



Published in final edited form as:

Neuropsychologia. 2009 February ; 47(3): 796–803. doi:10.1016/j.neuropsychologia.2008.12.009.

Knowing We Know Before We Know: ERP Correlates of Initial Feeling-of-Knowing

Christopher A. Paynter, Lynne M. Reder, and Paul D. Kieffaber
Carnegie Mellon University

Abstract

Subjects performed a rapid feeling-of-knowing task developed by Reder and Ritter (1992), while event-related potentials (ERPs) were recorded to identify the time course of “feeling-of-knowing” signals. Subjects were shown a series of math problems, some of which were repeated multiple times during the course of the experiment, and subjects had to rapidly decide whether the answer to a given problem could be quickly retrieved from memory (retrieval trials) or had to be calculated on scrap paper (calculate trials). Behavioral results replicated the 1992 study, showing that subjects can estimate whether the answer is known much faster than the answer can be retrieved. ERPs time-locked to the onset of the math problem showed that accurate retrieval trials were associated with greater positivity for an early frontal P2 component (epoching from 180–280 ms) and a frontal-central P3 component (epoching from 300–550 ms). Moreover, this feeling-of-knowing signal was not found for subjects who never obtained a successful on-time retrieval. We interpret these findings as suggesting that initial feeling-of-knowing relies on a rapid assessment of the “perceptual fluency” with which the stimulus is processed. If a stimulus is deemed sufficiently familiar, the activation level of an internal problem representation is used to arrive at a decision of whether to search for the answer or to calculate it.

Keywords

feeling-of-knowing; metacognition; arithmetic; ERP; EEG; P200

Task performance frequently involves selection among multiple strategies that could potentially lead to a correct response (Anderson & Lebiere, 1998; Reder, 1982; Reder, 1987; Siegler, 1996). People not only select among available strategies but also shift quickly and adaptively from one strategy to another depending on their cognitive abilities or features of the task environment (Lovett & Anderson, 1996; Reder, 1988; Reder & Ross, 1983; Reder, Wible, & Martin, 1986; Schunn & Reder, 2001; Schunn, Lovett & Reder, 2001). For people to select among strategies as quickly as they do, it is necessary that they possess heuristics that can be rapidly executed. Reder (1987) postulated that when deciding how to answer a question, people might use the familiarity of the question features to decide whether it is likely that the answer is known and that it is worthwhile to initiate a search of memory. Consistent with that conjecture, subjects were able to make a binary decision as to whether the answer to a general-knowledge question was likely to be known in considerably less time than they could begin

Correspondence: Christopher A. Paynter, Psychology Department, Carnegie Mellon University, 5000 Forbes Avenue, Pittsburgh, P.A. 15213, Phone: 412.268.4191, Fax: 412.268.2844, E-mail: cpaynter@andrew.cmu.edu.

Publisher's Disclaimer: This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final citable form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

articulating the answer itself, suggesting the heuristic could indeed influence the tendency to initiate a search (Reder, 1987).¹ Although a generally good predictor of answer availability, the heuristic was shown to be imperfect and could be subverted by inducing spurious feelings of familiarity with pairs of terms in the question (Jameson, Narens, Goldfarb, & Nelson, 1990; Reder, 1987).

Reder and Ritter (1992) conducted a further examination of the initial feeling-of-knowing (hereafter abbreviated FOK) heuristic in a task in which subjects were shown a series of unfamiliar math problems (e.g. 24×36), some of which were repeated many times over the course of the experiment. Subjects were required to respond in less than 850 ms whether or not they knew the answer. If “retrieve” was selected, the subject then had to quickly retrieve the answer. If “calculate” was selected, the subject had substantially longer to calculate the answer by hand. There was a monetary incentive to choose “retrieve,” but only if the correct answer could be given on time. Subjects performed this task with high accuracy. However, problems that looked similar but for which the answer was unknown resulted in spurious feelings-of-knowing. The conclusion of that study and a follow-up (Schunn, et al., 1997) is that people can rapidly assess whether they are likely to know the answer, but the assessment is not based on an early read of the answer. Instead, it is based on a partial match to the representation of a previously seen problem.

The current study adopts the paradigm of Reder and Ritter (1992) while measuring ERPs to identify possible neural correlates of the initial FOK heuristic. We are unaware of any ERP studies on FOK. This paper should thus provide novel insight into the temporal dynamics of an important metacognitive process. Of particular interest is whether ERP components can be found that distinguish between the rapid strategy choice of whether to attempt to retrieve or rely on calculation, and if so, how early these components are observed following the appearance of the problem. If ERP correlates of FOK are found, they should signal a heuristic that is used to decide whether to search for the answer. We do not expect these ERP correlates to be a perfect predictor of whether the answer is known because the judgments themselves are imperfect. However, since we expect the FOK signal to be based on identification of familiar problems, the recognition memory literature should prove relevant.

There is already an extensive literature on the ERP correlates of familiarity and recollection-based recognition, which can provide a useful guide as to how fast the FOK correlate could be expected to occur. The general consensus emerging from this literature is that familiarity-based processes are associated with frontal activity in the 300–500 ms time window, while recollection-based processes are associated with parietal activity in the 400–800 ms time window (Curran, 2000, 2004; see Rugg & Curran, 2007 for a review). Thus, if the FOK component emerges comparatively early (e.g. 300–500 ms), the result will provide evidence that initial FOK is indeed a familiarity-based effect. If, on the other hand, the FOK component is associated with late activation (emerging only after 400 ms), this would suggest reliance on a different mechanism, such as recollection of having seen the problem or partial retrieval of the answer.

Our study should also prove relevant to research on conscious intentionality. There is evidence that there can be an appreciable delay before a stimulus enters conscious awareness (see Libet, 2003 for a review). One early study (Libet, Alberts, Wright, Lewis, & Feinstein, 1975) used a paradigm in which electrical stimulation of somatosensory cortex was followed by physical stimulation of the skin. The subject’s task was to decide which stimulus came first.

¹Prior to Reder’s work on strategy selection, the term “feeling-of-knowing” (FOK) had referred to subjects’ ability to accurately predict, after a memory retrieval failure, whether the correct answer could be recognized (Hart, 1965). Most FOK studies have adopted a variant of Hart’s paradigm. Reder’s use of the same term may have created confusion in terminology.

Surprisingly, subjects reported that the skin stimulus occurred first even when it followed the cortex stimulation by up to 500 ms. This led to the conclusion that it takes several hundred ms for a stimulus to fully enter conscious awareness, at which time subjects backdate their estimate of when the stimulus occurred based on the onset of the early sensory components.² More recent work has shown that seemingly “free” decisions by subjects can sometimes be predicted from brain activity occurring as much as 10 seconds before the decision enters awareness (Soon, Brass, Heinze, & Haynes, 2008). These studies are consistent with the view that unconscious processes play a critical role in rapid FOK judgments. Other research has also suggested that metacognitive processes need not rely on conscious awareness (Cary & Reder, 2002; Nhouyvanisvong & Reder, 1998; Reder, 1996; Reder & Schunn, 1996; Spehn & Reder, 2000). Finding a very early ERP correlate of FOK decisions would further support this position.

Although we are aware that the ERP methodology contains inherent difficulties in localization, we believe there is still something to be gained by noting the approximate site where an ERP signal is strongest. Based on the available literature, we believe the most likely location from which an FOK correlate would emerge would be the frontal lobes, as there is extensive support in the literature for the idea that memory-monitoring processes in general are primarily dependent on this area (Fernandez-Duque, Baird, & Posner, 2000; Pannu & Kaszniak, 2005; Shimamura, 2000; Simons & Spiers, 2003). Studies of Alzheimer’s patients (Duke, 2001) and dysexecutive patients (Pinon, Allain, Zied Kefi, Dubas, & Le Gall, 2005), both of whom suffer primarily from damage to the frontal lobes, find that these patients are impaired (compared to healthy controls) in their ability to accurately predict whether they will later recognize an item that they have failed to retrieve. This provides further evidence for frontal involvement in metamemory. Thus, if it turns out that the ERP correlates of *initial* FOK (see footnote 1) suggest an origin in the frontal lobes, it would support the notion that the very rapid, initial FOK examined in this study relies on similar cognitive and neural processes as those used for other memory-monitoring tasks.

