performance.

Neuro-arithmetic

Recent work in cognitive neuropsychology has started to provide a more precise characterization of the functional architecture involved in number processing (e.g., Iguchi & Hashimoto, 2000; Niedeggen & Roesler, 1999; Dehaene & Cohen, 1997; Pauli, Lutzenberger, Birbaumer, Rickard, & Bourne, 1996; Rueckert et al., 1996; Takayama, Sugishita, Akiguchi, & Kimura, 1994; Dehaene, 1992; McCloskey, 1992). For instance, Niedeggen and Roesler (1999) used the ERP method to study how arithmetic facts are stored. They asked their participants to verify multiplication problems for which the proposed solutions were either correct or incorrect. They found that incorrect solutions were associated with larger N400 components than correct solutions. Most importantly, when the incorrect solutions belonged to the same multiplication table as the correct solution (i.e., table-related products), the amplitude of N400 effect (i.e., the difference between incorrect and correct solutions) was proportional to the numerical distance (small or medium) from the correct solutions (i.e., N400 was larger for $6 \times 4 = 32$ than for $6 \times 4 = 28$). In other words, the arithmetic N400 proved to be functionally equivalent to the N400 in language; this may indicate that similar computations may be involved by some aspects of arithmetic and semantic processing.

In a recent study (El Yagoubi et al., 2003), we recorded ERPs during an arithmetic verification task in which young people were presented with problems with two-digit addends (e.g., $37 + 61$) and were asked to decide whether the sum was smaller or larger than 100. The crucial manipulation concerned the size of the split between 100 and correct sums. For small-split problems,

correct sums were close to 100 (by 2% or 5%; e.g., $31 + 67$), whereas for large-split problems, correct sums were far from 100 (by 10% or 15%; e.g., $47 + 63$). As mentioned earlier, some authors have argued, on the basis of behavioral data, that different strategies (exact vs. approximate calculations strategies) are called into play to solve small- and large-split problems (e.g., Duverne & Lemaire, in press; Duverne et al., 2003; De Rammelaere et al., 2001; Pesenti et al., 2000; Allen et al., 1997; Zbrodoff & Logan, 1990; Ashcraft & Battaglia, 1978). The behavioral and ERP data reported by El Yagoubi et al. support this strategy interpretation. ERP differences between small- and large-split problems were found to start as early as 250 msec after the presentation of the second operand, and mainly influenced the P300 and N400 components. Moreover, the mean amplitude differences between small- and large-split problems were larger over the left than the right hemisphere. These differences in the ERPs may reflect the use of distinct cerebral networks for exact and approximate calculation strategies.

In the present study, ERPs and behavioral data were recorded, whereas older adults also performed an inequality verification task. In order to explore potential age-related changes in strategy use, these data were compared with our previous results in younger adults. Based on the literature reviewed above, we first predicted that reaction times (RTs) would be slower and the percentage of errors higher in older than in younger adults. Second, and most importantly, we hypothesized that older adults would be less flexible than younger adults in choosing strategies to perform the task. If older adults tend to use only one strategy to solve inequalities, independently of the size of the split, split effects should be smaller in older than in younger adults. Finally, the hemispheric asymmetry (left hemisphere advantage) reported for younger adults should be reduced (age-related hemispheric asymmetry reduction) in older adults if the phenomenon of age-related hemispheric asymmetry can be generalized to problem-solving tasks.

RESULTS

Behavioral Data

Preliminary analyses revealed similar outcomes for problems with solutions smaller or larger than 100. Therefore, subsequent analyses collapsed over this factor. RTs for correct responses and error rates were determined with analyses of variance (ANOVAs) using mixed design with age (younger vs. older adults) as a between-participants factor and split (small vs. large) as a within-participants factor. Results are presented in Table 1.

Reaction time analyses revealed main effects of age, with older adults being slower overall than younger

Table 1. Mean Reaction Times and Percentages of Errors in Younger and Older Adults for Each Block and Averaged across Blocks for Both Small- and Large-Split Problems

	<i>Younger Adults</i>		<i>Older Adults</i>	
	<i>RT</i> (<i>msec</i>)	<i>% Errors</i>	<i>RT</i> (<i>msec</i>)	<i>% Errors</i>
<i>Small-split</i>				
Block 1	863	6.32	1112	12.06
Block 2	847	7.24	1167	15.24
Block 3	839	6.64	1131	14.76
Block 4	868	7.52	1103	14.64
Mean across blocks	854 (68)	6.93 (0.18)	1128 (87)	14.33 (1.23)
<i>Large-split</i>				
Block 1	692	2.36	911	3.72
Block 2	684	2.29	959	4.06
Block 3	661	2.21	938	3.83
Block 4	675	2.24	896	3.64
Mean across blocks	678 (54)	2.27 (0.14)	926 (76)	3.81 (0.39)
Differences small – large split	176	4.66	202	10.52

SD in parentheses.

adults [1027 vs. 766 msec; $F(1,20) = 17.28$, $MSE = 2,036,341$, $p < .02$], and a main effect of split, with longer RTs for small-split problems than for large-split problems [991 vs. 802 msec; $F(1,20) = 32.25$, $MSE = 148,334$, $p < .04$]. The Age \times Split interaction was not significant ($F < 1$).

Analyses of error rates revealed that older adults made more errors overall than younger adults [9.1% vs. 4.6%; $F(1,20) = 12.64$, $MSE = 528$, $p < .01$]. Small-split problems yielded more errors overall than large-split problems [10.6% vs. 3.0%; $F(1,20) = 5.06$, $MSE = 743$, $p < .01$]. Most interestingly, the Age \times Split interaction was significant [$F(1,20) = 104.02$, $MSE = 616,240$, $p < .01$], with the effect of split being larger for older (10.5% errors) than for younger adults (4.7% errors). This larger split effect stemmed from older adults erring more than younger adults on small-split problems [$F(1,20) = 14.73$, $MSE = 634$, $p < .01$] and equally often on large-split problems ($F < 1$).

