Precursors of Insight in Event-related Brain Potentials

Simone Lang[1,2], Nadine Kanngieser[1], Piotr Jaśkowski[1,3], Hilde Haider[4], Michael Rose[5], and Rolf Verleger[1]

Abstract

■ Event-related potentials (ERPs) were investigated to find precursors of insightful behavior. Participants had to process successive pairs in strings of digits to obtain a final response in each trial. Within the sequence of five responses required in each trial, the last two responses mirrored the two preceding ones. This hidden regularity, allowing for shortcutting each trial from five to two responses, was discovered by 6 out of 26 participants. Both groups, solvers and nonsolvers, implicitly learned the regularity, reflected by faster responses to the repeated, predictable responses, but this differential effect was larger in solvers, whereas nonsolvers became unspecifically faster with all responses. Several ERP components were larger in solvers than in nonsolvers from the outset: slow positive wave, frontocentral P3a, anterior N1 to those digits that triggered the critical repeating responses, and P3b to the digit that evoked the immediately repeating response. Being already present in the first block, these effects were early precursors of insightful behavior. This early occurrence suggests that participants who will gain insight may be distinguished beforehand by their individual characteristics. ■

INTRODUCTION

Legend has it that Newton was sitting under an apple tree as an apple fell on his head. Suddenly he realized that the law of gravitation must also hold true for the universe and the moon's orbit to the earth (Keesing, 1998). Such conscious and verbalized knowledge is referred to as *explicit* knowledge (Willingham, Salidis, & Gabrieli, 2002) and, if coming suddenly to mind, as *insight* (Köhler, 1917/1973). This legend provides a suitable illustration for the object of the present study, namely, the circumstances that make people discover new regularities.

Models

Many theoretical assumptions try to account for this interesting and poorly understood issue. At least three positions can be distinguished. First, according to ''strength of representation'' theories, explicit knowledge may be the result of implicit knowledge turned explicit. The strength of some mental representation directly determines when the representation will reach awareness (Cleeremans, 2002; Cowan, 1995).

According to a second account, explicit and implicit knowledge are generated by separate systems (e.g., Dienes & Berry, 1997). Implicit associative learning is the default mode, whereas generation of reportable knowledge results from explicit hypothesis testing (Willingham & Goedert-Eschmann, 1999; Curran & Keele, 1993). To a large degree, this conclusion is based on comparisons between groups of participants who were instructed to search some regularity built into a task and ''incidental'' groups who did not receive such information (Willingham et al., 2002; Lelekov, Dominey, & García-Larrea, 2000; Dominey, Lelekov, Ventre-Dominey, & Jeannerod, 1998).

A third position holds that implicit and explicit knowledge interact. Like in the second position, explicit knowledge results from explicit hypothesis testing (Frensch et al., 2002; Dienes & Perner, 1999; Nissen & Bullemer, 1987). However, in contrast to that position, explicit hypothesis testing is assumed to result from implicit learning that occurs to a larger extent in those participants who will become aware of the regularity than in those who will remain unaware. Frensch et al. (2002) observed in the number reduction task (see below) that participants who gained insight into the covert rule had faster minimum response times (RTs) and, shortly before becoming aware of the rule, also higher variances of their RTs. These authors stated the ''unexpected event'' hypothesis thus: Processes involved in gaining insight start with attention-independent learning of regularities in the sequence, leading to faster

[1]University of Lübeck, Germany, [2]University of Heidelberg, Germany, [3]University of Finance and Management, Warsaw, Poland, [4]University of Köln, Germany, [5]University of Hamburg Medical School, Germany

responses. Participants might notice this speeding of their responses, and this unexpected event will trigger an intentional search for possible reasons, typically taking the form of hypothesis testing. These active search processes are reflected in higher RT variance prior to the moment of displaying awareness.

Experimental Tasks

The relationship between implicit learning and getting access to explicit knowledge has often been investigated in the serial reaction task in which the sequence of stimuli and responses obeys a covert rule (Reber, 1967). Responses become gradually faster with regular sequences and increasing practice, and are delayed when the rule is violated. Such behavior is considered evidence of implicit sequence learning (Reber, 1989; Nissen & Bullemer, 1987; Schacter, 1987). Additional explicit learning is present if participants become aware of the rule. The proportion of explicit learners in this kind of paradigm varies between 10% and 70%, depending on experimental conditions (Frensch et al., 2002) and on the criterion used for demonstrating explicit knowledge (Rüsseler, Hennighausen, Münte, & Rösler, 2003).

The number reduction task (NRT), first introduced as ''letter reduction task'' by Woltz, Bell, Kyllonen, and Gardner (1996) and modified by Frensch et al. (2002), offers the advantage that the time point of insight into the covert rule can be exactly determined because explicit knowledge of the rule leads to an abrupt, qualitative shift in responding. Consecutive pairs within some string of digits have to be processed in each trial until the result reached with the final digit is entered. Unmentioned to participants, the sequence of responses is mirror symmetric such that the second half of responses in each trial is predictable. Insight into this rule allows one to shortcut the sequence by giving the final response in advance (see Figure 1). By this construction of the task, several learning effects can be distinguished. First, there is a general effect of procedural learning, resulting in decreasing RTs for all responses. Second, implicit learning of the mirror symmetric regularity will result in faster RTs for the predictable responses. Third, participants who become aware of the regularity will be able to speed up performance more substantially by reducing the number of responses.

Recent studies using functional magnetic resonance imaging (fMRI) in this task showed that procedural learning is principally mediated by the basal ganglia, and that implicit serial learning implies activation within the medial temporal lobe including the hippocampus (Rose, Haider, Weiller, & Büchel, 2002, 2004), although up to now there is no known fMRI correlate of gaining explicit insight. Nocturnal sleep doubled the proportion of explicit learners (Wagner, Gais, Haider, Verleger, &

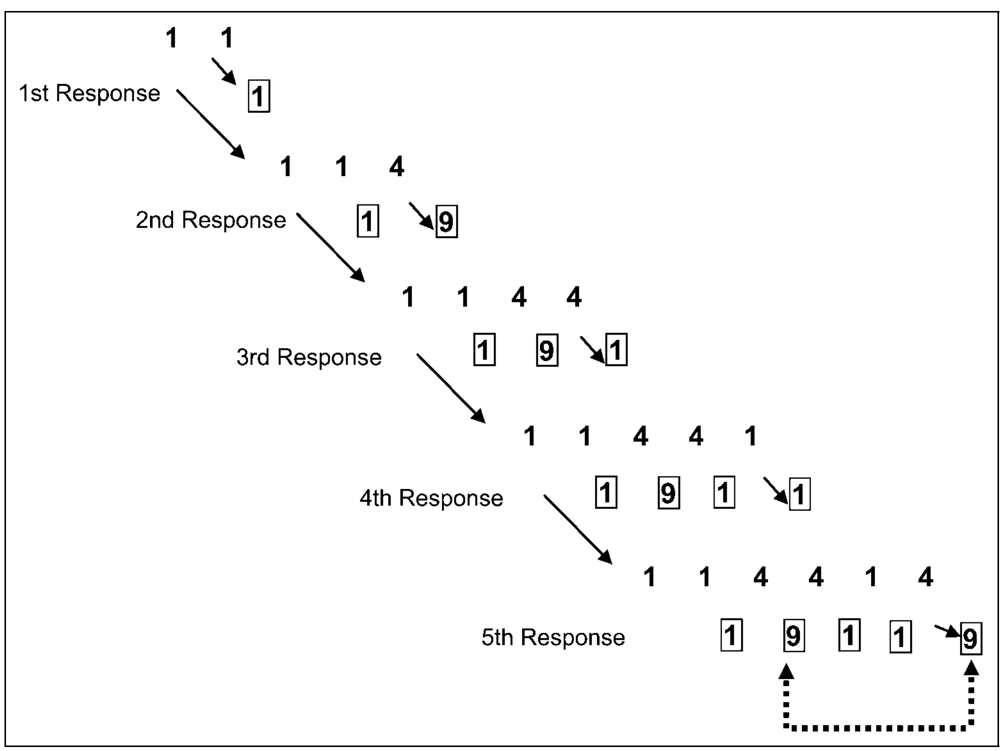

Figure 1. Sample trial of the number reduction task (NRT). Each trial consisted of five digit presentations and five responses. (1) The first presented pair in this trial is ''1 1.'' According to the ''identity rule,'' ''1'' and ''1'' makes ''1.'' This response is entered. (2) A ''4'' is presented and has to be combined with the just entered response ''1.'' According to the ''difference rule,'' ''4'' and ''1'' makes ''9.'' (3) Another ''4'' is presented and has to be combined with the recent response, ''9,'' which makes ''1'' according to the ''difference rule.'' (4) ''1'' is presented, and combined with the recent response ''1'' makes ''1.'' (5) ''4'' is presented, combined with the recent response ''1'' makes ''9.'' This fifth response is the final result, to be confirmed by pressing the enter key. Thereafter, a new trial will start. The covert rule follows the pattern ''ABCCB''; that is, the fifth response is always the same as the second response (symbolized by the dashed arrows). Having gained insight into this rule, participants may shortcut the response sequence by pressing the enter key after the second response, to confirm this response as the final result of the trial.