Method

Participants

Participants were 18 males and 17 females, with a median age of 21, who were recruited from the campus community. They received compensation of fifteen dollars plus a bonus of up to fifteen additional dollars that depended on performance. The average compensation was \$21.11. Fifteen participants who were CMU students also received research credit in addition to being paid.

Design/Materials

The experiment consisted of 180 regular trials and 32 filler trials.³ Half of the problems in the experiment used the multiplication operator, while the other half used a novel operator called *sharp*. By the end of the experiment, subjects found the sharp operator slightly easier than multiplication. The answer to a sharp problem was calculated by taking the sum of the tens

²We should note as a caveat that this experiment used stimuli that could only just be detected, and that more intense stimuli are believed to enter awareness somewhat more quickly (the precise minimum time needed for a stimulus to enter awareness has not been firmly established) (Libet, 2003). Nevertheless, a finding that the ERP correlates of FOK emerge well before 500 ms, would provide evidence that information exists in the brain as to which strategy will be chosen even before subjects have become aware of the stimulus.

³The filler trials consisted of two additional classes of problems. These classes were the “swap” problems, which were problems that used the operands of a previously seen problem but with a different operator, and the “rare-operand” problems. In the study design, the numbers 13, 37, 38, and 39 were set aside to appear in only a small number of special “rare-operand” problems to see how subjects would respond to a problem with particularly low familiarity. Sixteen “swap” problems and 16 “rare-operand” problems were included out of a total of 212 problems. These trials were included in the study in order to keep the design as close as possible to the original Reder and Ritter (1992) study and to ensure that there were still problems late in the experiment that had never been seen previously. The filler problems will not be discussed further because there were not enough to analyze using ERP.

place digits for the two operands, multiplying this number by the sum of the ones place digits, and multiplying this product by three. (For example, $24 \# 16$ would be equal to $(2 + 1) * (4 + 6) * 3$, which would equal 90). Subjects were told to give only the last two digits of the problem answer.

The design varied the frequency of presentation of the top and bottom operands. The 180 trials were created from four different sets of 45 trials, following the design shown in Figure 1. Each set of 45 trials contained four unique problems of different frequencies. The upper branches in Figure 1 reflect the number of presentations per set of a problem with a high-frequency top operand versus a low-frequency one. The lower branches further subdivide this by whether a high or low-frequency bottom operand was used. This means that in each set of 45 trials, there was one problem that used a high-frequency top operand and high-frequency bottom operand that appeared twenty times, one problem that used a high-frequency top operand and low-frequency bottom operand that appeared ten times, one problem that used a low-frequency top operand and high-frequency bottom operand that appeared ten times, and a final problem that used a low-frequency top operand and low-frequency bottom operand that appeared five times.

The four rows of letter-operator-letter “problems” listed at the bottom of the figure reflect the templates used for the different problem conditions. The numbers between 14 and 36, excluding those that are divisible by five,⁴ were used as problem operands. In each problem set, four of these numbers were randomly assigned without replacement to be high-familiarity top operands, four to be low-familiarity top operands, four to be high-familiarity bottom operands, and four to be low-familiarity bottom operands.

Procedure

Prior to the start of the experiment, participants were given a set of sixteen practice problems, which they were asked to work out by hand while the impedances on the cap were adjusted. Half of these problems used ordinary multiplication, while the other half used the novel sharp operator that had been employed in the Reder and Ritter (1992) study. Participants were also given pieces of scrap paper on the side to calculate the answers to problems by hand during the experiment. They were instructed to put each piece of scrap paper face down in a box after they had used it for a problem to ensure that they could not refer to the scrap paper later in the experiment. Subjects were instructed to minimize blinks and head movements, especially at the time when a new problem first appeared. An additional series of fourteen practice problems were presented on the computer prior to the experiment.

A fixation cross appeared briefly (for approximately 1 second) prior to the onset of each new problem in the experiment. Upon seeing the problem, participants had to make a rapid judgment (within 850 milliseconds) whether to solve it by calculating the answer on scrap paper or by retrieving the answer from having seen the problem before. Participants were instructed to base this judgment on their initial feeling as to whether they knew the answer. If participants chose “retrieve,” they had an additional 2 seconds to type in the answer, while if they chose “calculate,” they had 25 seconds to calculate the answer. After typing in the answer, the screen displayed (for 1 second) whether the response was correct. This was followed by a feedback screen showing again whether the response was correct, the time taken for the initial strategy selection, whether that time was fast enough, the time taken to provide the answer, whether that time was fast enough, and finally how many points had been received, based on accuracy and deadline requirements. This remained on the screen until subjects pressed the space bar to move forward. Finally, a screen displayed the problem and the correct answer for a minimum

⁴Numbers divisible by five were excluded both from the original Reder and Ritter study and from this study because they are easier to multiply and also more memorable.

of two seconds, giving participants time to study the answer. Given that subjects were told to type in only the last two digits of the answer, the ones and tens place digits were displayed in bold white against the black screen, while the other digits were displayed in a lighter gray color.

The payoff system rewarded correct on-time retrievals with fifty points. Correct on-time calculates were worth five points. Correct answers for which either the strategy selection times or the answer times were late were worth one point, while incorrect answers were worth zero points. Each point corresponded to half-a-cent in bonus compensation. After the experiment was finished, participants were debriefed and given payment.

ERP recording

Participants were seated in an electrically shielded booth. Stimuli were presented on a standard CRT monitor situated approximately one inch behind radio-frequency shielded glass. Participants were seated approximately two feet from the screen and gave their strategy selection responses as well as their problem answer responses on a standard keyboard. ERP recordings were made using 32 Ag-AgCl sintered electrodes (10–20 system) and a bioamplification system (Neuroscan Inc., Sterling VA). Impedances were adjusted to be less than 20 k Ω . Data were sampled at a rate of 1 kHz with a band pass filter of 0.1 to 200 Hz. Vertical eye movements (i.e. VEOG) were recorded using electrodes placed immediately above and below the orbit of the left eye. Horizontal eye movements (i.e. HEOG) were monitored with an additional pair of electrodes at the external canthi. Cortical channels were referenced to the left mastoid online and an active right mastoid reference electrode was employed. The data were re-referenced to algebraically linked mastoids and epoched offline.

The continuous data were segmented from –100 to 650 ms relative to stimulus (i.e., problem) onset for each of the trial types.⁵ Trials contaminated with muscular artifact and/or voltages above 100 μ V or below –100 μ V were excluded from the analysis. Data were corrected for ocular artifacts using a regression analysis in combination with artifact averaging (Semlitsch, Anderer, Schuster, & Presslich, 1986) and were baseline corrected over the pre-stimulus interval. The segmented data were then averaged across trials within participants for each condition and smoothed using a 30 Hz lowpass filter.

Results

Nine of the 35 participants failed to produce a single correct on-time retrieval and were therefore analyzed separately from the other subjects. They are discussed at the end of this section. An additional seven subjects had to be excluded due to technical problems. Therefore, 19 subjects (11 males and 8 females) were included in the analyses comparing retrieval and calculate trials. For these subjects, we first report the behavioral analyses followed by the ERP analyses.

Behavioral Analysis

Effects of Operator—We first analyzed the extent to which the multiplication and sharp operators yielded different behavioral patterns for the following measures: percent of trials for which retrieve was selected, percent of trials for which strategy selection was late, strategy selection time, and correct answer time. The analyses were remarkably consistent in showing little or no effect of operator. The only significant effects were that subjects were somewhat more likely to choose retrieve for sharp problems than for multiplication problems (23.4% compared with 16.4%), $t(18) = 2.39$, $p < 0.05$,⁶ and subjects took less time to complete sharp problems than multiplication problems when calculate was chosen (8207 ms compared with

⁵ERPs were not analyzed past 650 ms because subjects tended to begin preparing or executing their behavioral responses by this point.