Finally, note that to verify that the level of performance was similar across the four blocks of the experiment, ANOVAs were also computed on both RTs and percentage of errors that included age as a between-participant factor and both split (large vs. small) and

blocks (4) as within-participants factors. Results showed that no main effect of blocks or interactions involving the block factor were significant for either RTs or error rates ($F < 1$). Thus, the level of performance was stable across the four experimental blocks.

ERP Data

Grand average ERPs were computed for each age group and compared for small- and large-split problems over the entire recording period (3200 msec), at midline (Figure 1) and lateral electrodes (Figures 2 and 3). As can be seen in Figure 1, N1–P2 complexes are elicited by the warning stimulus, and by the first and second operands. Interestingly, although the ERPs elicited in the two conditions (small- and large-split problems) perfectly overlap until 200 msec post-second operand onset for both younger and older adults, morphological differences can nevertheless be observed within this time range between the two groups. Although the ERP traces return to the baseline after the presentation of the first operand in younger adults, this is not the case for older adults at parietal sites. Moreover, the peak-to-peak amplitude of the N1–P2 complex to the second operand is clearly reduced in amplitude in older compared to younger adults. Then, 250 msec after the second operand onset, the ERPs associated with the resolution of small- and large-split problems start to diverge, with generally larger positivities to large-split than small-split problems. Although this effect is present in both younger and older adults, it is clearly largest and temporally more localized (between 250 and 1000 msec following the onset of the second operand) for younger than older adults.

Table 2 (overall analyses) and Table 3 (breakdown of analyses for each age group) summarize the results of the analyses performed in successive latency bands, corresponding, respectively, to the presentation of the fixation bars (0–300 msec), of the first operand (300–800 msec) and of the second operand. In this last case, five latency ranges of main interest were distinguished, both from visual inspection of the ERP traces and from a comparison with previous results in the literature: 0–250, 250–450, 450–600, 600–900, and 900–2400 msec after the second operand onset (i.e., 800–1050, 1050–1250, 1250–1400, 1400–1700, and 1700–3200 msec, respectively, from the onset of the trial).

From 0 to 300 msec (warning stimulus), ANOVAs showed a main effect of age at midline electrodes [$F(1,20) = 4.95$, $MSE = 350.41$, $p < .04$]: Mean amplitudes in this latency band were larger overall for younger (3.27 μ V) than for older adults (0.44 μ V) (see Table 2 and Figure 1). From 300 to 800 msec (first operand), there were no significant main effects or interactions at either midline or lateral electrodes.

From 800 to 1050 msec (i.e., 0–250 msec latency band after second operand onset), results showed no signif-

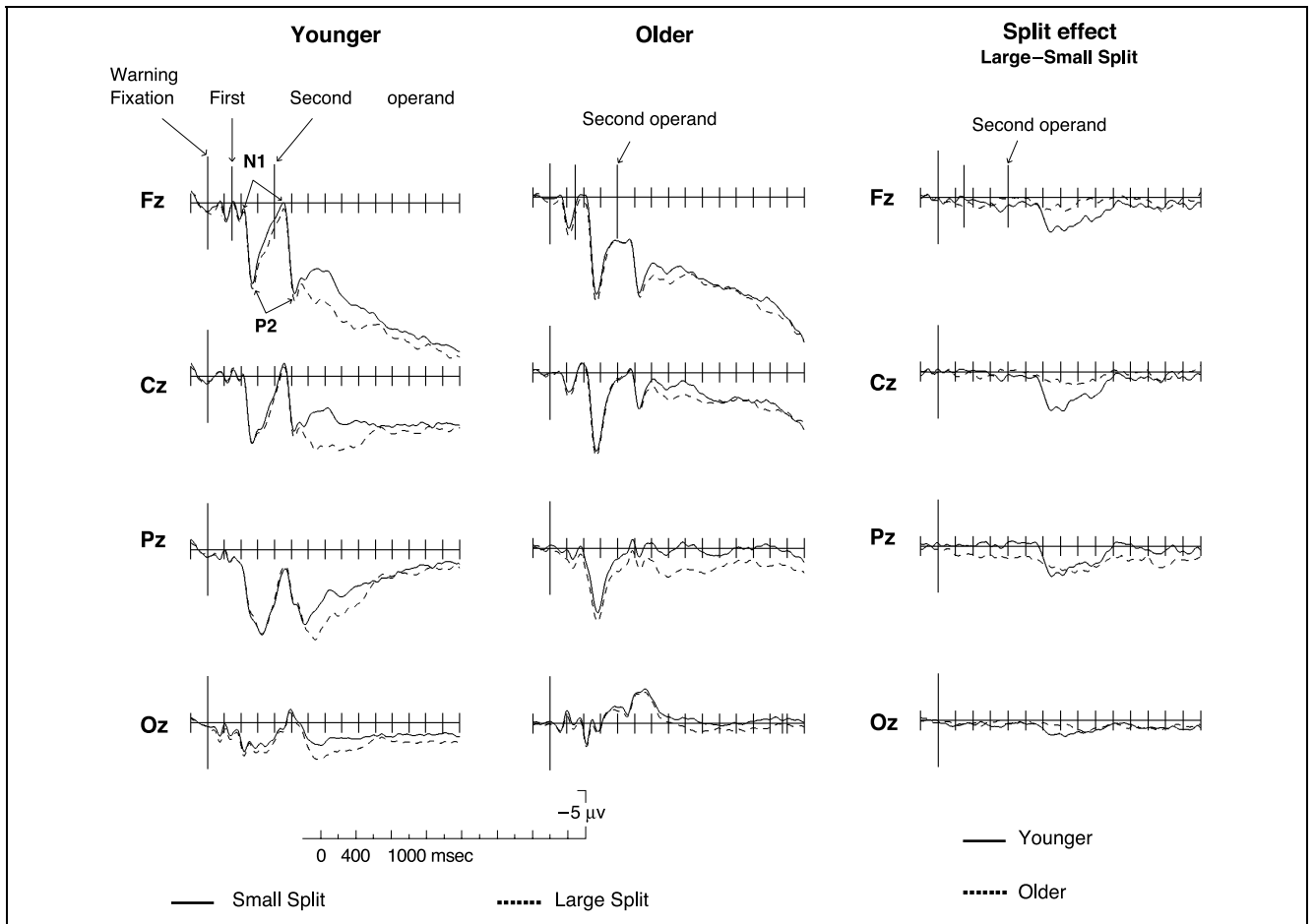


Figure 1. Grand average ERPs recorded from 11 younger adults (left column) and 11 older adults (central column) at midline electrodes (Fz = frontal; Cz = central; Pz = parietal; Oz = occipital). ERPs are compared in two experimental conditions: small-split and large-split problems. The split effect (i.e., the difference between large- and small-split) for younger and older adults is represented in the right column. In this and subsequent figures, amplitude (μV) is represented on the ordinate, with negative voltage up, and time (msec) on the abscissa.