Born, 2004) possibly because memory representations are reconfigured during sleep, increasing the probability to become aware of the rule.

Hypotheses

The main goal of the present study was to further disclose the cognitive brain processes leading to explicit knowledge by recording event-related potentials (ERPs) of the electroencephalogram (EEG) that reflect information processing time-locked to stimuli or responses. In order to make optimum use of the high temporal resolution of ERPs, we aimed at assigning ERPs to each event. Therefore, in our version of the NRT, the string of digits in each trial did not occur simultaneously as in the studies of Wagner et al. (2004) and Rose et al. (2002, 2004), but digits were displayed successively (Frensch et al., 2002). Responses followed the pattern ABCCB so participants could finish each trial after the second response if they become aware of this rule (see Figure 1). Participants who used this shortcut could be classified as "solvers," the others as "nonsolvers."

As mentioned above, working memory processes might play a decisive role for gaining insight. These processes are not only restricted to short-term storage. In addition, long-term memory representations of the material maintained in working memory may get activated during the task, as well as transient, intermediate stores whose role may be to support the translation of information from working memory to long-term memory (Ruchkin, Grafman, Cameron, & Berndt, 2003). Activation of those longer lasting processes is typically reflected in slow-wave ERPs, and amplitudes of these slow waves are larger when the capacity of working memory is more taxed, thereby differing between participants with high and low working-memory span, both within the healthy population (Vos, Gunter, Kolk, & Mulder, 2001; Müller, King, & Kutas, 1997; Gunter, Jackson, & Mulder, 1995) and likewise between healthy participants and patients with mild working-memory impairment (Ruchkin et al., 1994). The polarity of these slow waves was sometimes negative, sometimes positive. Gunter et al. (1995) and Ruchkin, Johnson, Canoune, and Ritter (1990) provided evidence that positive polarity of slow waves was related to storing items into memory (in contrast to retrieving items from memory) and, of importance to the present task, this was specifically found for memorizing digits (Rösler & Heil, 1991). Therefore, we assume that if working memory plays a role in attaining insight, solvers will show larger slow positive waves than nonsolvers.

Alternatively, or in addition, the critical factor for attaining explicit knowledge might be the strength of representation of events. If this applies to the representation of single stimuli, stimulus-related potentials evoked by the digit presentations should be larger in solvers than in nonsolvers. Relevant components in this respect are the posterior (temporo-occipital) N1, reflecting effort invested for discriminating stimuli (Vogel & Luck, 2000), the anterior (frontocentral) N1, which may be enhanced by voluntary shifts of attention in space (He, Fan, Zhou, & Chen, 2004) or by built-up motor preparation (Vogel & Luck, 2000), the frontal part of the P3 complex (P3a) reflecting reorientation evoked by stimuli (Gaeta, Friedman, & Hunt, 2003; Escera, Alho, Winkler, & Näätänen, 1998; Verleger, Jaśkowski, & Wauschkuhn, 1994), and the parietal part of the P3 complex (P3b) reflecting monitoring of response selection (Verleger, Jaśkowski, & Wascher, 2005).

As described above, a particular role is assigned by the unexpected event hypothesis to the representation of somatosensory reafference of one's own responses: Becoming aware of the fact that one's responses have become faster to certain stimuli might be an important prerequisite of attaining insight into the rule that the responses evoked by these stimuli are actually predictable. Therefore, components of potentials evoked by response onset should be larger in solvers than in nonsolvers. Probably, the relevant component is again a type of P3 complex evoked by the increased perceived relevance (Gaeta et al., 2003; Johnson, 1986) of the responses.

Some of these presumed ERP difference between solvers and nonsolvers might be present already from the very outset of the task. These differences would then be indices of differences in mental set between solvers and nonsolvers. Other differences might develop during the task, and therefore would indicate a role of data-driven processes, accumulating over time (Frensch et al., 2002; Haider, 1997). To investigate both these possibilities, we compared ERPs from the first block to ERPs from the final block before insight in solvers and in nonsolvers.

METHODS

Participants

Thirty healthy students recruited at the University of Lübeck participated in the experiment. Four of them had to be excluded due to technical problems. The final sample comprised 26 participants (14 men, 12 women, mean age 24 years). All participants except one were right-handed, and all had normal or corrected-to-normal vision. Informed written consent was obtained prior to the study. During the experiment, participants were comfortably seated in a sound-attenuated room.

Stimuli and Procedure

Each trial consisted of the interwoven left-to-right presentation of two rows of digits: the material to be processed (in red, at screen center) and participants' responses (in yellow, below screen center). Trials started by the onset of a row of six white dashes, 1 cm below screen center. These dashes served as a warning signal and denoted the positions where the six digits would be presented. After 500 msec, the first two digits simultaneously appeared above the two leftmost dashes. The following digits were separately presented, so there were five "digit presentations" (first and second, third, fourth, fifth, sixth digit) requiring five responses. Digit strings consisted of varying combinations of the numbers 1, 4, and 9 (see Figure 1). A "final result" had to be determined in each trial by pairwise processing of the digits from left to right according to two simple rules: (1) The "identity rule" stated that two identical digits yield that very digit (e.g., "1" and "1" makes "1"), (2) the "difference rule" stated that two different digits yield the remaining third digit (e.g., "4" and "1" makes "9"). The "1," "2," and "3" keys of the numerical pad were labeled "1," "4," and "9," respectively, by adhesive tape and served as response keys. Each entered response immediately appeared in yellow on the screen in a row positioned about 3 cm below screen center, from left to right. At 500 msec after a response, the next digit appeared in the upper row, requiring combined processing with the just entered response (see Figure 1). After the last response, which indicated the final result, participants had to verify the result by pressing the "enter" key. The time for any single response was limited to 4 sec and to a total of 12 sec for all responses until pressing enter. Pressing the enter key was reflected by a change of color, from yellow to blue, of the entered final response on the screen. After another 1000 msec, feedback was provided. In case of a correct final result, all listed responses, in addition to the final one, changed their color from yellow to blue, whereas a short sound rang in case of an incorrect final result. The screen was cleared after 500 msec, and the next trial started.

Most important and unmentioned to participants, the responses followed a hidden rule of the form "ABCCB" ("A," "B," and "C" representing the digits "1," "4," and "9," respectively). Thus, the last two responses were always mirrored by the prior two responses, although the actual digit strings and responses changed from trial to trial. This implied that the second response was always the same as the final result. During initial instruction, participants were informed that the enter key could be pressed whenever the response was believed to be the final result. Thus, in case of gaining insight, participants could press the enter key after the second response, whereupon the trial was finished and the next trial started. Of importance, this instruction was not emphasized explicitly in order to rule out active problem-solving behavior.

By this successive presentation of each digit string (in contrast to the studies of Wagner et al., 2004; Rose et al., 2002), the time point when a stimulus pair was processed could be recorded accurately. Above all, the time point of responding, involving somatosensory reafference of the keypress and visual reafference of the entered digit (by its appearance on the screen), was clearly separated from any further processing of the list because the next digit only appeared after an interval of 500 msec. On the other hand, this successive presentation made insight into the covert rule more difficult. In order to compensate for this increased difficulty, string length was reduced to six digits (from eight digits in Wagner et al., 2004, and Rose et al., 2002) expecting to thereby facilitate insight into the rule.

Before the experiment started, participants had to perform practice blocks of 10 trials guided by extensive standardized instruction given by the computer. The practice blocks ended when participants made less than four errors. The actual experiment included eight blocks of 54 trials each. All eight blocks were presented if no insight into the hidden rule was gained. In case of insight, defined as at least 36 correct shortcuts in one block, the task was terminated.