9906 ms), $t(18) = 4.16, p < 0.001$. Because very few differences were found, all future analyses were collapsed across operator.

Effects of Problem Familiarity on Strategy Selection and Calibration—Problems were divided into four quartiles of familiarity (1–5, 6–10, 11–15, and 16–20 times). The percentage of retrieval selections and the accuracy of those selections are displayed for each quartile in Figure 2. Tendency to select retrieve increased as a function of the number of times the problem had been presented, $F(3, 54) = 26.6, p < 0.001, MS_e = 0.0143$. Accuracy of the retrieval attempts also increased with greater problem familiarity, $F(3, 39) = 45.0, p < 0.001, MS_e = 0.041$.⁷ The percent accuracy of retrievals was then determined as a function of how many total problems had already been seen by the subject over the course of the experiment by dividing the full set of problems into quartiles. The percent accuracy of retrievals did not show a consistent trend, changing from 27.3%, to 20.0%, to 36.4%, to 45.2% in the first, second, third, and fourth quartiles respectively. Furthermore, the difference did not reach significance, $F < 3.5$. Thus, it seemed that the increase in retrieval accuracy was primarily a function of problem familiarity rather than time in the experiment.

The overall calibration of the subjects' strategy selection judgments was measured using d' (Swets, 1986a, 1986b). Hits were defined as trials in which the subject selected "retrieve" on-time and then gave the correct answer within 2 seconds. False alarms were defined as trials in which subjects selected "retrieve" but then either gave an incorrect answer or failed to give an answer within 2 seconds. Subjects who had no hits were assigned default Z scores of -3 , while subjects who had no false alarms were assigned default Z scores of $+3$. Using this measure, subjects proved to be calibrated in their strategy selection judgments, as the average d' across subjects was 2.17. For comparison, the overall d' was 2.04 for the Reder and Ritter (1992) study, suggesting rather little difference in calibration of subjects.

ERP Analysis

To examine the effects of familiarity, the trials were divided within-subjects into three levels of problem familiarity: low-familiarity trials (seen 1–2 times), medium-familiarity (seen 5–7 times), and high-familiarity (seen 11–20 times). These ranges were chosen to ensure roughly the same number of observations per familiarity level. The waveforms were visually inspected to identify peaks of interest (see Figure 3). An N1 component was analyzed in the range between 150 and 230 ms over posterior recording sites. A P2 component was analyzed in the range between 180 and 280 ms over fronto-central recording sites, and a visual P3 component was analyzed in the range between 300 and 550 ms at central recording sites (see Figures 3–4). The average number of observations per subject was 13.8 for high-familiarity calculate trials, 7.3 for high-familiarity accurate retrieval trials, 18.8 for medium-familiarity calculate trials, and 4.8 for medium-familiarity inaccurate retrieval trials. Due to the nature of the task, we could only analyze accurate retrieval trials of high familiarity (for low-familiarity and medium-familiarity problems, subjects had not seen the problem enough times to obtain many successful on-time retrievals). Similarly, we could only analyze inaccurate retrieve trials of medium familiarity (for low-familiarity problems, subjects had not seen the problem often enough to even attempt a retrieval, while for high-familiarity problems almost all retrieval selections were followed by accurate answers).⁸

⁶All analyses, including ERP analyses, excluded trials with late strategy selection judgments, except, of course, the behavioral analyses of the percentage of times subjects were late to choose a strategy. The analysis of correct answer times excludes trials with late answer times.

⁷There were five subjects who did not attempt retrieval in any of the problems in at least one of the quartiles and therefore could not be included.

⁸The data were also looked at using longer deadlines for the strategy selection judgment and answer response for a retrieval trial to be counted as on-time. Doing this did not lead to a viable number of medium or low familiarity retrieval trials being considered on-time to perform meaningful analyses.

The dependent measures in the ERP analyses were the mean amplitudes of the ERP components in the given time ranges. The amplitudes were compared using repeated measures ANOVAs with sensor and strategy choice as factors. A Greenhouse-Geisser correction was used when the assumption of sphericity was violated. Another set of ANOVAs was run with sensor and problem familiarity (collapsed across strategy) as factors. The decision to treat response type as a factor follows a precedent set by Gardiner and Java (1990) and Gardiner (1988) on the grounds that this constitutes an instructional manipulation. We recognize that this assumption is somewhat questionable but have included it to directly analyze interactions involving response type.

Visual ERPs—It was first necessary to establish that the visual evoked responses were the same across problem types. Thus, the mean amplitudes of the waveform for the O1, OZ, and O2 electrodes were taken for the N1 component. Repeated measures ANOVAs were performed with sensor and strategy choice as factors. As expected, there was no difference in this component between accurate retrievals and calculates of similar familiarity for any of the N1 components, $F < 1.0$. The N1 amplitudes were -0.12 uV for high-familiarity accurate retrieval trials and -0.45 uV for high-familiarity calculate trials, with standard errors of 0.82 and 0.86 respectively. Similarly, there was no difference in the N1 component for inaccurate retrieval trials and calculate trials of similar familiarity, $F < 1.0$. The mean amplitudes were 0.64 uV for the inaccurate retrieval trials and 1.17 uV for the medium-familiarity calculate trials, with standard errors of 1.54 and 0.79 respectively.

Effects of Strategy Selection and Accuracy on P2 and P3 components—Visual inspection of the waveforms showed that the P2 component was centered at the frontal-central region while the P3 component was more broad and was centered around the central and central-parietal regions (see Figure 4). Therefore, the P2 analyses included the FCZ electrode and the four surrounding electrodes (FZ, FC3, FC4, and CZ), while the P3 analyses included the CZ electrode and the four surrounding electrodes (FCZ, C3, C4, and CPZ).

Figure 5 plots the mean amplitudes of the P2 and P3 components as a function of problem familiarity and strategy chosen. As can be seen, high-familiarity accurate retrieval trials had more positive P2 amplitudes than high-familiarity calculate trials, $F(1, 18) = 18.9$, $p < 0.01$, $MS_e = 20.2$. There was no significant effect of sensor, $F < 3.0$, and no significant interaction, $F < 1.0$, between sensor and strategy. For the P3 component, high-familiarity accurate retrieval trials again had more positive amplitudes than high-familiarity calculate trials, $F(1, 18) = 11.4$, $p < 0.01$, $MS_e = 79.4$. There was a significant main effect of sensor, $F(4, 72) = 7.4$, $p < 0.01$, $MS_e = 11.7$, with the highest value (12.8 uV) being found at the C4 electrode. There was again no significant interaction between sensor and strategy, $F < 1.0$.

Both the P2 and P3 components appeared to be larger in the right than in the left hemisphere. A post-hoc Bonferroni-corrected comparison of the FC4 and FC3 electrode for the P2 amplitudes was significant, $p < 0.05$, as was a similar comparison between the C3 and C4 electrode for the P3 amplitudes, $p < 0.001$. When the medium-familiarity inaccurate retrieval trials were compared against medium-familiarity calculates, there were no significant effects, except a main effect of sensor for the P3 component, $F(4, 60) = 4.5$, $p < 0.05$, $MS_e = 19.6$, with the largest amplitude (9.7 uV) recorded over C4.

Effects of Problem Familiarity on P2 and P3 components—Figure 6 plots the P2 and P3 amplitudes as a function of problem familiarity (collapsed across strategy chosen) and whether or not the subject obtained a successful on-time retrieval trial. The mean amplitude of the P2 component was again taken for the FCZ electrode and its four neighbors (FZ, FC3, FC4, and CZ), while the mean amplitude of the P3 component was taken for the CZ electrode and its four neighbors (FCZ, C3, C4, and CPZ). As illustrated in Figure 6, both the P2 component

and the P3 component increased in amplitude with greater problem familiarity, $F(2, 36) = 10.5$ and 39.0 , $MS_e = 22.3$ and 15.1 , respectively, both $p < 0.001$. The P2 component showed a main effect of sensor, $F(4, 72) = 5.0$, $p < 0.01$, $MS_e = 5.9$, with the highest amplitude (8.7 uV) being found at the FC4 electrode. No significant interaction between sensor and familiarity, however, was found, $F < 1.0$. For the P3 component, there was also a main effect of sensor, $F(4, 72) = 8.5$, $p < 0.001$, $MS_e = 10.6$, with the highest amplitude (10.3 uV) being found at the C4 electrode. An interaction between sensor and familiarity reached significance, $F(8, 144) = 3.4$, $p < 0.05$, $MS_e = 2.7$. The difference in P3 amplitude for high-familiarity and low-familiarity problems was greatest at the CZ electrode. Both components had higher amplitudes in the right hemisphere than the left. A post-hoc Bonferroni-corrected comparison showed a higher P2 amplitude at the FC4 compared with the FC3 electrode, $p < 0.05$. A similar comparison showed a higher P3 amplitude at the C4 than the C3 electrode, $p < 0.001$.