icant main effects or interactions at midline electrodes. At lateral electrodes, neither the main effects of age or split were significant, but the Split \times Localization interaction was significant [$F(2,40) = 5.96$, $MSE = 146.81$, $p < .006$, $\epsilon = .87$]. However, this interaction was not significant in the separate analyses for either younger or older adults (see Table 3).

From 1050 to 1250 msec (i.e., 250–450 msec latency band after the second operand onset), the main effect of age was not significant at midline or lateral electrodes ($F < 1$ in both cases). However, the main effect of split and, most importantly, the Split \times Age interaction were significant both in the ANOVAs including midline electrodes [Split : $F(1,20) = 5.83$, $MSE = 583.13$, $p < .02$; Split \times Age: $F(1,20) = 6.44$, $MSE = 643.44$, $p < .02$] and in the ANOVAs including lateral electrodes [Split: $F(1,20) = 4.92$, $MSE = 1377.56$, $p < .03$; Split \times Age: $F(1,20) = 4.39$, $MSE = 1230.04$, $p < 0.04$].

In order to further analyze the Split \times Age interactions, separate analyses were computed for younger and older adults (see Table 3 and Figures 2 and 3). Results

showed a significant main effect of split for younger adults at both midline [$F(1,10) = 10.31$, $MSE = 1225.83$, $p < .009$] and lateral electrodes [$F(1,10) = 8.17$, $MSE = 2605.51$, $p < .02$]. Moreover, at lateral sites, the Split \times Hemisphere interaction was also significant in younger adults [$F(1,10) = 7.15$, $MSE = 42.50$, $p < .04$]: The ERP differences between small- and large-split problems were larger over the left (4.6 μV) than over the right (2.8 μV) hemisphere. Finally, the Split \times Localization interaction was also significant [$F(2,20) = 4.08$, $MSE = 125.43$, $p < .03$, $\epsilon = .91$], with the split effect being larger over frontal (5.97 μV) than parietal (3.41 μV) regions. By contrast, the main effect of split was not significant for older adults, either at midline or lateral electrodes ($F < 1$), and the Split \times Hemisphere interaction was not significant either ($F < 1$). However, the Split \times Localization interaction was significant [$F(2,20) = 8.76$, $MSE = 125.36$, $p < .02$, $\epsilon = .86$]: In contrast to the results found for younger adults, the split effect was larger over parietal (2.67 μV) than frontal (0.86 μV) regions.¹