EEG Recording and Processing

EEG was recorded (band pass: 0.03–35 Hz) by Ag/AgCl electrodes placed at 17 scalp sites (Fp1, F7, F3, Fz, F4, F8, Fp2, C3, Cz, C4, P7, P3, Pz, P4, P8, O1, O2) and at the left mastoid. Electrodes were referred to the right mastoid and rereferenced off-line to the average of the left and right mastoids. In addition, the vertical and horizontal electrooculogram (EOG) was recorded by means of two pairs of electrodes placed above and below one eye and at the left and right orbital rim. Continuously recorded data were digitized with 200 Hz and stored on disk.

Two different types of epochs, long and short, were extracted from these continuous data. Long epochs were to cover slow waves over the course of the trial. These epochs started 100 msec before onset of the string of placeholder lines and lasted for 6 sec. Short epochs of 800 msec were defined for analyzing ERPs to each single stimulus and response within a trial. This had to be done separately from long epochs because the time points of participants' responses and, therefore, of each following digit presentation within a trial were variable with respect to trial onset. Short epochs time-locked to each of the five digit presentations ranged from 100 msec before until 700 msec after stimulus onset, short epochs time-locked to each of the five responses ranged from 400 msec before until 400 msec after the keypress. Stimulus- and response-locked epochs could overlap. Baselines for all short epochs were the 100 msec before the respective event. Epochs from trials with incorrect responses were rejected from further analysis.

Long and short epochs were separately edited for artifacts. First, epochs with amplifier blocking (zero lines) were excluded. Then, the impacts of vertical and horizontal EOG deflections on each EEG channel were separately estimated by linear regression (Anderer, Semlitsch, Saletu, & Barbanoj, 1992; Verleger, Gasser, & Möcks, 1982). These artifacts were then removed from the EEG by subtraction. Thereafter, epochs were excluded when there were still slow drifts larger than 80 μV or fast shifts larger than 100 μV per 200 msec.

The remaining epochs were separately averaged for the first block and for the final block before insight. For nonsolvers, a block was selected as control for this final block by matching three or four out of the 20 nonsolvers, randomly selected, to each of the six solvers. For instance, if one solver gained insight after the third block, the third block was also selected in three nonsolvers. After rejection of trials with wrong responses and artifacts, the long epochs both of the first block and of the final block before insight comprised between 15 and 43 trials in solvers (mean, 36) and between 30 and 53 trials in nonsolvers (mean, 44). These numbers were slightly larger for short epochs; for example, stimulus-locked averages of the first digit pair comprised between 36 and 51 trials in solvers (mean, 44) and between 33 and 53 trials in nonsolvers (mean, 49).

Data Analysis

RTs to the five digit presentations within a trial were separately averaged, using entirely correctly responded trials only, for the first block and for the final block before insight (again matching three or four nonsolvers to each solver, to obtain control blocks for the final block before insight). These mean RTs were first evaluated statistically by an overall analysis of variance (ANOVA) with the factors Block (first block, final block before insight) and Response (1, 2, 3, 4, 5) as repeated measurement factors, and Group (solvers, nonsolvers) as between-subject factor. Then, in order to precisely distinguish between direct response repetition (third vs. fourth response) and the delayed response repetition that was decisive for gaining insight (second vs. fifth response) separate ANOVAs were performed for each of these two pairs of responses, replacing the five-level Response factor by a two-level Predictability factor (unpredictable vs. predictable, i.e., third vs. fourth and second vs. fifth response, respectively).

Event-related Potentials

In the long epochs covering the first 6 sec, a slow positive wave (SPW) was prominent, most marked at parietal sites. The SPW was quantified by computing the mean amplitudes from 0.2 to 5 sec after onset of the first digit pair. Additionally, this global measure was divided into mean amplitudes of five successive 1-sec windows from 0.2 sec after onset of the first digit pair to 5.2 sec. Separate ANOVAs were run for each time window, with the repeated measures factors Electrodes (Fz, Cz, Pz) and Block (first block, final block before insight) and the between-subject factor Group (solvers, nonsolvers). Only the midline electrodes (Fz, Cz, Pz) were included in this and all further analyses (except for posterior N1) because the observed components were most prominent at these electrodes.

Three features were prominent in the stimulus-locked short-epoch ERPs: a negative component between 170 and 280 msec at P7 and P8 (posterior N1), a negative component at midline electrodes between 100 and 200 msec (anterior N1), and a P3 complex from 200 to 500 msec, encompassing a distinct early frontocentral peak at 250 msec, classified as P3a and a tonic positivity at parietal sites, classified as P3b. In the response-locked ERPs, a positive wave was prominent from 200 to 400 msec postresponse, probably reflecting a P3-type component evoked by somatosensory reafference and visual perception of the entered digit, called rl-P300 in the following ("rl" denoting "response locked"). Peak amplitudes were measured for anterior N1, whereas mean amplitudes across the denoted time windows were measured for posterior N1, P3a, P3b, and rl-P300. In the ANOVAs on these ERP components measured in short epochs, the ANOVA design used for long epochs was extended by a five-level factor that denoted the events within a trial. This was Digit Presentation for the stimulus-locked components and Response for rl-P300. The stimulus-locked P3 complex at the first digit pair was omitted from analysis, being principally identical to the first part of SPW analyzed in the long epoch. As with analysis of RTs, the five-level factor was split into pairs of the two-level factor Predictability (second vs. fifth digit presentation and third vs. fourth, respectively) to investigate whether implicit knowledge of either type of predictability was reflected in ERPs and whether there were group differences depending on the regularity type. Therefore, only effects of Group and interaction effects of Group and Predictability will be considered in these subanalyses. Effects of factors that had more than two levels were corrected by adjusting the degrees of freedom by Greenhouse–Geisser's epsilon (ε). For exploring significant interactions, subsets of the data were analyzed separately.

RESULTS

Overt Behavior

Six of the 26 participants gained insight into the hidden rule, as evidenced by their consistently pressing the enter key already after the second response. This occurred for 1 participant in the fourth block, for 2 in the sixth, for 1 in the seventh, and for 2 in the eighth block.

The 20 participants who did not choose this shortcut were asked after the eighth block whether they had noticed some regularity. None of them had, so all 20 were classified as nonsolvers.

RTs are depicted in Figure 2. RTs became generally faster in the course of the task, by 140 msec, on average, from the first block to the final block before insight [Block: $F(1,24) = 12.6$, $p = .002$] indicating procedural learning on how to execute responses according to the ''new arithmetic.'' However, this RT decrease differed between groups and responses [Block × Group × Response: $F(4,96) = 6.8$, $\varepsilon = .54$, $p = .002$; see Figure 2]. Only the predictable responses (fourth and fifth) became faster in solvers [effect of Block in solvers for predictable responses 4 and 5: $F(1,5) = 8.7$, $p = .03$; for unpredictable responses 1–3: $F(1,5) = .5$, *ns*], although all responses became faster in nonsolvers [effect of Block in nonsolvers for predictable responses 4 and 5: $F(1,19) = 17.6$, $p < .001$; for unpredictable responses 1–3: $F(1,19) = 13.6$, $p = .002$].

Being possibly relevant for gaining insight, effects of predictability were separately analyzed for the direct response repetition and for the decisive delayed response repetition. With the direct repetition (fourth vs. third response), predictable responses were generally faster than the preceding unpredictable ones [Predictability: $F_{1,24} = 84.2$, $p < .001$], even already at the beginning of the task [first block: $F(1,24) = 42.9$, $p < .001$]. Of particular interest, although clearly present in both groups [solvers: $F(1,5) = 18.8$, $p = .007$, nonsolvers: $F(1,19) = 20.2$, $p < .001$], the difference between predictable fourth and unpredictable third response increased across blocks more in solvers than in nonsolvers [Predictability × Group: $F(1,24) = 6.1$, $p = .02$; Predictability × Block × Group: $F(1,24) = 11.3$, $p = .003$] primarily because RTs to the unpredictable third response remained stable across blocks in solvers [effect of Block for the third response: $F(1,5) = .7$, *ns*] and became faster in nonsolvers [$F(1,19) = 19.6$, $p < .001$], whereas RTs for the predictable fourth response decreased equally in both groups across blocks [Block × Group for the fourth response only: $F(1,24) = 1.5$, *ns*].