Non-Retrieval Subjects—There were nine subjects in the experiment who never obtained a successful on-time retrieval trial. Unlike the subjects who did obtain successful on-time retrieval trials, there was no consistent increase in the P2 amplitude with greater problem familiarity for these seven subjects (see Figure 6). There was a slight trend of greater P3 amplitude with greater problem familiarity, but this effect was not nearly as large as the effect found for retrieval subjects. The only statistically significant effect for the non-retrieval subjects was a main effect of sensor for the P3 component $F(4, 32) = 4.7$, $p < 0.05$, $MS_e = 20.1$, with the highest amplitude (7.4 uV) being recorded at the C4 electrode.

Discussion

Subjects were shown a series of math problems, some of which were repeated up to twenty times over the course of the experiment, and were asked to rapidly estimate (in less than 850 ms) whether the answer could be quickly retrieved from memory or had to be calculated. The behavioral findings replicated Reder and Ritter (1992) and Schunn et al. (1997), showing that subjects could make this decision accurately within the time limit and that the likelihood of choosing “retrieve” increased with problem familiarity. Stimulus-locked ERP analyses showed that high-familiarity accurate retrieval trials were associated with greater positivity for a P2 and a P3 component compared with calculates of similar familiarity. Furthermore, we found an independent effect of problem familiarity on the relevant ERP components, with more familiar problems being associated with greater positivity for both the P2 and the P3 components.

These neural correlates of FOK emerged quite early in processing, within 200 ms following stimulus onset, and were largest over frontocentral regions of the scalp. Although scalp topography is not an accurate index of neural sources, the frontal distribution of these components is consistent with a number of fMRI and neuropsychology studies that show that the frontal lobes are crucial in memory-monitoring processes (Fernandez-Duque, Baird, & Posner, 2000; Pannu & Kaszniak, 2005; Shimamura, 2000; Simons & Spiers, 2003). This suggests that initial FOK may rely on similar neural networks as other metamemory processes. The data also suggest some degree of hemispheric laterality for the FOK components. Overall, these components tended to be greater in amplitude in the right hemisphere than in the left, suggesting there may be a specific right-hemisphere involvement in FOK processes.

We were surprised that the differences between the accurate retrieval trials and the other conditions were observed as early as 200 ms following the onset of the stimulus. This was unexpected given that, as discussed earlier, most ERP research suggests that familiarity-based processing does not occur until at least 300 ms following stimulus onset. The P2 component has generally been associated with perceptual processing of stimuli (Doyle, Rugg, & Wells, 1997; Rugg & Nagy, 1987; Rugg & Nieto-Vegas, 1999), suggesting the use of a rapid heuristic

based on the perceptual processing of the stimulus to guide strategy selection in the FOK task. This interpretation is consistent with the proposal that the ease with which perceptual processing takes place (sometimes referred to as “perceptual fluency”) is used to guide metamemory judgments (see Benjamin, 1999; Kamas & Reder, 1994; Koriat & Levy-Sadot, 2001; Whittlesea, 1993). As such, it is reasonable to speculate that the P2 amplitude may itself be used to drive “perceptual fluency,” although more research is required to assess the validity of this claim. The P2 component has also been associated with ERP priming effects and implicit memory (see Rugg & Doyle, 1994 for a review), which is noteworthy, since it is consistent with work suggesting that repetition priming and familiarity effects rely on the same representations (Reder, Park & Kieffaber, in press).

Diana, Vilberg and Reder (2005) also found a frontal P200 component that seems similar in latency and scalp distribution to the P2 component observed in this study (see also Walsh, Dutcher, Oates & Reder, under review). The component was interpreted by the authors as corresponding to the initiation of an attempt to recollect the study episode for those stimuli deemed sufficiently familiar. We believe the P2 component in our study may be playing a quite similar role by performing a quick assessment of whether a stimulus seems sufficiently familiar to merit an effortful search. Problems that pass this initial assessment continue to be analyzed while those deemed too unfamiliar are rejected. This finding is noteworthy since in Reder’s SAC model, activation of the problem node in an FOK task is analogous to episodic recollection (Reder et al., 2000; Reder & Schunn, 1996). In either task an attempt to assess whether search should be attempted depends on a quick evaluation of the familiarity of the stimulus. It is therefore consistent that preliminary evaluation of a FOK judgment and a decision to initiate search in a recollection task both rely on the P200 ERP component.

The P3 component traditionally has been more strongly associated with memory processing than has the P2 component. It is generally believed that the central-parietal P3 component is associated with activation and updating of existing memory representations after a relevant stimulus has been processed (Donchin, 1981; Polich, 2003, 2007; Squire & Kandel, 1999). Thus, the P3 component observed in our study could correspond to activation of an internal memory representation of a previously seen problem that was activated by the elements of the problem, reflected in the P2 component. When this internal representation of a familiar problem becomes sufficiently active, a decision is made to choose “retrieve.” It is worth noting that the computational model proposed by Reder and Schunn (1996) and Schunn et al. (1997) describes a model in which the problem features are activated and spread to a node that represents the binding of the problem features. If the problem node becomes sufficiently active, the subject selects “retrieve” and the search continues to try to retrieve the answer associated with the problem node. This model is largely consistent with the interpretation of the ERP findings we have suggested, since the P3 amplitude would map onto the activation of the internal problem representation, which then drives a decision to actually search for the answer.

It is noteworthy that both of the ERP components found to be correlated with initial FOK were manifest well before the time necessary for stimuli to be consciously processed according to Libet (2003). Given that these neural correlates of initial FOK are the product of unconscious processing, it follows that this rapid FOK can be used to guide strategy selection in question answering, specifically whether to search memory or use some other question answering process such as computation or plausible reasoning. Other work has supported the view that strategy selection shifts can indeed occur without conscious awareness by the subject (e.g., Cary & Reder, 2002). Reder (1987) varied the base rate of success of two different question-answering strategies (direct retrieval and plausible reasoning). Subjects were able to rapidly shift their tendency to use one strategy or another based on the likelihood of the strategy’s success, but were completely unaware of the differences in the success rates or even that multiple strategies had been used. Other work has found similar effects of adaptive strategy

selection without awareness in such diverse domains as arithmetic verification tasks (Lemaire & Reder, 1999), air-traffic control tasks (Reder & Schunn, 1999), visual search tasks (Chun & Jiang, 1998; Reder, Weber, Shang & Vanyukov, 2003), and problem-solving tasks (Lovett & Anderson, 1996; Schunn, Lovett & Reder, 2001).

Since the ERP correlates of FOK described in this study seem to emerge sooner than the problem stimulus could be registered into conscious awareness, it follows that they reflect the operation of unconscious processes that correlate with adaptive strategy selection. These components could therefore provide a neural underpinning for how people adaptively choose among different strategies without becoming aware of what they are doing. This has clear implications for work on metacognition and strategy selection generally.