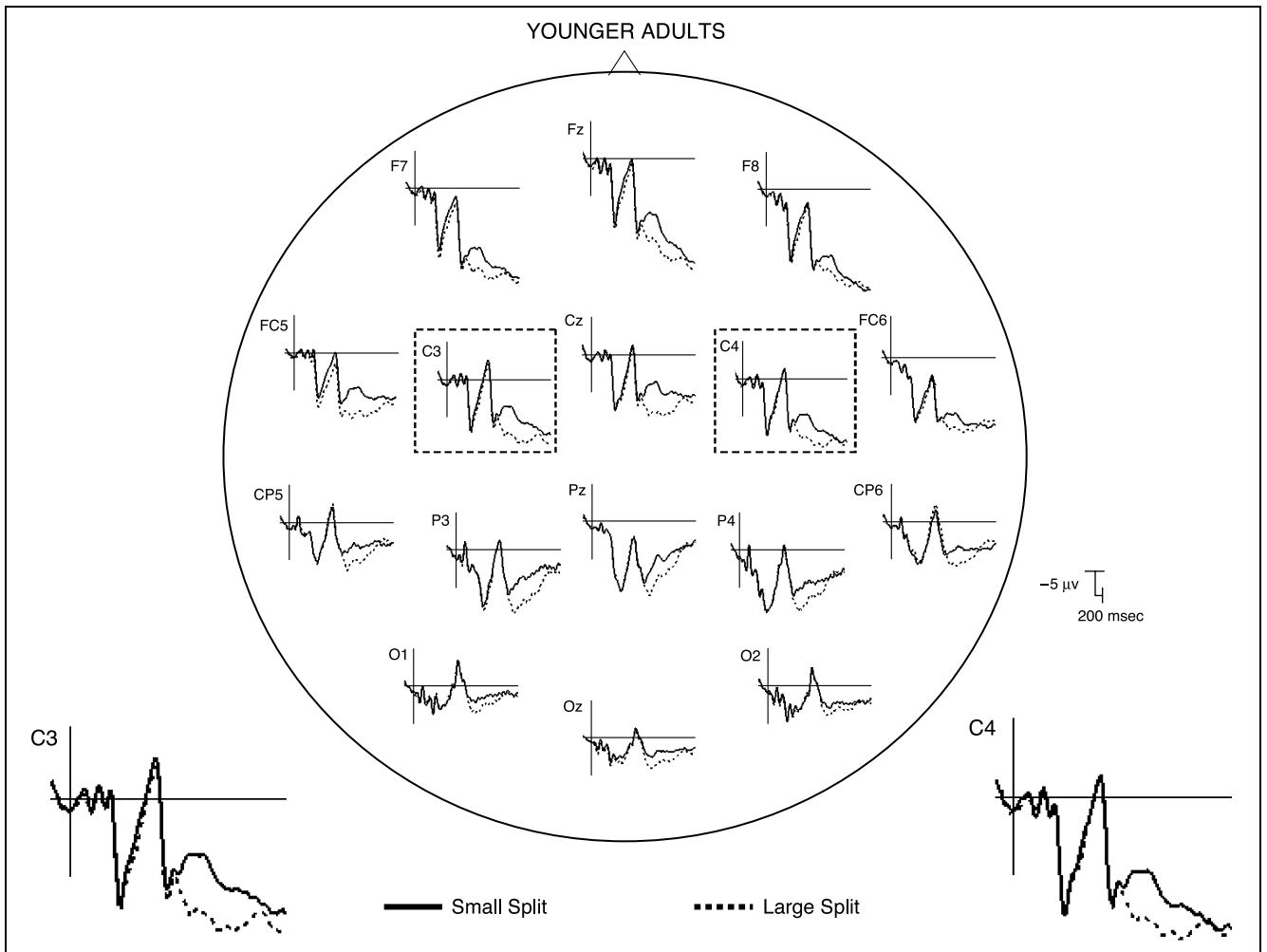


Figure 2. Overlapped are the grand average ERPs, for younger adults (11 participants) to small-split (965 trials) and large-split (1080 trials) problems recorded from 16 selected scalp sites. Recordings from central sites (C3 and C4) are enlarged at the bottom of the figure.

From 1250 to 1400 msec (i.e., 450–600 msec latency band after the second operand onset), the main effect of age was not significant at midline or lateral electrodes ($F < 1$). However, the main effect of split and the Split \times Age interaction were significant at midline electrodes [Split: $F(1,20) = 5.48$, $MSE = 381.20$, $p < .03$; Split \times Age: $F(1,20) = 5.95$, $MSE = 413.96$, $p < .02$]. Separate analyses for younger and older adults showed that although the split effect was still significant for younger adults [$F(1,10) = 8.90$, $MSE = 794.82$, $p < .01$], it was still not significant for older adults ($F < 1$). Moreover, for younger adults, at lateral sites, the Split \times Hemisphere interaction was also significant [$F(1,10) = 5.69$, $MSE = 17.53$, $p < .04$]: The ERP differences between small- and large-split problems were larger over the left (1.9 μ V) than right (0.7 μ V) hemisphere. No such interaction was found for older adults (see Table 3).

Finally, from 1400 to 1700 msec and from 1700 to 3200 msec (i.e., 600–900 msec and 900–2400 msec latency bands after the second operand onset), there were no significant differences between groups and

types of problems at neither the midline nor lateral electrodes (all $ps > .10$).

DISCUSSION

The ERP results revealed two findings that are especially relevant to the issues raised in the introduction. First, the effects of age and split were interactive in both the 250–450 msec and 450–600 msec latency ranges after the second operand onset. Second, in these same latency bands, the effects of split were larger over the left than the right hemisphere for younger adults, but not for older adults. These findings are considered in turn, together with the behavioral data, in the following discussion.

In line with our hypothesis, the Age \times Split interaction was significant. Although the ERPs associated with large and small-split problems differed significantly for younger adults, the ERP split effect was smaller and not significant for older adults. Such differences between the two groups occurred in the expected latency bands

(from 250 to 600 msec post-second operand onset); that is, when participants were performing the cognitive computations needed to solve small- and large-split problems. The fact that these differences were not significant before the second operand was presented, or while the perceptual information triggered by the presentation of the second operand was processed (up to 250 msec post-second operand onset), is consistent with the assumption that participants did not choose different strategies before stimulus onset. Rather, they seem to select the appropriate strategy once the two operands had been presented. However, it should be noted that the main effect of age was significant right at the beginning of the trial, when the warning stimulus was presented. The N1–P2 exogenous complex, which is elicited by the presentation of the warning stimulus and reflects the sensory–perceptual visual encoding stages (e.g., Coles & Rugg, 1995), was smaller in older than in younger adults. This finding is in line with previous results in the literature, showing a general decrease in

the amplitude of ERP component with aging (e.g., Bellis et al., 2000; Golob & Starr, 2000; Iragui et al., 1993; Merrill & Kobus, 1993).

We have argued previously that the significant split effect found in the ERPs of younger adults, manifesting itself in increased positivity to large-split problems (or in increased negativity to small-split problems), is consistent with the hypothesis that different strategies are used to solve large- and small-split problems (e.g., El Yagoubi et al., 2003). Following a similar line of reasoning, the finding that the split effect was smaller and not significant in the 250–450 msec latency band in older adults is in line with the hypothesis that they used only one strategy to solve both types of problems. Thus, regardless of the size of the split, older adults may always perform a similar set of computations to solve the problems. Interestingly, for younger adults, the ERPs elicited by small- and large-split problems are both qualitatively and quantitatively different; although a negative component is associated to the resolution of small split