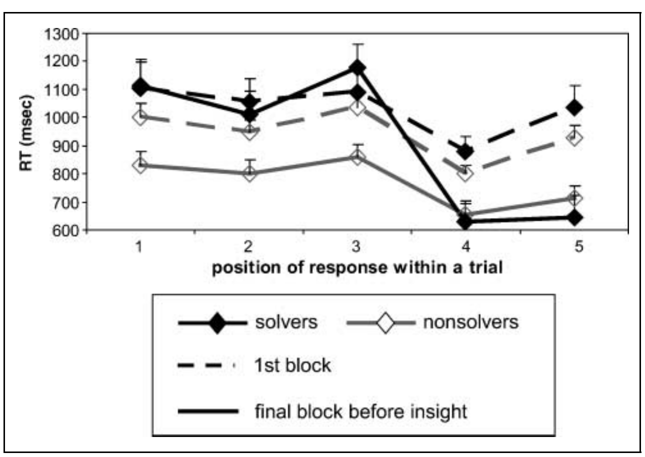

Figure 2. Means and standard errors of RTs across participants. Black lines denote solvers, gray lines denote nonsolvers. Dashed lines denote the first block, solid lines the final block before insight.

Even more important, the decisive covert rule (the fifth response repeating the second) was also implicitly acquired in both groups [Predictability for fifth vs. second response: $F(1,24) = 10.6$, $p = .003$]. In contrast to the more trivial direct response repetition, this decisive effect was absent in the first block and developed during the experiment [Block × Predictability: $F(1,24) = 17.6$, $p < .001$; first block: $F(1,24) = .3$, *ns*; final block: $F(1,24) = 19.9$, $p < .001$]. Furthermore, although both groups had acquired this rule implicitly in the final block [solvers: $F(1,5) = 10.2$, $p = .02$, nonsolvers: $F(1,19) = 4.0$, $p = .06$], the difference between predictable fifth and unpredictable second response increased across blocks more in solvers than in nonsolvers [Predictability × Group: $F(1,24) = 3.3$, $p = .08$; Predictability × Block × Group: $F(1,24) = 7.7$, $p = .01$]. Again this occurred primarily because RTs to the unpredictable second response remained stable across blocks in solvers [effect of Block for the second response: $F(1,5) = 1.0$, *ns*] and became faster in nonsolvers [$F(1,19) = 10.8$, $p = .004$] whereas the RT decrease across blocks did not differ between groups for the predictable fifth response [Block × Group for the fifth response only: $F(1,24) = 2.2$, $p = .16$].

Electroencephalogram

Long Epochs

Grand-average ERP waveforms are shown in Figure 3 for the first block and in Figure 4 for the final block before insight. The visual potential evoked by onset of the fixation line, 500 msec before onset of the first digit pair, can already be discerned before 0 msec, but will not be further considered. Short-term potentials evoked by onset of the first digit pair will be considered below, in analysis of short epochs. Of interest here is the long-lasting SPW, most marked at Pz (''SPW''). Means and standard deviations of SPW at Pz are compiled in Table 1, and the means are additionally shown in Figure 3.

SPW tended to be larger in solvers than in nonsolvers ($F(1,24) = 3.1$, $p = .09$). This tendency became significant when analysis was restricted to Pz recordings [$F(1,24) = 5.6$, $p = .03$]. Furthermore, when breaking down the 5-sec time window to five windows of 1 sec each, the group difference was present as a main effect across blocks and recordings in the first window [200–1200 msec: $F(1,24) = 5.1$, $p = .03$; $F(1,24) < 2.5$, $p > .12$ in the following time windows]. Across groups, SPW decreased at Pz from the first block onward [Block ×

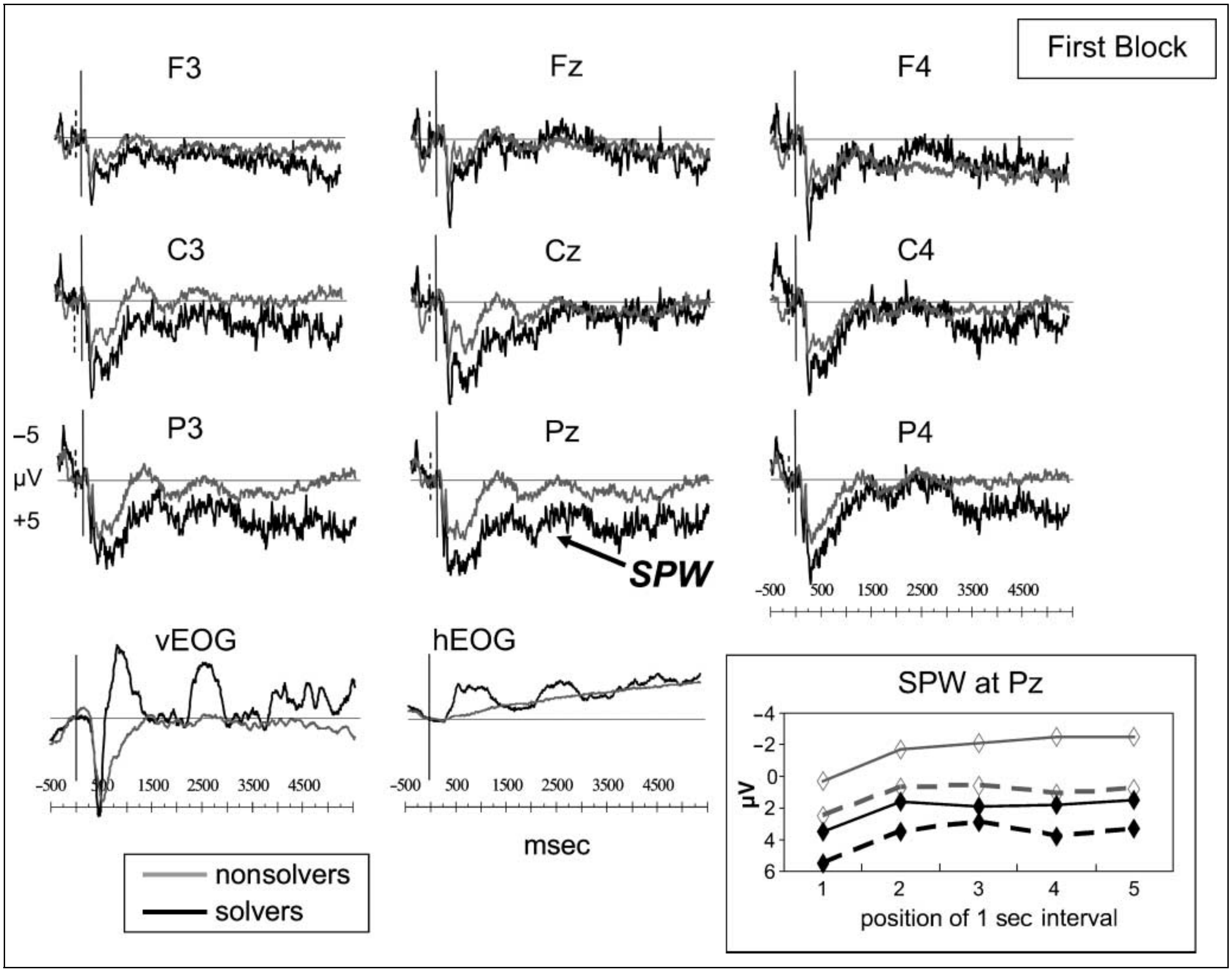

Figure 3. Grand mean ERP waveforms of the first block during the first 6 sec of each trial, separately averaged across solvers (black lines) and nonsolvers (gray lines). Time point zero denotes presentation of the first digit pair, 500 msec after the warning signal. The dashed vertical lines denote the beginning of the baseline interval, 100 msec prior to the first digit pair. Negativity in this and the following figures is plotted upwards. See Figure 2 for legend of the inset (slow positive wave [SPW] amplitude at Pz, separately for five 1-sec intervals, from 0.2 sec onward).

Electrode: $F_{2,48} = 4.5$, $\varepsilon = .96$, $p = .02$; effect of Block at Pz: $F(1,24) = 8.8$, $p = .008$].

Short Epochs

Stimulus-locked ERPs. Short epochs of 700 msec after presentation of each digit in the first block are displayed for midline recordings in Figure 5 and for lateral posterior recordings in Figure 6. Means and standard deviations of selected midline parameters are compiled in Table 1 and the means are additionally shown in Figure 5.