As in earlier studies using this paradigm, there were some subjects (in this case, seven) who never had a successful, on-time retrieval trial. Previously, these subjects had been modeled by adding a special parameter reflecting a meta-decision to never use the retrieve option (Schunn, et al., 1997). The ERP results of this study suggest, however, that instead of adopting a meta-strategy to always choose calculate, the subjects did not receive the neural signals necessary to initiate a retrieval attempt in the first place. As illustrated in Figure 6, typical subjects, who did obtain successful retrievals, showed clear effects of problem familiarity on their mean P2 and P3 amplitudes, while these special “non-retrieval” subjects showed little or no such effect. We believe this different pattern for subjects who did not choose retrieve bolsters the case that the P2 and P3 components are indeed related to initial FOK. If high positive amplitudes for these particular ERP components were indeed critical to choosing the retrieve strategy, one would expect that they would not be observed in subjects who consistently failed to select retrieve, and this is indeed what was found.

A final point worth mentioning is that the inaccurate retrieval trials showed no significant ERP differences with calculates of similar familiarity. This shows that the neural signals found in our experiment were in fact more predictive of ability to retrieve the answer than the actual behavioral responses of the subjects. This is intriguingly similar to a set of language studies reporting effects in which ERP signatures were more accurate than behavioral responses at detecting non-grammatical constructions (McLaughlin, Osterhout, & Kim, 2004; Tokowicz & MacWhinney, 2005). In our case, the reduced accuracy for behavioral responses compared with the ERP responses might have been influenced by the heavy incentive subjects were given to select retrieve: the pay-off was ten times as large for a correct retrieval than a correct calculate. It is worth noting that subjects were quite calibrated in their strategy selection, rarely choosing the incorrect strategy. For example, there were more almost four times as many calculate selections than inaccurate retrievals for trials of medium-familiarity.

In conclusion, our study reinforces the idea that initial FOK is based on processes that come on-line quite rapidly. ERP recordings showed that correlates of the FOK phenomenon emerged as rapidly as 200 ms following the appearance of the problem stimulus. Furthermore, these correlates did not appear to be epiphenomenal, since they were effectively absent in those few subjects who failed to obtain a successful, on-time retrieval. In short, it appears we can know that we know something in much less time than would have been expected.

Acknowledgements

This work was supported by NIH grants: 2RO1-MH052808 to the second author; the first and third authors were supported by T32MH019883-09; and the first author was also supported by T32GM081760-01. We thank Evan Stade for writing the original code, Matthew Sokolowsky for help with the analysis program, Joyce Oates, Marissa Krimsky, and Jason Ralph for assistance in running subjects, Matthew Walsh for commenting on the manuscript and Rachel Diana for consultation on all phases of the project.

References

- Anderson, JR.; Lebiere, C. Atomic components of thought. Mahwah, NJ: Erlbaum; 1998.
- Benjamin AS. The role of subjective fluency in predicting the future and reconstructing the past. Dissertation Abstracts International: Section B: The Sciences and Engineering 1999;59(9B):5122.
- Cary, M.; Reder, LM. Metacognition in strategy selection: Giving consciousness too much credit. In: Chambres, P.; Izaute, M.; Marescaux, PJ., editors. Metacognition: Process, Function, and Use. New York, NY: Kluwer; 2002. p. 63-78.
- Chun MM, Jiang Y. Contextual cueing: Implicit learning and memory of visual context guides spatial attention. *Cognitive Psychology* 1998;36(1):28–71. [PubMed: 9679076]
- Curran T. Effects of attention and confidence on the hypothesized ERP correlates of recollection and familiarity. *Neuropsychologia* 2004;42:1088–1106. [PubMed: 15093148]
- Curran T. Brain potentials of recollection and familiarity. *Memory and Cognition* 2000;28(6):923–938.
- Diana R, Vilberg KL, Reder LM. Identifying the ERP correlate of a recognition memory search attempt. *Cognitive Brain Research* 2005;24:674–684. [PubMed: 15885990]
- Donchin E. Surprise!... Surprise? *Psychophysiology* 1981;18:493–513. [PubMed: 7280146]
- Doyle MC, Rugg MD, Wells T. A comparison of the electrophysiological effects of formal and repetition priming. *Psychophysiology* 1997;33:132–147. [PubMed: 8851241]
- Duke LM. Underawareness of deficit in Alzheimer's disease: Convergent validation of metamemory tasks and the relationship to risky behavior. Dissertation Abstracts International: Section B: The Sciences and Engineering 2001;61(8B):4399.
- Fernandez-Duque D, Baird JA, Posner MI. Executive attention and metacognitive regulation. *Consciousness and Cognition* 2000;9:288–307. [PubMed: 10924249]
- Gardiner JM. Functional aspects of recollective experience. *Memory & Cognition* 1988;16(4):309–313.
- Gardiner JM, Java RI. Recollective experience in word and nonword recognition. *Memory & Cognition* 1990;18:23–30.
- Hart JT. Memory and the feeling-of-knowing experience. *Journal of Experimental Psychology: General* 1965;116:119–136.
- Jameson KA, Narens L, Goldfarb K, Nelson TO. The influence of near-threshold priming on metamemory and recall. *Acta Psychologica* 1990;73:1–14.
- Jung TP, Makeig S, Westerfield M, Townsend J, Courchesne E, Sejnowski TJ. Removal of eye activity artifacts from visual event-related potentials in normal and clinical subjects. *Clinical Neurophysiology* 2000;111:1745–1758. [PubMed: 11018488]
- Kamas, E.; Reder, LM. The role of familiarity in cognitive processing. In: O'Brien, E.; Lorch, R., editors. Sources of coherence in reading: A festschrift in honor of Jerome L. Myers. New Jersey: L. Erlbaum; 1994. p. 177-202.
- Kikyo H, Ohki K, Miyashita Y. Neural correlates for feeling-of-knowing: An fMRI parametric analysis. *Neuron* 2002;36:177–186. [PubMed: 12367516]
- Koriat A, Levy-Sadot R. The combined contributions of the cue-familiarity and accessibility heuristics to feelings of knowing. *Journal of Experimental Psychology: Learning, Memory, and Cognition* 2001;27(1):34–53.
- Lemaire P, Reder LM. What affects strategy selection in arithmetic? An examination of parity and five effects on product verification. *Memory & Cognition* 1999;27(2):364–382.
- Libet, B. Cerebral physiology of conscious experience: Experimental studies in human subjects. In: Osaka, N., editor. Neural Basis of Consciousness. Amsterdam, Netherlands: John Benjamins Publishing Company; 2003. p. 57-84.
- Libet, B.; Alberts, WW.; Wright, EW.; Lewis, M.; Feinstein, B. Cortical representation of evoked potentials relative to conscious sensory responses and of somatosensory qualities in man. In: Kornhuber, HH., editor. The Somatosensory System. Stuttgart: Thieme Verlag; 1975.
- Lovett MC, Anderson JR. History of success and current context in problem solving: Combined influences on operator selection. *Cognitive Psychology* 1996;31(2):168–217.
- McLaughlin J, Osterhout L, Kim A. Neural correlates of second-language-learning: Minimal instruction produces rapid change. *Nature Neuroscience* 2004;7:703–704.