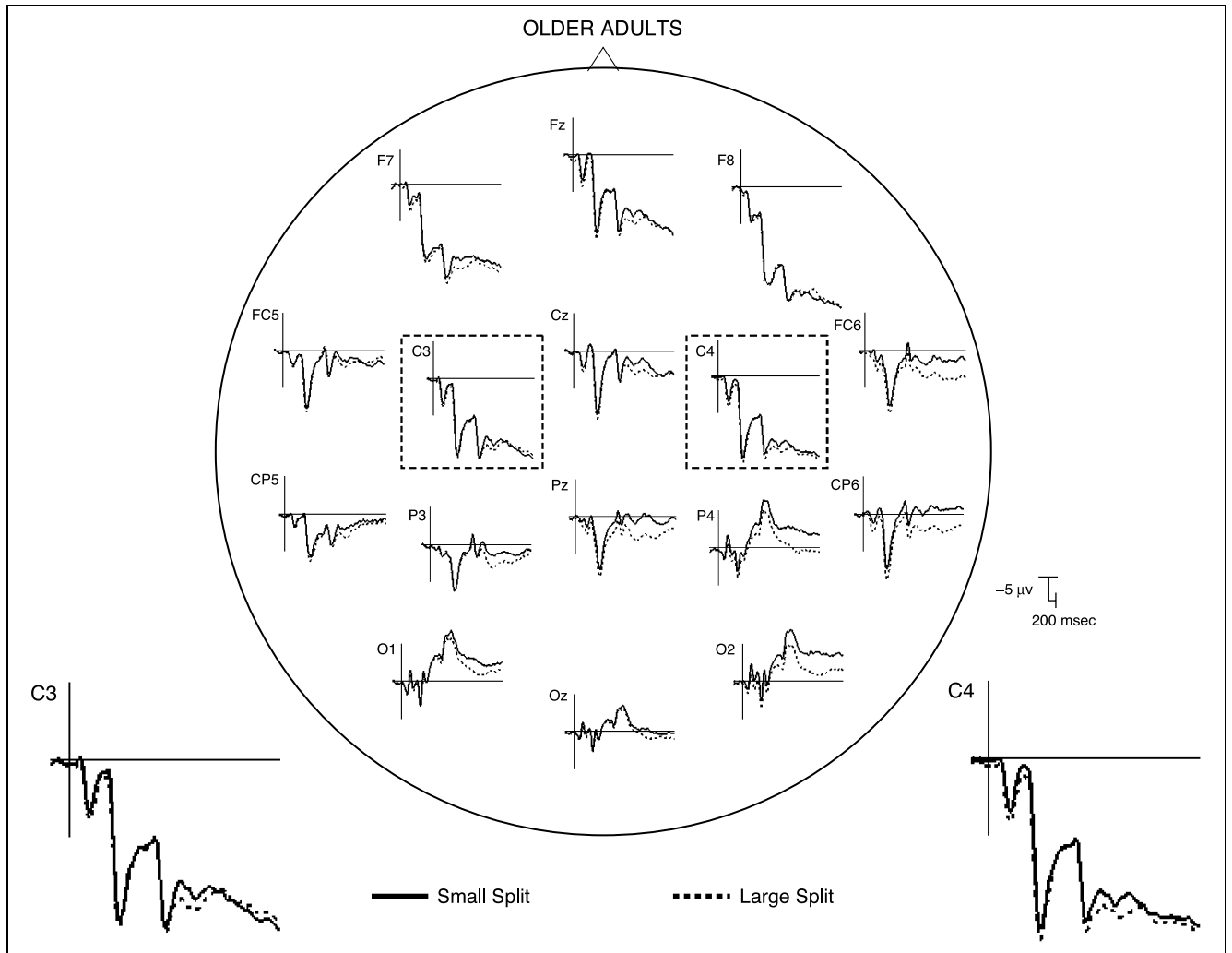


Figure 3. Overlapped are grand average ERPs for older adults (11 participants) to small-split (827 trials) and large-split (931 trials) problems recorded from 16 scalp selected scalp sites. Recordings from central sites (C3 and C4) are enlarged at the bottom of the figure.

Table 2. Summary of Results Regarding the Effects of the Different Factors in the Different Latency Ranges for Midline and Lateral Electrodes

Latency Bands	Midline							Lateral								
	X	A	B	XA	XB	AB	XAB	X	A	XA	XC	AC	XAC	XD	AD	XAD
0–300 msec	+	–	+	–	–	–	–	–	–	–	–	–	–	–	–	–
300–800 msec	–	–	+	–	–	–	–	–	–	–	–	–	–	–	–	–
800–1050 msec	–	–	+	–	–	–	–	–	–	–	–	–	–	–	+	–
1050–1250 msec	–	+	+	+	–	–	–	–	+	+	–	–	–	–	+	–
1250–1400 msec	–	+	+	+	–	–	–	–	–	–	–	–	–	–	–	–
1400–1700 msec	–	–	+	–	–	–	–	–	–	–	–	–	–	–	–	–
1700–3200 msec	–	–	+	–	–	–	–	–	–	–	–	–	–	–	–	–

Note: + = significant effects ($p < .05$); – = nonsignificant effect; X = age, A = split; B = electrodes; C = hemisphere; D = localization.
 0–300 msec: warning-fixation stimulus; 300–800 msec: first operand display; second operand was shown 800 msec after warning stimulus onset.

problems, a positive component is associated to large split problems. The relative increase in negativity elicited by small-split problems is possibly related to the N400-like component reported by Niedeggen and Roesler (1999) and Niedeggen et al. (1999). By contrast, for older adults, the ERPs to small- and large-split problems are both quantitatively and qualitatively similar, and the split-effect is not significant.

Previous results in the literature have shown that older adults may be less flexible than younger adults in the choice among strategies used to perform the task at hand (e.g., Duverne & Lemaire, in press; Duverne et al., 2003; Lemaire & Lecacheur, 2001). Furthermore, previous studies on children indicate that they become more and more flexible and adaptive as they grow older (e.g., Lemaire & Siegler, 1995; Geary & Burlingham-

Table 3. Summary of Results for Younger and Older Adults and for Each Factor in the Different Latency Ranges at Midline and Lateral Electrodes

Age Groups	Latency Bands	Midline			Lateral							
		A	B	AB	A	C	AC	D	AD	CD	ACD	
Younger	0–300 msec	–	–	–	–	–	–	–	–	–	–	–
	300–800 msec	–	–	–	–	–	–	–	–	–	–	–
	800–1050 msec (0–250)	–	+	–	–	–	–	+	–	–	–	–
	1050–1250 msec (250–450)	+	+	–	+	–	+	+	+	–	–	–
	1250–1400 msec (450–600)	+	+	–	–	–	+	–	–	–	–	–
	1400–1700 msec (600–900)	–	+	–	–	–	–	+	–	–	–	–
	1700–3200 msec (900–2400)	–	+	–	–	–	–	+	–	–	–	–
Older	0–300 msec	–	–	–	–	–	–	–	–	–	–	–
	300–800 msec	–	+	–	–	–	–	–	–	–	–	–
	800–1050 msec	–	+	–	–	–	–	+	–	–	–	–
	1050–1250 msec	–	+	–	–	–	–	+	+	–	–	–
	1250–1400 msec	–	+	–	–	–	–	+	–	–	–	–
	1400–1700 msec	–	+	–	–	–	–	+	–	–	–	–
	1700–3200 msec	–	+	–	–	–	–	+	–	–	–	–

Note: + = significant effects ($p < .05$); – = nonsignificant effect; A = split; B = electrodes; C = hemisphere; D = localization.
 0–300 msec: warning-fixation stimulus; 300–800 msec: first operand display; second operand was shown 800 msec after warning stimulus onset.