At midline, anterior N1 was visible as a more or less distinct negative peak at about 120 msec, sometimes (e.g., second and fifth digit presentation at Cz and Pz) riding on a slower negative wave. N1 was followed by a P3 complex, consisting of a distinctly peaking P3a component at Fz and Cz and of a sustained positivity at central parietal electrodes (P3b).

N1 amplitudes tended to be affected by an interaction of Group × Digit [$F(4,96) = 2.6$, $p = .07$] and were therefore separately analyzed for each type of predictability (second vs. fifth digit presentation and third vs. fourth). N1 amplitudes to the decisive second and fifth presentations were larger in solvers than in nonsolvers [Group: $F(1,24) = 5.4$, $p = .03$]. In contrast, groups did not differ for the third and fourth digits [Group: $F(1,24) = .4$, *ns*, Group × Predictability: $F(1,24) = .8$, *ns*].

Posterior N1 amplitudes at P7 and P8 did not differ between solvers and nonsolvers [Group: $F(1,24) = .2$, *ns*; Group × Digits: $F(4,96) = .2$, *ns*].

The P3 complex, analyzed for digit presentations 2 to 5 (to avoid replicating the SPW effect, clearly seen at

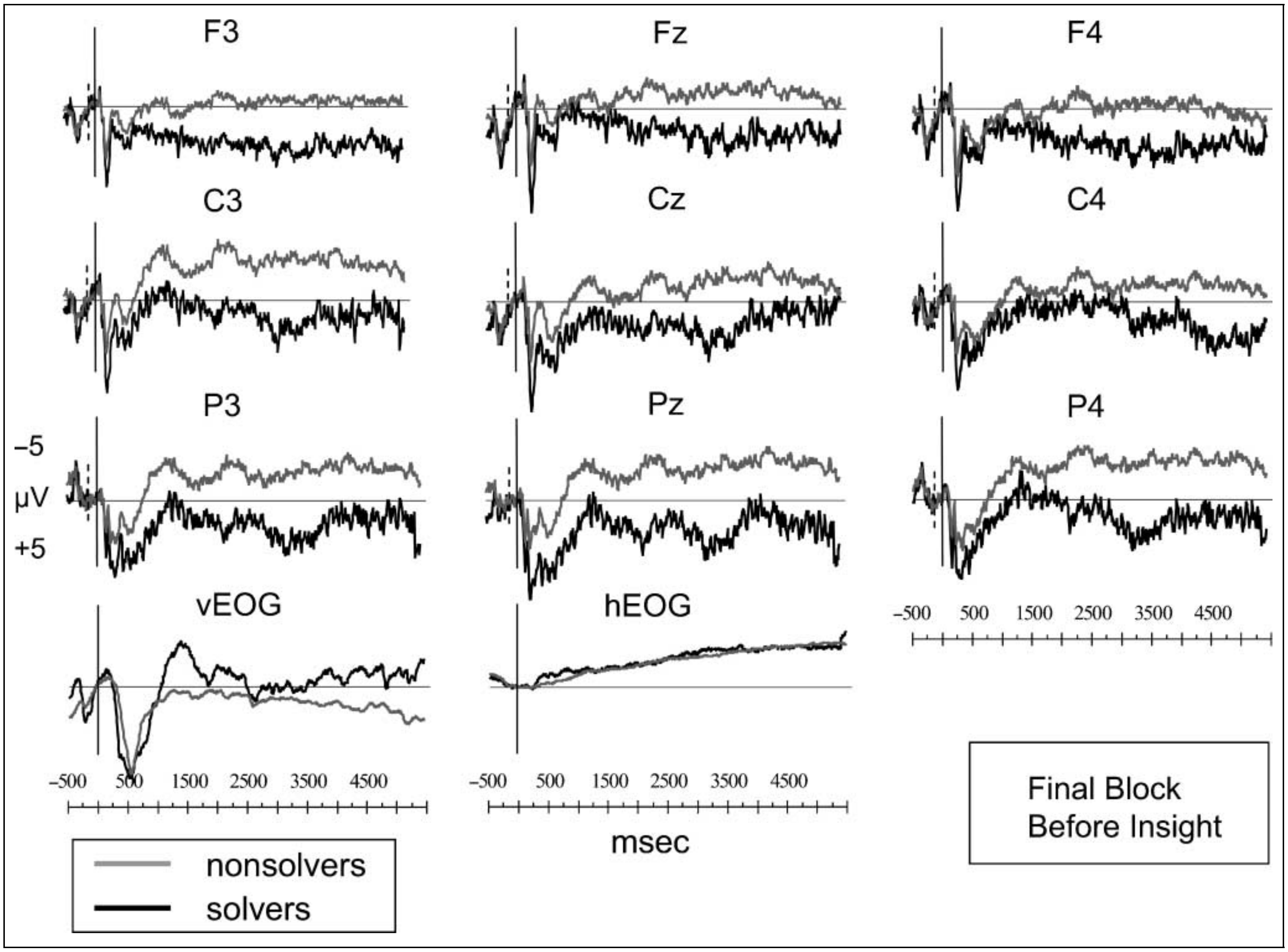

Figure 4. Grand mean ERP waveforms of the final block before insight during the first 6 sec of each trial. See legend of Figure 3 for further details.

the first digit presentation) was larger in solvers than in nonsolvers at Fz [$F(1,24) = 5.1, p = .03$], reflecting the P3a peak and its ensuing return to baseline. Because of the interaction of Block × Electrode × Digit × Group [$F(6,144) = 3.3$, $p = .02$], each type of predictability was analyzed separately. In solvers only, P3b at Pz was larger at the second than at the fifth digit presentation in the final block before insight [effect of Predictability: $F(1,5) = 5.1$, $p = .07$ in solvers; $F(1,19) = .0$, *ns* in nonsolvers; see Figure 7, left]. Also in solvers only, the P3 complex was larger at the third than at the fourth digit across blocks [see Figure 7, right; Group × Predictability: $F(1,24) = 8.7, p = .007$; effect of Predictability: $F(1,5) = 11.4$, $p = .02$ in solvers; $F(1,19) = 2.3$, $p = .15$ in nonsolvers]. Being largest at Pz [$F(1,5) = 26.4$, $p = .004$], this effect likewise reflected the P3b part of the P3 complex.

Response-locked ERPs. Grand-average response-locked ERP waveforms of the final block before insight are shown in Figure 8. Of interest was the positive component following response onset, possibly indicating evaluation of one's response. This rl-P300, compiled in Table 1, was largest at the first and the fifth responses [Response: $F(4,96) = 5.3, \varepsilon = .61, p = .005$], although in the final block before insight (shown in Figure 8) only the fifth response elicited a larger rl-P300 than the other responses [Response × Block: $F(4,96) = 3.6$, $\varepsilon = .77$, $p = .02$]. More importantly, no effects of Group were found. Nevertheless, when single comparisons were made between solvers and nonsolvers at each recording site in each block for each type of Predictability due to the a priori hypothesis about the importance of response evaluation, the most significant result was the tendency for an effect of Group at Pz in the final block before insight in analysis of the two immediately repeating responses (third and fourth), $F(1,24) = 3.3, p = .08$.

DISCUSSION

Overall Performance

Participants who discovered the covert rule could be clearly distinguished from participants who did not. Like in our previous study (Wagner et al., 2004), solvers

Table 1. Means and Standard Deviations (in Parentheses) of Relevant Parameters (in Microvolts)