- Nelson TO, Gerler D, Narens L. Accuracy of feeling-of-knowing judgments for predicting perceptual identification and relearning. *Journal of Experimental Psychology: General* 1984;113:282–300. [PubMed: 6242754]
- Nelson TO, Narens L. Norms of 300 general-information questions: Accuracy of recall, latency of recall, and feeling-of-knowing ratings. *Journal of Verbal Learning and Verbal Behavior* 1980;19:338–368.
- Nhouyvanisvong, A.; Reder, LM. Rapid feeling-of-knowing: A strategy selection mechanism. In: Yzerbyt, VY.; Lories, G.; Dardenne, B., editors. *Metacognition: Cognitive and social dimensions*. Vol. 35. London: Sage; 1998. p. 52
- Pannu JK, Kaszniak AW. Metamemory experiments in neurological populations: A review. *Neuropsychology Review* 2005;15(3):105–130. [PubMed: 16328731]
- Pinon K, Allain P, Zied Kefi M, Dubas F, Le Gall D. Monitoring processes and metamemory experience in patients with dysexecutive syndrome. *Brain and Cognition* 2005;57(2):185–188. [PubMed: 15708214]
- Polich J. Updating P300: An integrative theory of P3a and P3b. *Clinical Neurophysiology* 2007;118:2128–2148. [PubMed: 17573239]
- Polich, J. Overview of P3a and P3b. In: Polich, J., editor. *Detection of change: Event-related potential and fMRI findings*. Norwell, MA: Kluwer Academic Press; 2003. p. 83-98.
- Potts GF. An ERP index of task relevance evaluation of visual stimuli. *Brain and Cognition* 2004;56:5–13. [PubMed: 15380870]
- Potts GF, Tucker DM. Frontal evaluation and posterior representation in target detection. *Cognitive Brain Research* 2001;11(1):147–156. [PubMed: 11240117]
- Reder, LM., editor. *Implicit Memory and Metacognition*. Mahwah, N.J.: L. Erlbaum; 1996.
- Reder LM. Strategy selection in question answering. *Cognitive Psychology* 1987;19(1):90–138.
- Reder LM. Plausibility judgments vs. fact retrieval: Alternative strategies for sentence verification. *Psychological Review* 1982;89:250–280.
- Reder LM, Nhouyvanisvong A, Schunn CD, Ayers MS, Angstadt P, Hiraki K. A mechanistic account of the mirror effect for word frequency: A computational model of remember/know judgments in a continuous recognition paradigm. *Journal of Experimental Psychology: Learning, Memory, & Cognition* 2000;26(2):294–320.
- Reder LM, Park H, Kieffaber P. Memory systems do not divide on consciousness: Reinterpreting memory in terms of activation and binding. *Psychological Bulletin*. in press
- Reder LM, Ritter F. What determines initial feeling of knowing? Familiarity with question terms, not with the answer. *Journal of Experimental Psychology: Learning, Memory, and Cognition* 1992;18:435–451.
- Reder LM, Ross BH. Integrated knowledge in different tasks: The role of retrieval strategy on fan effects. *Journal of Experimental Psychology: Learning, Memory and Cognition* 1983;9:55–72.
- Reder, LM.; Schunn, CD. Bringing together the psychometric and strategy worlds: Predicting adaptivity in a dynamic task. In: Gopher, D.; Koriat, A., editors. *Cognitive Regulation of Performance: Interaction of Theory and Application*. Attention and Performance XVII. MIT Press; 1999. p. 315-342.
- Reder, LM.; Schunn, CD. Metacognition does not imply awareness: Strategy choice is governed by implicit learning and memory. In: Reder, LM., editor. *Implicit Memory and Metacognition*. Mahwah, N.J.: L. Erlbaum; 1996. p. 45-77.
- Reder LM, Weber K, Shang J, Vanyukov PM. The adaptive character of the attentional system: Statistical sensitivity in a target localization task. *Journal of Experimental Psychology: Human Perception and Performance* 2003;29(3):631–649. [PubMed: 12848330]
- Reder LM, Wible C, Martin J. Differential memory changes with age: Exact retrieval versus plausible inference. *Journal of Experimental Psychology: Learning, Memory, and Cognition* 1986;12(1):72–81.
- Rugg MD, Curran T. Event-related potentials and recognition memory. *Trends in Cognitive Sciences* 2007;11(6):251–257. [PubMed: 17481940]
- Rugg, MD.; Doyle, MC. Event-related potentials and stimulus repetition in direct and indirect test of memory. In: Heinze, HJ.; Munte, TF.; Mangun, GR., editors. *Cognitive electrophysiology*. Boston, MA: Birkhauser; 1994. p. 124-148.

- Rugg MD, Nagy ME. Lexical contribution to non-word repetition effects: Evidence from event-related potentials. *Memory and Cognition* 1987;15:473–481.
- Rugg MD, Nieto-Vegas M. Modality-specific effects of immediate word repetition: Electrophysiological evidence. *Neuro-Report* 1999;10:2661–2664.
- Schnyer DM, Nicholls L, Verfaellie M. The role of VMPC in metamemorial judgments of content retrievability. *Journal of Cognitive Neuroscience* 2005;17(5):832–846. [PubMed: 15904549]
- Schnyer DM, Verfaellie M, Alexander MP, LaFleche G, Nicholls L, Kaszniak AW. A role for right medial prefrontal cortex in accurate feeling-of-knowing judgments: Evidence from patients with lesions to frontal cortex. *Neuropsychologia* 2004;42(7):957–966. [PubMed: 14998710]
- Schunn CD, Lovett MC, Reder LM. Awareness and working memory in strategy adaptivity. *Memory & Cognition* 2001;29(2):254–266.
- Schunn CD, Reder LM. Another source of individual differences: Strategy adaptivity to changing rates of success. *Journal of Experimental Psychology: General* 2001;130:59–76. [PubMed: 11293460]
- Schunn CD, Reder LM, Nhoyvanisvong A, Richards DR, Strohffolino PJ. To calculate or not calculate: A source activation confusion (SAC) model of problem-familiarity's role in strategy selection. *Journal of Experimental Psychology: Learning, Memory, & Cognition* 1997;23:1–27.
- Semlitsch HV, Anderer P, Schuster P, Presslich O. A solution for reliable and valid reduction of ocular artifacts, applied to the P300 ERP. *Psychophysiology* 1986;23(6):695–703. [PubMed: 3823345]
- Shimamura AP. Toward a cognitive neuroscience of metacognition. *Consciousness and Cognition* 2000;9:313–323. [PubMed: 10924251]
- Siegler, RS. *Emerging minds: The process of change in children's thinking*. New York: Oxford University Press; 1996.
- Simons JS, Spiers HJ. Prefrontal and medial temporal lobe interactions in long-term memory. *Nature Reviews: Neuroscience* 2003;4:637–648.
- Soon CS, Brass M, Heinze H, Haynes J. Unconscious determinants of free decisions in the human brain. *Nature Neuroscience* 2008;11(5):543–545.
- Spehn MK, Reder LM. The unconscious feeling of knowing: A commentary on Koriat's paper. *Consciousness and Cognition* 2000;9:187–192. [PubMed: 10924237]
- Squire, LR.; Kandel, E. *Memory from mind to molecules*. New York: Scientific American Library; 1999.
- Swets JA. Form of empirical ROCs in discrimination and diagnostic tasks: Implications for theory and measurement of performance. *Psychological Bulletin* 1986a;99:181–198. [PubMed: 3515382]
- Swets JA. Indices of discrimination or diagnostic accuracy: Their ROCs and implied models. *Psychological Bulletin* 1986b;99:100–117. [PubMed: 3704032]
- Tokowicz N, MacWhinney B. Implicit and explicit measures of sensitivity to violations in second language grammar: An event-related potential investigation. *Studies in Second Language Acquisition* 2005;27:173–204.
- Walsh MM, Dutcher J, Oates JM, Reder LM. ERP correlates of familiarity and recollection in face recognition. under review
- Whittlesea BWA. Illusions of familiarity. *Journal of Experimental Psychology: Learning, Memory, and Cognition* 1993;19(6):1235–1253.