Dubree, 1989). Thus, it is tempting to speculate that there would be gradual changes from low cognitive flexibility in early childhood to large cognitive flexibility in late childhood and adulthood, with a reversal during aging.

Such tentative conclusions on the basis of ERP data should, however, be further considered in light of the behavioral data. As expected from results in the literature using other cognitive tasks (e.g., Salthouse & Coon, 1994; Geary, Frensch, & Wiley, 1993), our results revealed that older adults were slower and made more errors in the inequality verification task than younger adults. The two most important findings are as follows: First, the split effect on RT and error rate measures was significant for both younger and older adults and second, on error rates, the split effect was larger, rather than smaller, for older (10.5%) than younger adults (4.7%). Therefore, from these results, it is tempting to conclude that older adults, like younger adults, were using two different strategies to solve small- and large-split problems.

One way to reconcile the seemingly conflicting conclusions on the basis of ERP and behavioral data is to consider that split effects in older adults' behavioral measures are not the result of their use of two different strategies. Rather, split effects in older adults may stem from using exact calculation strategies on both small- and large-split problems. Executing exact-calculation strategy would take more time and generate more errors on harder problems (i.e., small-split problems) than on easier, large-split problems. Indeed, some processes within the exact-calculation strategy are harder to trigger and execute when operating on harder problems. Comparison between proposed and correct answers is one potential source of difficulty. It is indeed well known in arithmetic that comparing small-distance numbers (e.g., which is smallest, 8 or 9) takes more time and generates more errors than comparing large-distance numbers (e.g., 3 or 8); (e.g., Dehaene, 1996). Interestingly, detailed analyses of the error data revealed that although the percentage of errors was very similar for older (3.8%) and younger adults (2.3%) on large-split problems, it was almost twice as large for older (14.3%) than younger adults (6.9%) on small-split problems. Thus, these results are in line with previous results showing that aging has a greater effect on processes that are cognitively more demanding; this is often seen in an Age \times Complexity interaction on either latencies or error rates or both (see Park & Schwarz, 2000, for reviews in different cognitive domains). Here, this Age \times Complexity interaction was only seen in error rates, as an Age \times Split interaction. A simple effect of complexity, or split, was seen in RTs. It is possible that older adults sought to maintain high level of speed in the present task, as they were pressed to, slightly sacrificing accuracy on harder, small-split problems. An alternative hypothesis to account for the split effects in older adults is to assume

that they used an additional time-consuming, double-checking process when verifying small-split problems. However, this should yield a higher level of accuracy, which was not observed here. Finally, it is of interest to note that older adults were clearly able to perform the task at hand, and to maintain concentration for the entire duration of the experiment (4 blocks of 7 min each). Indeed, analyses of the level of performance within each block showed that both RTs and error rates measures were very stable across the four blocks of the experiment.

The second finding of interest is related to differences in scalp distribution of split effects between younger and older adults. Indeed, the present analyses revealed that, for younger adults, split effects were larger over the left than the right hemisphere, in both the 250–450 msec and 450–600 msec latency bands following the second operand onset. As discussed previously by El Yagoubi et al. (2003), this hemisphere asymmetry in problem-solving is consistent with Dehaene and Cohen's model of number processing (e.g., Dehaene & Cohen, 1991, 1997). Based on the study of the patient N. A. U., who showed a double dissociation between exact and approximate calculations, these authors have proposed that different cerebral networks are involved, depending upon the type of strategy used to solve problems. Thus, whereas exact calculation is more likely to involve language areas in the left hemisphere, approximate calculation is more likely to activate cerebral pathways bilaterally. Recent results by Stanescu-Cosson et al. (2000) also point in the same direction; in their ERP and functional magnetic resonance imaging (fMRI) study, volunteers performed exact and approximation calculation tasks with small and large numbers. ERP results showed a significant difference between exact and approximate calculations as early as 200–300 msec following problem presentation, and ERPs were also influenced by number size. fMRI results showed bilateral intraparietal, precentral, dorsolateral, and superior prefrontal region activation during approximation, whereas the left inferior PFC and the bilateral angular regions were more activated during exact calculation (see also Pesenti, Zago, et al., 2001; Pinel, Dehaene, Rivière, & LeBihan, 2001; Pesenti, Thioux, et al., 2000; Stanescu-Cosson et al., 2000; Dehaene & Cohen, 1991, 1997; Dehaene, 1996).

It is also of interest to note that the fine-grained temporal analyses computed here allowed us to show that in the earliest latency band (250–450 msec post-second operand onset), the split effect was not only left-lateralized, but it was also larger over frontal than parietal regions (see Figure 4; 1000–1200 msec latency bands). This last finding is consistent with others in the functional brain imaging literature showing prefrontal activity in different cognitive tasks using both verbal and nonverbal materials (e.g., Dolcos, Rice, & Cabeza, 2002).