	SPW: Pz	*N1: Cz*	*P3a: Fz*	*P3b: Pz*	*rl-P300: Pz*
Solvers					
First block					
1	5.5 (3.3)	−0.8 (1.1)	3.9 (1.8)	6.2 (3.3)	−3.9 (4.1)
2	3.5 (3.8)	−2.8 (1.6)	4.0 (2.7)	2.9 (3.1)	−3.9 (4.1)
3	2.9 (3.9)	−2.3 (1.6)	4.4 (2.3)	3.8 (2.5)	−2.1 (3.8)
4	3.8 (4.3)	−2.5 (2.0)	3.5 (2.9)	2.4 (4.0)	−2.4 (3.3)
5	3.3 (3.4)	−2.0 (2.5)	3.1 (1.2)	2.5 (2.1)	−0.8 (3.4)
Final block					
1	3.5 (3.7)	−1.2 (1.2)	3.2 (2.1)	4.4 (3.2)	−2.2 (2.6)
2	1.6 (4.4)	−3.5 (1.5)	3.2 (2.1)	4.4 (3.2)	−4.6 (2.6)
3	1.9 (3.9)	−1.7 (1.6)	3.4 (2.5)	2.6 (2.3)	−2.6 (4.2)
4	1.8 (3.7)	−1.6 (1.0)	3.0 (1.6)	1.4 (0.6)	−6.1 (3.4)
5	1.5 (3.4)	−3.5 (2.4)	3.3 (1.5)	1.0 (1.8)	−1.8 (2.3)
Nonsolvers					
First block					
1	2.5 (2.7)	−1.7 (3.5)	1.5 (3.2)	3.9 (2.3)	−4.1 (3.8)
2	0.7 (3.6)	−1.2 (1.9)	2.5 (1.5)	2.8 (2.7)	−4.1 (3.8)
3	0.6 (3.1)	−1.0 (1.5)	2.0 (1.4)	3.2 (2.4)	−4.0 (3.0)
4	1.1 (3.3)	−0.8 (2.2)	2.2 (1.4)	2.4 (3.0)	−4.4 (3.3)
5	0.8 (2.8)	−1.1 (1.7)	2.1 (2.0)	2.7 (3.1)	−1.7 (2.2)
Final block					
1	0.3 (2.5)	−2.1 (3.0)	1.1 (3.2)	1.9 (1.9)	−3.1 (3.7)
2	−1.7 (3.9)	−1.7 (2.1)	2.4 (2.4)	1.8 (2.0)	−4.0 (3.2)
3	−2.1 (4.5)	−1.8 (1.7)	2.1 (1.7)	1.5 (2.7)	−4.1 (2.8)
4	−2.5 (5.1)	−1.3 (2.1)	2.8 (1.9)	2.1 (2.6)	−5.3 (4.8)
5	−2.5 (4.3)	−1.8 (2.9)	1.8 (1.6)	1.9 (3.1)	−2.2 (2.2)

The numbers 1, 2, 3, 4, and 5 in the first column denote the number of 1-sec intervals (beginning at 0.2 sec) for SPW, number of digit presentations for the stimulus-locked components N1, P3a, and P3b (i.e., 1, 2, 3, 4, 5 corresponds to presentation of first and second, third, fourth, fifth, sixth digit), and number of responses for the response-locked component rl-P300.

formed a minority. Their proportion (6/26, 23% of all participants) comes very close to the rates of the control groups in that previous study. Thus, by reducing the length of the digit strings from eight to six, we could compensate for the presumably increased difficulty of discovering the rule, produced by presenting the digits successively rather than simultaneously.

Response Times

Both solvers and nonsolvers learned the covert rule implicitly, as indicated by their decreased RTs for predictable compared to unpredictable responses. This is in line with other NRT studies (Rose et al., 2004; Wagner et al., 2004; Frensch et al., 2002; Rose et al., 2002). One might argue that fast responses to the last digit presentation were simply due to the fact that these were the final responses to the string. But it was demonstrated by Rose et al. (2004) that such fast responses only occur in strings conforming to the underlying rule.

RTs differed between predictable and unpredictable responses more in solvers than in nonsolvers, both for the direct repetition and for the critical delayed repetition. Thus, it may appear that implicit learning of these

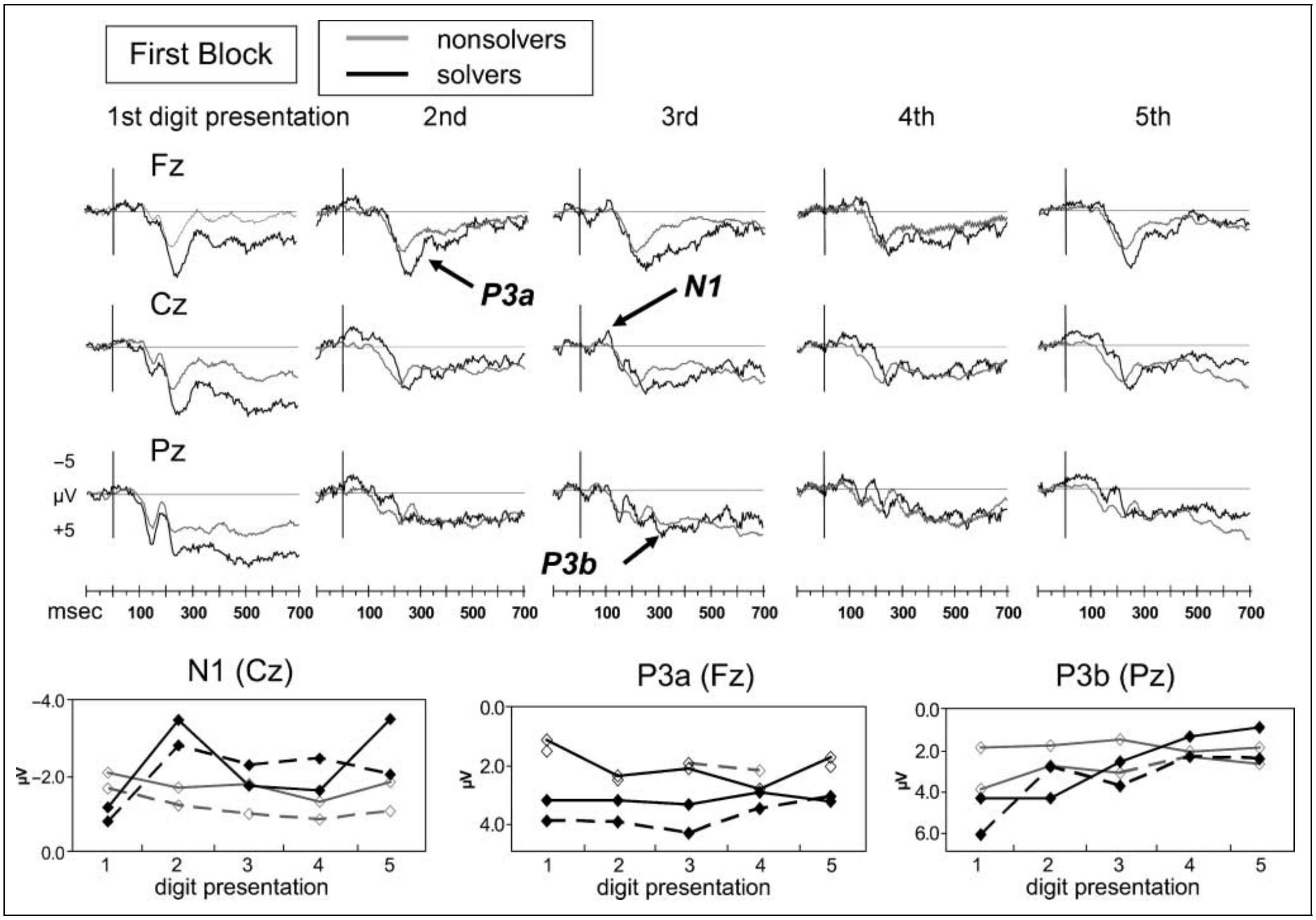

Figure 5. Grand mean ERP waveforms for each digit presentation, averaged across trials of the first block, separately for solvers (black lines) and nonsolvers (gray lines). Time point zero, illustrated by the solid vertical lines, denotes onset of digit presentation. See Figure 2 for legend of the three insets.

repetitions occurred to a greater extent in solvers. However, solvers' RT difference was not increased by their being consistently faster when responses were predictable, but rather by their being consistently slower than nonsolvers when responses were unpredictable. In fact, whereas nonsolvers increased their response speed