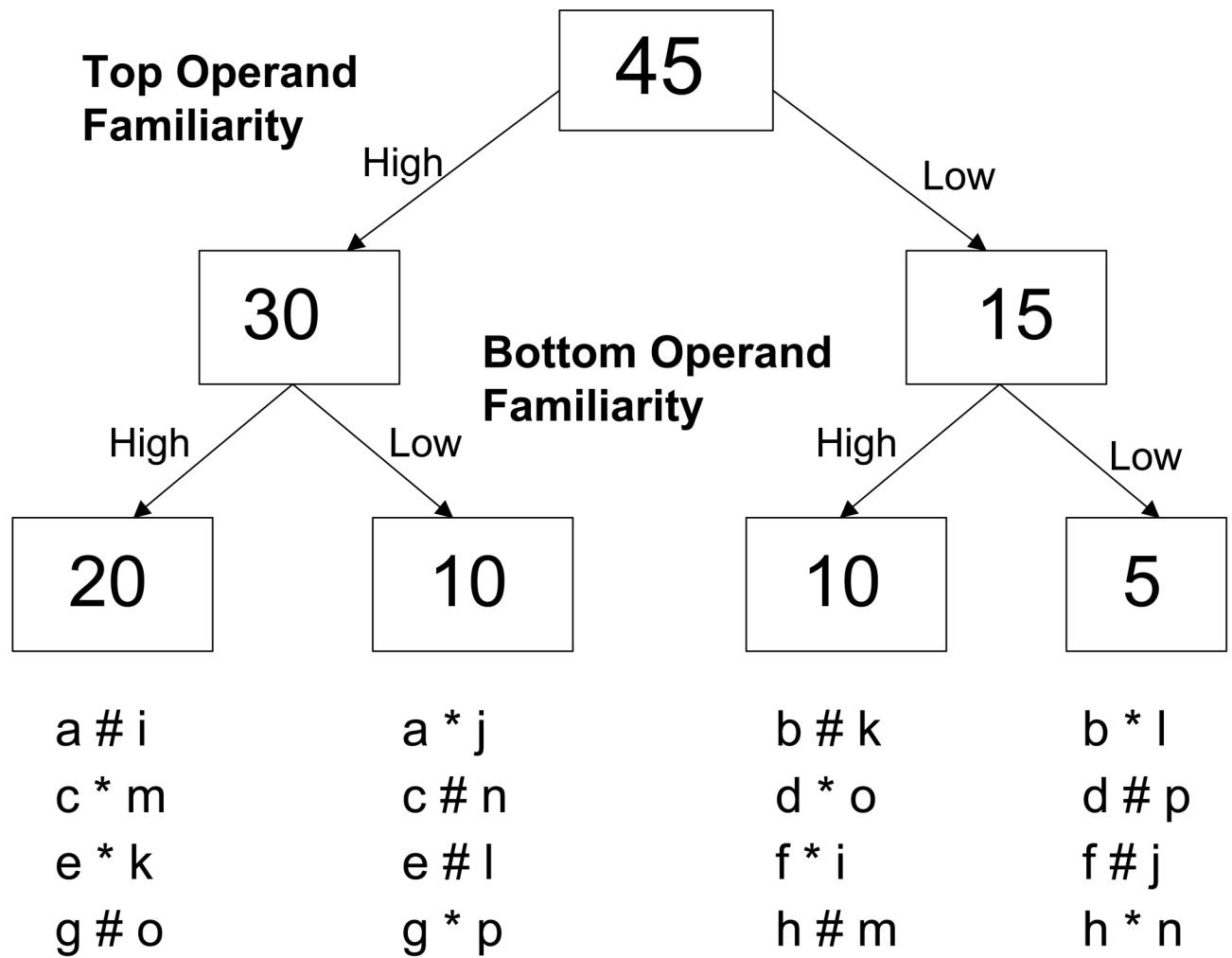


Figure 1.
Design of problem sets in experiment. (After Figure 4 in Reder & Ritter, 1992).

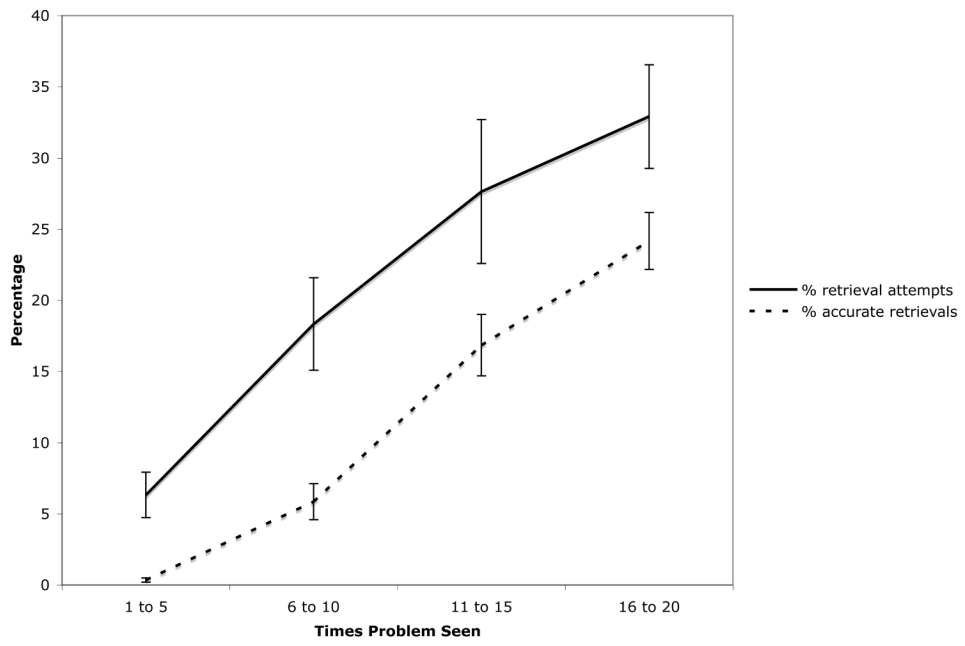


Figure 2. Retrieval percentages across levels of problem familiarity.

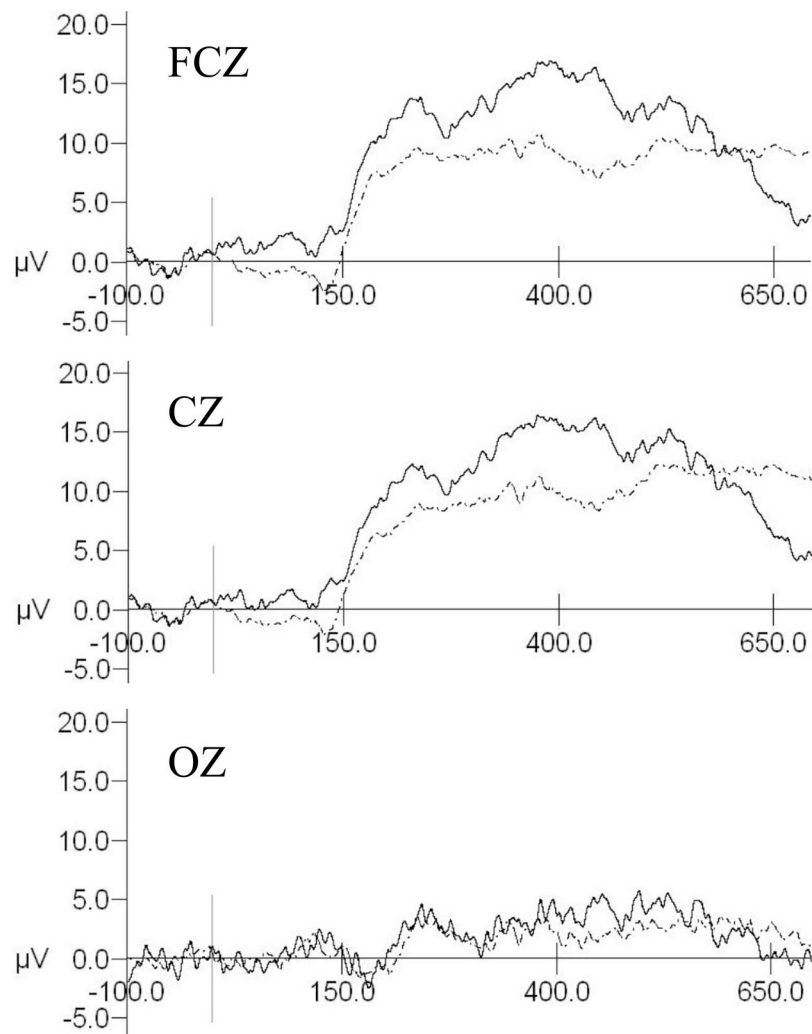


Figure 3. Stimulus-locked waveforms for FCZ, CZ, and OZ electrodes. Solid lines refer to high-familiarity problems with accurate, on-time retrievals. Dotted lines refer to high-familiarity problems with accurate, on-time calculates. Time in milliseconds.