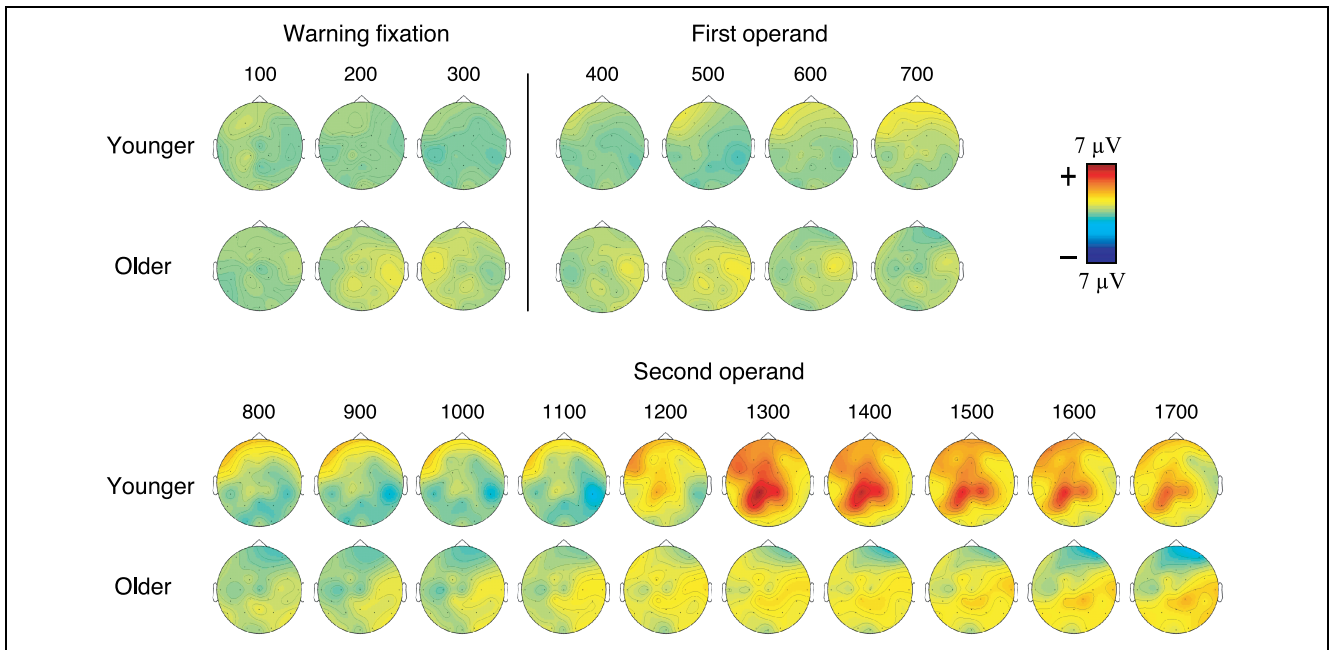


Figure 4. For both younger and older adults, scalp potential maps were computed from the difference waveforms (large-split minus small-split problems) in successive 100-msec latency bands from the beginning of the trial (warning-fixation onset) until 1700 msec, that is, until 900 msec after the onset of the second operand (at 800 msec from trial onset).

Contrary to the results for younger adults, the Split \times Lateralization interaction was not significant in older adults in either of the two latency bands of main interest (250–450 and 450–650 msec). Interestingly, however, the Split \times Localization interaction was significant in the earlier latency band (250–450 msec). However, in contrast to what was found for younger adults, the split effect was largest over parietal regions, which again is consistent with other results showing age-related reduction in frontal lobe activity (e.g., Cabeza et al., 1997; Whelihan and Leshner, 1985), but may be in contrast with results showing a more frontal distribution of the P300 in older adults (see Friedman, 2003; Fabiani & Wee, 2001). However, taken together, the observed differences (left lateralization and fronto-parietal distribution) in the scalp topography of the split effect between younger and older adults are in line with previous findings in the ERPs and aging literature, demonstrating a more equipotential distribution of the P300 and N400 components in older than in younger adults (e.g., Friedman, 2003; Fabiani & Wee, 2001; Kutas & Iragui, 1998; Friedman et al., 1997). Moreover, they add support to the HAROLD model, developed by Cabeza and colleagues (e.g., Cabeza, 2002; Dolcos et al., 2002), according to which frontal activity during cognitive tasks tends to be less lateralized in older than in younger adults. These results also extend the validity of the HAROLD model to a cognitive domain, arithmetic, in which to our knowledge, it has never been tested before.

The functional significance of such changes in brain activity localization with aging is still a matter of debate

(e.g., Cabeza, 2002; Dolcos et al., 2002). From a cognitive perspective, they may reflect differences in the cognitive strategies used to perform the task. Thus, in the present experiment, differences in the scalp topography of the split effects may be linked to the use of two strategies, exact and approximate calculations, for younger adults, but only one strategy, exact calculation, for older adults. Following a neurophysiological perspective, the asymmetry reduction found for the older adults performing the present task may reflect a compensatory effect, with the less efficient processing of one hemisphere being compensated by the involvement of both hemispheres to perform the same task. It may also reflect some changes in neural architecture, with different neural networks being activated in older than in younger adults. Finally, it may be linked to a dedifferentiation of the processes required to perform a task, so that different functions would rely on similar resources (see Dolcos et al., 2002). Although the present data do not allow us to disentangle these different possibilities, future experiments using a similar design and the fMRI method should provide interesting information to address these issues.

METHODS

Participants

After giving informed consent, 14 older adults were tested in this experiment, which is part of a larger project approved by the local ethical committee in

Marseille. Because of a large number of artifacts, the data from three participants were excluded from the grand ERP averages. Thus, a total of 11 older adults (4 men and 7 women, mean age 67.10 years; range = 61.2–82.3 years) were tested individually in a session that lasted for about 2 hr. These data were compared to those obtained from 11 young adults (6 men and 5 women, mean age 23.6 years; range = 19.4–32.7 years) tested previously.² Younger and older people were matched on the number of years of formal education (>12 years). All were right-handed, neurologically normal (none of the participants were under specific medication), and had normal or corrected-to-normal vision (as controlled for at the beginning of the experiment). All participants were paid for their participation. All older adults took the Mini-Mental State Examination (MMSE; Folstein, Folstein, & MacHugh, 1975) for potential dementia screening. All individuals had scores higher than 27 (mean 29.6) and, therefore, none were excluded from the study.

Stimuli

The stimuli were 240 arithmetic problems (i.e., addition), presented in a standard form (i.e., $a + b$) with the operands a and b being two-digit numbers. Numbers were displayed at the center of a computer screen (SVGA color computer screen, placed 60 cm in front of the participant), and participants were asked to decide whether or not the result of the addition was smaller than 100. Results were smaller than 100 (e.g., $31 + 67$) for half the problems, and larger than 100 (e.g., $29 + 73$) for the other half. Inequalities were constructed to create two experimental conditions, depending upon the size of splits between 100 and the correct sums: (a) for small-split problems, correct sums were $\pm 2\%$ or $\pm 5\%$ away from 100 (e.g., $37 + 61$; $29 + 76$), and (b) for large-split problems, correct sums were $\pm 10\%$ or $\pm 15\%$ away from 100 (e.g., $38 + 72$; $18 + 67$).