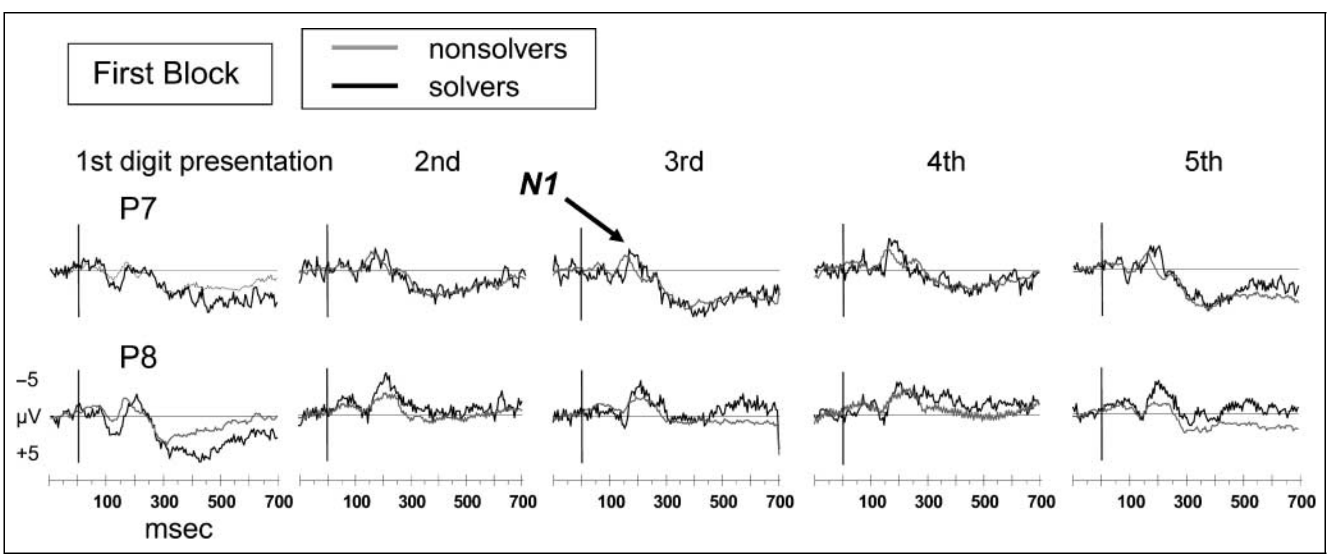

Figure 6. Grand mean ERP waveforms at electrode sites P7 and P8 averaged across solvers (black lines) and nonsolvers (gray lines) to all digits of the first block. Time point zero denotes onset of digit presentation.

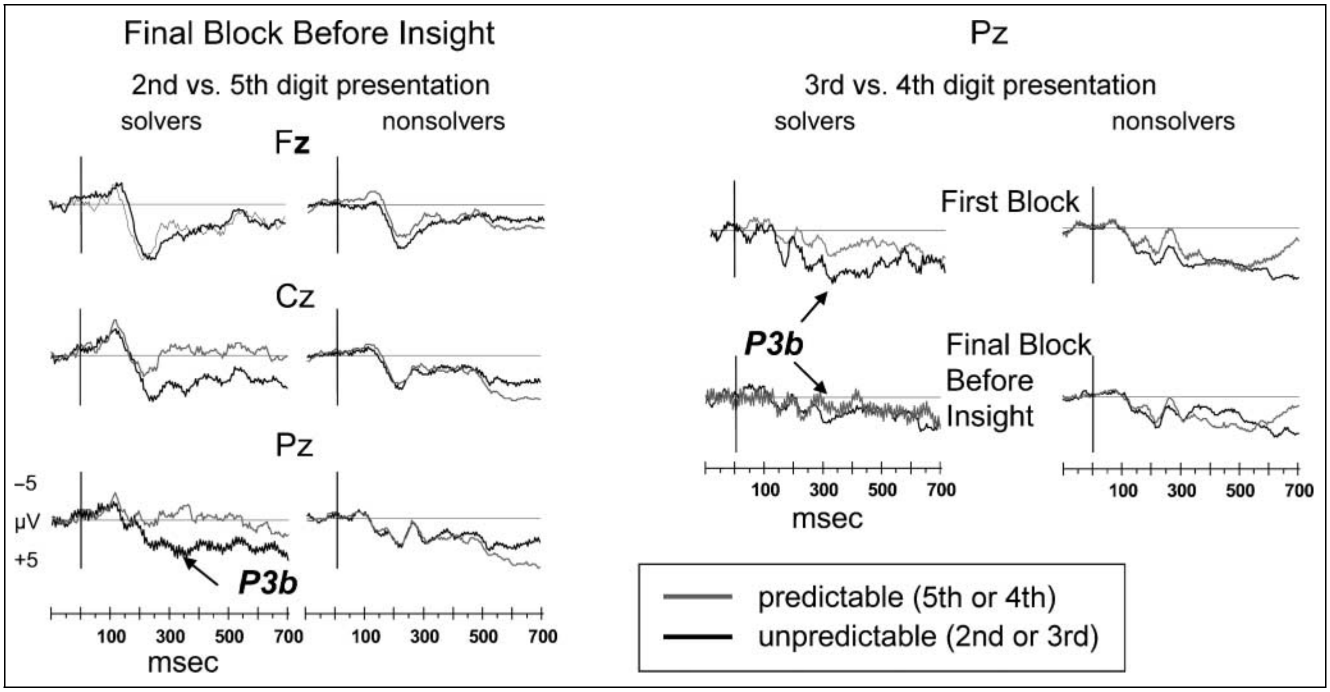

Figure 7. Selected grand mean ERP waveforms evoked by digits that required response repetitions. ERPs related to unpredictable first responses are displayed in black, ERPs related to predictable repeating responses are displayed in gray. Left: midline recordings of the delayed repetition in the final block before insight (unpredictable response to second digit presentation, predictable response to fifth one). Right: Pz recordings of the immediate repetition (unpredictable response to third digit presentation; predictable to fourth one), separately for the first block and for the final block before insight. Within either panel, solvers' grand means are on the left, nonsolvers' on the right.

with these unpredictable responses throughout the experiment, solvers did not. As detailed in the Introduction, gains in response speed with unpredictable responses were expected due to procedural learning, that is, due to applying the two newly learned formulas, ''identity'' and ''difference,'' and improving response selection and execution. It might be of particular interest that solvers did not show such a general procedural learning effect. Wagner et al. (2004), who had obtained similar results, had suggested that the solvers' slower responses to unpredictable responses might be related to processes of search and task analysis (Jiménez, Mendez, & Cleeremans, 1996) triggered by an incipient representation of the hidden rule. An alternative, intriguing possibility is that procedural learning may impede declarative learning, perhaps by involving participants in irrelevant details, preventing them from seeing the forest behind the trees. On the other hand, this difference between solvers' and nonsolvers' RTs with unpredictable responses did not show up in several experiments in Haider and Frensch's laboratory (Haider & Frensch, submitted); therefore, this issue is not yet resolved and might be related to the special version of the present experiment, with its successive presentation of digits.

In the Introduction, three classes of hypotheses were described on the relationship between implicit learning and explicit awareness: Class 1 assumes that mere strength of implicit learning leads to its being transformed to explicit knowledge, Class 2 assumes that the processes differ from the very outset, and Class 3 assumes that increased strength of implicit learning leads to guided search, which in turn leads to awareness. It appears that the solvers' lack of procedural learning is most compatible with Class 2 hypotheses. Alternatively, when interpreting the slow RTs with unpredictable responses as being due to search processes (Wagner et al., 2004) the RT results can be reconciled with Class 3 hypotheses.

Event-related Potentials

RTs did not differ between solvers and nonsolvers at the beginning of the experiment, and thus gave no hint for predicting who would discover the regularity and who would not. The main question asked by the present study was whether indices of brain activity as measured by ERPs (event-related brain potentials) would be precursors of insight and might also reveal some of the involved mechanisms. Indeed, several differences in ERPs were found.

Most conspicuous was the large, parietally focused SPW in solvers (Figures 3 and 4). This slow wave spanned several seconds, certainly encompassing the first three digit presentations, probably even more. (SPW was probably attenuated by the lower bound of 0.03 Hz in amplifying the recorded EEG signals because this amplifier