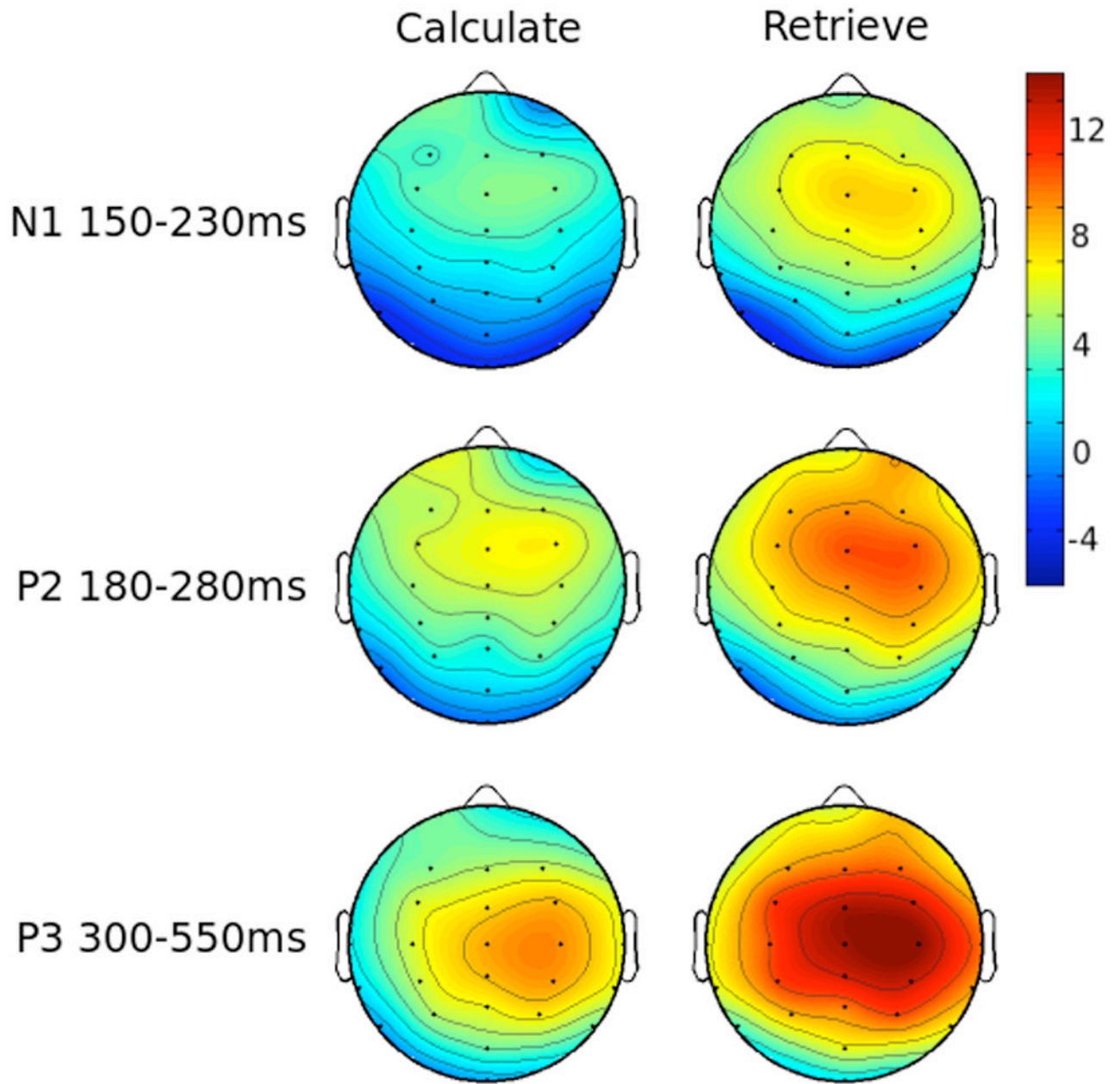


Figure 4. Headplots following stimulus onset for high-familiarity problems. (Note that “retrieve” refers to accurate retrieves).

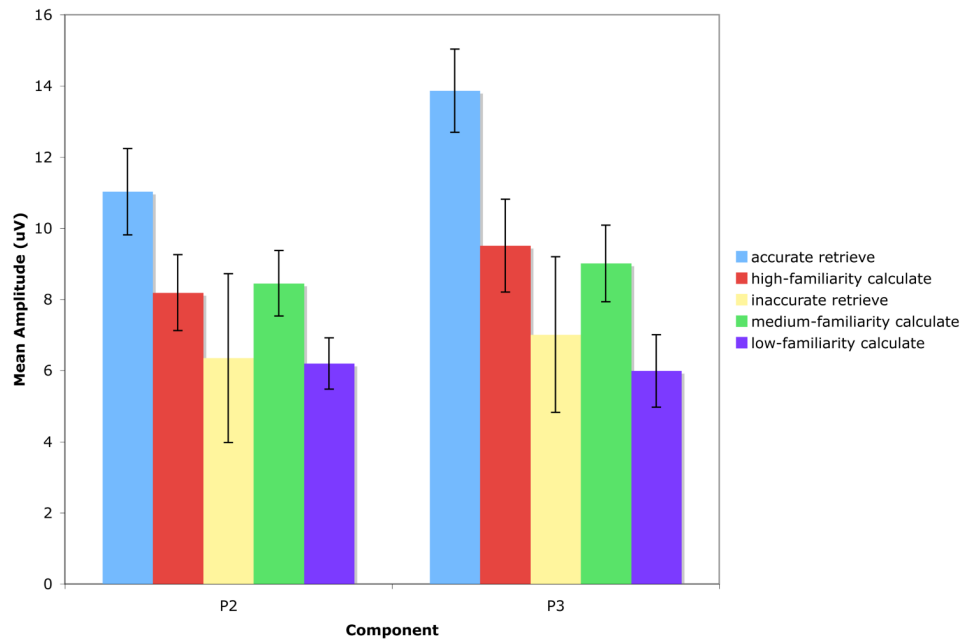


Figure 5.
Effect of trial type on mean P2 and P3 amplitudes.

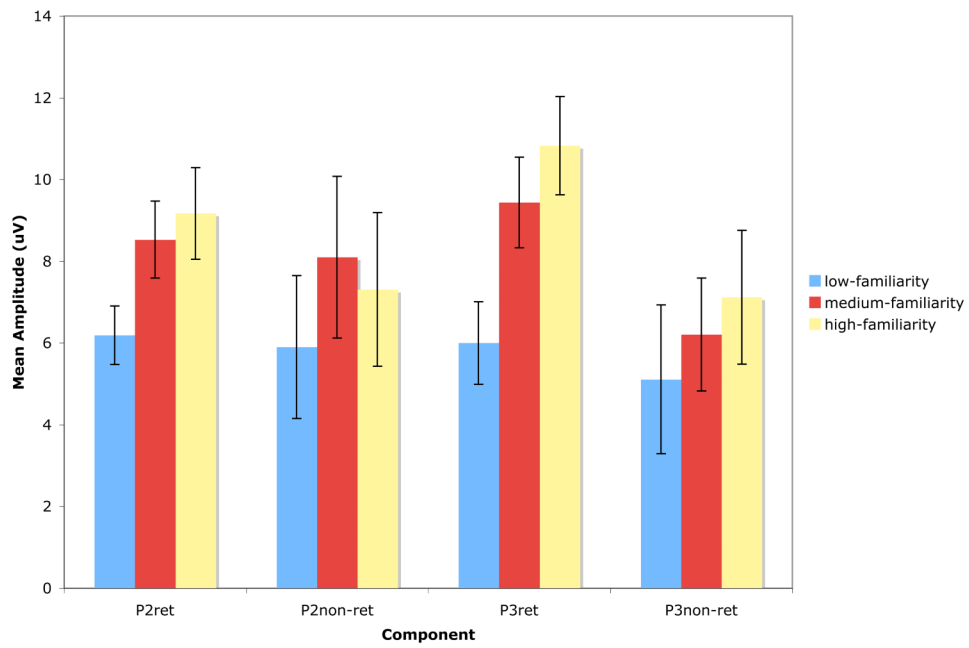


Figure 6. Effect of problem familiarity on mean P2 and P3 amplitudes. (“ret” refers to subjects who did obtain successful on-time retrieves, while “non-ret” refers to the seven subjects who did not).