Based on previous findings in arithmetic, problems were selected according to several constraints in order to avoid a number of potential confounds (see Dehaene, 1997; Ashcraft, 1995; Geary, 1994, for reviews). First, the order of the operands was controlled so that the first operand was larger (e.g., $62 + 36$) in half of the problems. Second, no operand had a unit digit equal to 0 or 5 (e.g., Lemaire & Reder, 1999; Campbell, 1994). Third, no problems had operands with the same unit digit (e.g., $28 + 78$). Finally, we presented an equal number of problems with two even operands (e.g., $36 + 62$), with two odd operands (e.g., $31 + 59$), and with one even operand (e.g., $43 + 52$).

Procedure

Participants were comfortably seated in a Faraday box and were instructed to solve the problems mentally, as

quickly and accurately as possible. They were asked to press the “YES” button if the sum was smaller than 100, and the “NO” button if the sum was larger than 100. Response hands were counterbalanced across participants. The set of 240 problems was divided into 4 blocks of 60 problems each, with an equal number of correct and incorrect solutions within each block. The order of blocks was counterbalanced across participants, and the type of problem (small vs. large split) was randomized for each participant within each block. Each block of trials lasted approximately 7 min, and short rest periods were provided between blocks. To familiarize participants with the task, the experiment started with a practice session including 16 problems with a similar structure, but different from the experimental problems. During the intertrial interval (ITI) of the practice session, participants heard auditory feedback when they responded incorrectly.

All stimuli were displayed in white on a black background. The visual angle was 3.34° . The sequence of events within a typical trial was as follows (see Figure 5). A warning-fixation stimulus was displayed at the center of the screen for 300 msec, followed by the first operand, displayed for 500 msec. Then, the second operand replaced the first operand on the screen and remained until the participant responded. A clock began timing when the second operand appeared and stopped when the participant pressed one of the two response buttons. Participants were given 2200 msec from second operand onset to give their answers. The ITI, lasting for 2000 msec, followed the participant’s response. During the ITI four Xs appeared at the center of the screen to inform participants that they could blink and move their eyes. Participants were asked to refrain from moving (except for the button press response) and blinking during the critical phase of EEG recording.

Data Acquisition and Analyses

EEG was recorded for 3200 msec, starting 200 msec before the onset of the warning signal (baseline) until a row of XXXX appeared on the screen, from 28 scalp electrodes mounted on an elastic cap and located at standard left and right hemisphere positions over frontal, central, parietal, occipital, and temporal areas (Inter-

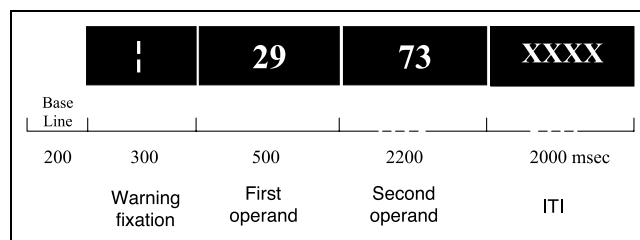


Figure 5. Sequence of events within a trial of the arithmetic verification task.

national 10/20 System, at Fz, Cz, Pz, Oz, Fp1, Fp2, F3, F4, C3, C4, P3, P4, O1, O2, F7, F8, T3, T4, T5, T6, Fc5, Fc1, Fc2, Fc6, Cp5, Cp1, Cp2, and Cp6). These recording sites plus an electrode placed over the right mastoid were referenced to the left mastoid electrode. The data were re-referenced off-line to the algebraic average of the left and right mastoids. Impedances of these electrodes never exceeded 3 k Ω . The horizontal electrooculogram (EOG) was recorded from a bipolar montage with electrodes placed 1 cm to the left and right of the external canthi; the vertical EOG was recorded from an electrode beneath the right eye, referenced to the left mastoid, to detect blinks and vertical eye movements. The EEG and EOG were amplified by an SA Instrumentation amplifier with a band pass of 0.01–30 Hz, filtered for 50 Hz and were digitized at 250 Hz by a PC-compatible microcomputer (Compaq Prosignia 486). Trials containing ocular artifacts, movement artifacts, or amplifier saturation were excluded from the averaged ERP waveforms (approximately 15% of the trials).

ERP data were analyzed for correct responses only by computing the mean amplitude in selected latency windows relative to a 200-msec baseline. ANOVAs were used for all statistical tests. ANOVAs were conducted separately for midline and lateral electrodes. ANOVAs for midline electrodes used a mixed design with age (younger vs. older adults) as a between-participants factor, and split (small vs. large) and electrodes (Fz, Cz, Pz, Oz) as within-participants factors. ANOVAs for lateral electrodes also used a mixed design with age as a between-participants factor, and split (small vs. large), hemispheres (left vs. right), localization (3 regions of interest [ROIs]: frontal, central, and parietal), and electrodes (3 for each ROI with frontal including: F3, F7, FC1 and F4, F8, FC2; central including: C3, FC5, T3 and C4, FC6, T4; parietal including: CP1, CP5, P3 and CP2, CP6, P4) as within-participants factors. Results regarding the effects of main interest (i.e., main effects of age and split) are always reported. The interactions between the effects of these factors, as well as the results of separate analyses for younger and older adults, are reported only when significant. In this report, unless otherwise noted, differences were considered significant at $p < .05$. Topographic maps were computed using ICA (scn.ucsd.edu/scott/ica.html) (e.g., Delorme & Makeig, 2004).

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Notes

1. ANOVAs were also computed in successive 100-msec latency bands from the second operand onset. Results confirmed that the earliest time window in which the main effect of split was significant is the 1000–1100 msec range (200–300 msec from the second operand onset). This effect lasted until 1400–1500 msec. The Age \times Split interaction was significant both in the 1100–1200 msec and the 1200–1300 msec latency windows.
2. The data from 12 young adults were analyzed in our previous experiment (El Yagoubi et al., 2003). Thus, in order to compare the data from the 11 older adults tested here with an equal number of younger adults, the data from one younger adult, chosen randomly, were excluded from the present analyses.

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