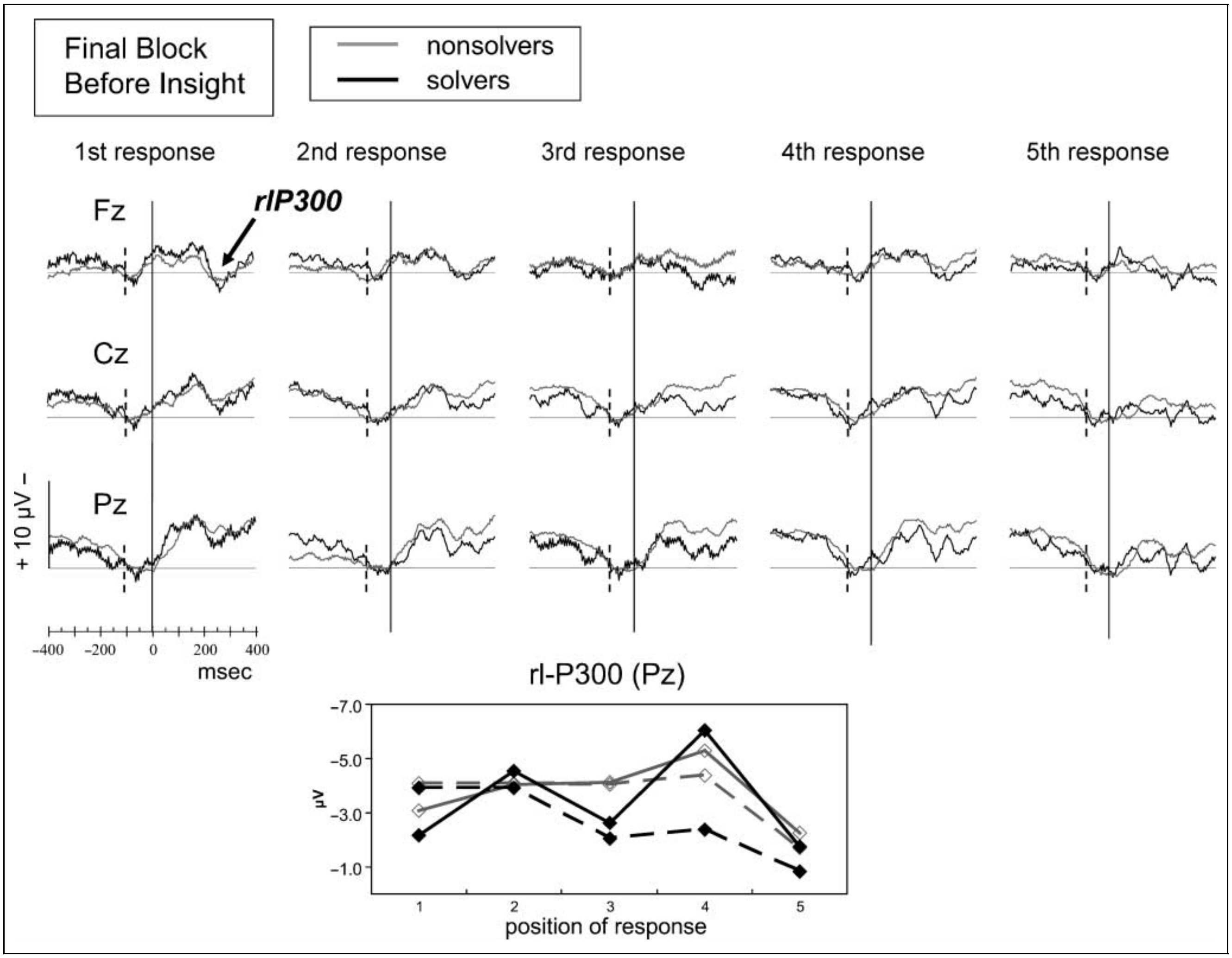

Figure 8. Grand mean ERP waveforms of solvers (black lines) and nonsolvers (gray lines) during the final block before insight, averaged time-locked to response onsets. The solid vertical line illustrates response onset. The dashed vertical lines denote the beginning of the baseline interval 100 msec prior to each response. See Figure 2 for legend of the inset.

setting reduces any constant signal to one third of its starting value after 5 sec.) There is ample evidence that posterior positivity elicited by visual stimuli, in particular by digits, is related to short-term (Ruchkin et al., 2003; Mecklinger & Pfeifer, 1996; Rösler & Heil, 1991; Ruchkin et al., 1990) as well as to long-term memory (termed ''dm,'' difference due to memory: Guo, Voss, & Paller, 2005; Schott, Richardson-Klavehn, Heinze, & Düzel, 2002; Van Petten & Senkfor, 1996) and, as mentioned in the Introduction, larger amplitude of slow waves is related to more capacity invested in working-memory processing (Vos et al., 2001; Müller et al., 1997; Gunter et al., 1995; Ruchkin et al., 1994). Therefore, these larger amplitudes might indicate that solvers encoded the digits and responses of each trial in memory, more deeply than nonsolvers.

Furthermore, likewise in the first block already, the frontocentral P3a was larger in solvers than in nonsolvers, at all digits. Applying concepts on correlates of P3a from the literature to this result suggests that solvers were more surprised by each new digit (Verleger et al., 1994), treated each digit as more distinct from other stimulation (Gaeta et al., 2003), and were more induced by each digit to reorient their attention (Escera et al., 1998). These descriptions converge to the bottom line that solvers paid more attention to the single digits than did nonsolvers.

Two other effects in solvers' ERPs, also already present in the first block, were specific to particular digit positions. The P3 complex decreased from the third to the fourth digit presentation, probably because the fourth digit presentation, by triggering an immediate repetition of the previous response, was redundant in its informational value, in line with the notion that P3 reflects the informational value and relevance of events (Kotchoubey & Lang, 2001; Wascher, Verleger, Jaśkowski, & Wauschkuhn, 1996; Gratton et al., 1990; Johnson, 1986). Furthermore, anterior N1 amplitudes evoked by the digit presentations that evoke the critical repeating second and fifth responses were larger in solvers, possibly by riding on slow negative shifts. As noted in the Introduction, this result may indicate voluntary shifts of attention (He et al., 2004). Alternatively, not necessarily in conflict, the underlying slow negative shifts might be responsible for this effect (Vogel & Luck, 2000), as type of Contingent Negative Variation (Brunia, 2003; Verleger, Wauschkuhn, van der Lubbe, Jaśkowski, & Trillenberg, 2000), which might have developed between previous response and the present digit and which might indicate that solvers prepared more intensively their responses to these critical digits.

Finally, another difference between solvers and nonsolvers was only visible in the final block before insight: Specifically in solvers' ERPs, the P300 complex decreased from the second to the fifth digit presentation. This effect may be interpreted in parallel to the solvers' just mentioned P300 decrease from the third to the fourth presentation: In the final block before insight, solvers attributed more relevance and extracted more information from the second than from the fifth digit presentation, beginning to realize that the second presentation may be used to determine the final result. Thus, this result appears to be less a precursor rather than a correlate of insightful behavior.

Within the context of Class 3 hypotheses, a special hypothesis assumed that solvers pay increased attention to their fast responses with response repetitions. Therefore, the positivity evoked by response onset (rl-P300) was analyzed. Results provided only weak evidence in support of this hypothesis. A tendency (p = .08) for larger rl-P300 in solvers was found for the immediate repetition in the final block before insight. Even if significant, this effect to the less decisive immediate repetition occurred in the same block when the critical second digit presentation already evoked an enhanced P300, indicating that solvers already had assigned some special role to this digit. Thus, the rl-P300 cannot be easily made responsible for the upcoming insight. It might, however, be argued in favor of this hypothesis that circumstances for its testing were adverse: Because digits were presented sequentially rather than simultaneously in a fixed interval (0.5 sec) after each response, participants could not make speeded responses below a certain limit, unlike, for example, in Rose et al. (2002). Thus, the unexpected event of responding faster than allowed by instructions was not easily accessible to participants. Indeed, when comparing conditions when participants could make premature responses versus when they could not, Haider and Frensch (submitted) found that the percentage of solvers almost doubled when premature responses were allowed.

To summarize the interpretation of the ERP results as proposed in the foregoing, solvers stored the perceived events to memory to a greater extent (as indicated by the SPW), paid more attention to the presented digits (as indicated by frontal P3a), paid more attention to the direct repetition of responses (as indicated by P300 decrease to fourth digit presentation), and even appeared to select the critical second and fifth digit presentations (as indicated by anterior N1). All these effects already emerged during the first block. Most astonishing is the selective early effect on anterior N1. Possibly, the reason for this effect is not that solvers had already specifically selected these digits to be critical but that solvers simply paid more attention to these digits for some other reason, perhaps because of the positions of the digits that marked the start and the end of the presentation of single digits. Whether such incidental selection of the critical digits was causal to later insight or was simply a correlate of more attentive behavior during the experiment cannot be decided.

What may be said is that by their early appearance in the task, these effects form evidence for Class 2 hypotheses: Solvers approach the task differently from nonsolvers, and their explicit knowledge is based on some processing that differs from implicit learning from the very beginning. So if we apply this result to the instance quoted in the Introduction, we may safely conclude the following: Not everybody would have gained insight into the law of gravitation by an apple falling on his or her head, rather it had to be somebody interested in the laws of physics.

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Reprint requests should be sent to Rolf Verleger, University of Lübeck, Department of Neurology, Ratzeburger Allee 160, 23538 Lübeck, Germany, or via e-mail: rolf.verleger@neuro.uni-luebeck.de.

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