

Problem-solving without awareness: An ERP investigation

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ABSTRACT

When subjects are given the balls-and-boxes problem-solving task (Kotovsky & Simon, 1990), they move rapidly towards the goal after an extended exploratory phase, despite having no awareness of how to solve the task. We investigated possible non-conscious learning mechanisms by giving subjects three runs of the task while recording ERPs. Subjects showed significant differences in their ERP components during the exploratory phase between correct and incorrect moves. Exploratory incorrect moves were associated with a shallower response-locked N1 component and a larger response-locked P3 component compared with exploratory correct moves. Subjects who solved the task more quickly exhibited a trend towards larger N1 and P3 components. These results suggest that the brain processes information about the correctness of a move well before subjects are aware of move correctness. They further suggest that relatively simple attentional and error-monitoring processes play an important role in complex problem-solving.

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Traditionally, problem-solving has been viewed as an area of “higher cognition” that is presumed to depend on conscious reasoning. However, work in the last two decades has shown that it can be significantly influenced by non-conscious processes as well (Kotovsky & Simon, 1990; Lovett & Anderson, 1996; Reber & Kotovsky, 1997; Squire & Frambach, 1990). In a seminal study by Berry and Broadbent (1984), subjects were asked to keep the output of a hypothetical sugar factory within a certain range. These subjects improved in their ability to perform this task with practice even though they could never articulate the rule determining the output levels. Other work has shown that patients suffering from anterograde amnesia still show improvements with practice for some problem-solving tasks (Phelps, 1989; Squire & Frambach, 1990). Different lines of research have shown that non-conscious learning mechanisms can be equally important in other areas of higher cognition, most notably metacognition (Diana & Reder, 2004; Nhouyvanisvong & Reder, 1998; Reder, 1996; Spehn & Reder, 2000) and language-learning (Dienes, Altmann, Kwan, & Goode, 1995; Reber, 1989; Tunney & Altmann, 2001).

There have been a number of efforts to explore non-conscious problem-solving, but the neural substrates of these phenomena still remain unclear. Neuropsychology studies suggest that the frontal lobes may be important because frontal lobe patients show

deficits in solving problems that do not require conscious learning (Goel & Grafman, 1995; Morris, Miotto, Feigenbaum, Bullock, & Polkey, 1997). It has also been suggested that the left dorsolateral prefrontal cortex may be particularly crucial for non-conscious problem-solving by allowing comparisons of non-verbal stimuli (Colvin, Dunbar, & Grafman, 2001).

A particular problem that lends itself readily to study of non-conscious problem-solving is the “balls-and-boxes” task, originally developed by Kotovsky and Simon (1990). In this problem-solving task, five balls are shown that are inside of five boxes (see Fig. 1). The goal is to get all of the balls out of their boxes. A ball can only be moved in or out of its box if and only if the top of its box is open. There are two rules governing whether or not the top of a box is open. First, the top of the rightmost box is always open. Second, the top of one of the other boxes can only be open if the ball immediately to its right is inside of its box and any balls further to the right are outside of their boxes. There are 32 possible states for this problem, a state being defined simply as the configuration of which balls are in or out of their box, which in turn determines which boxes have their tops open. For this experiment, a standard start state was used in which all balls were initially inside their boxes. From this state, a minimum of 21 moves is needed to reach the goal. Subjects must sometimes place a ball back into a box and at other times take a ball out to reach the goal state. The rules for this problem are such that there is a linear problem space—that is, there are always only two moves available, one of which will take one closer to the goal while the other takes one further from it. This allows for convenient analysis since any move the subject makes is unambiguously correct or incorrect. Distance from the goal is always well-defined, albeit unknown to the subject.

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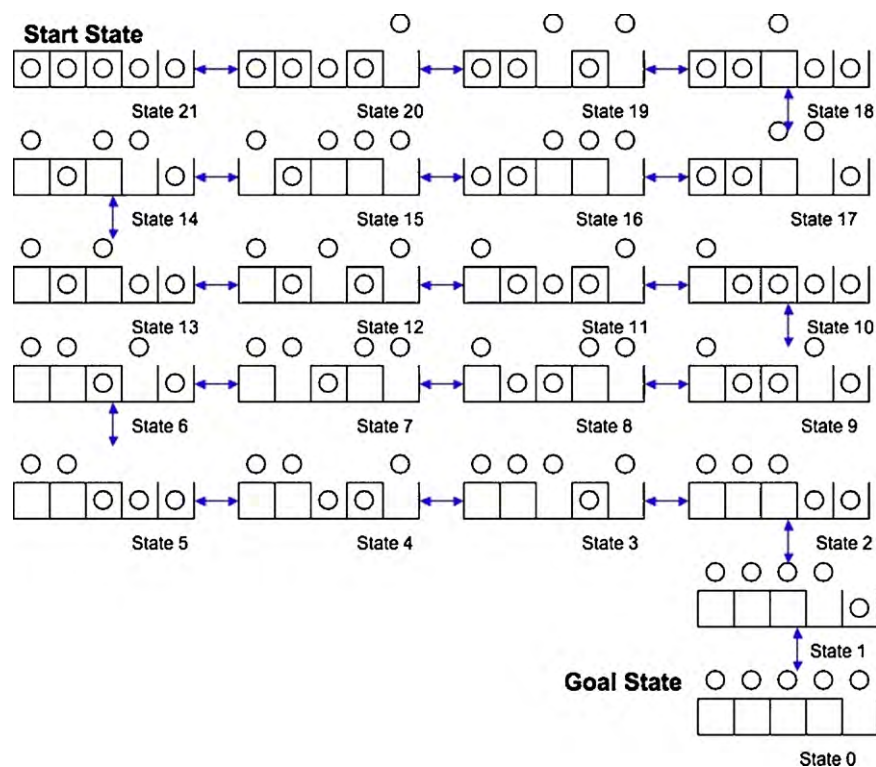


Fig. 1. Problem space of balls-and-boxes task moving from the start state to the goal state.

When subjects were asked to perform this task, they showed an initial exploratory phase (an average of 77 moves, *S.D.* = 4.9) before suddenly making an average of 18.4 correct moves (*S.D.* = 1.0) in succession to reach the goal state. This long string of correct moves at the end with no interrupted incorrect moves was referred to in a follow-up study as a “final path” (Reber & Kotovsky, 1997). It is clear that subjects had tacitly learned the rules because it is highly improbable statistically that subjects would make so many correct moves in succession by chance. A similar dichotomous exploratory-final path move-making phenomenon has been observed with other problems as well (Kotovsky, Hayes, & Simon, 1985). Despite strong evidence of learning, it is well-documented that subjects do not report any awareness of how to solve the puzzle during or after the experiment. A verbal protocol analysis by Reber and Kotovsky (1997) of subject verbalizations during the task yielded no useful information about how to solve the problem and no indications that subjects were aware of whether a given move was correct or incorrect. Furthermore, subjects were at chance when given a test after the experiment asking them if a given move would take them closer or further from the goal. When subjects were given the same task a second time, they showed a shorter exploratory phase (suggesting tacit learning across runs) before again moving straight to the goal (Reber & Kotovsky, 1997).

The current study uses the balls-and-boxes task in conjunction with ERP to monitor brain activity during the performance of this task. If problem-solvers are tacitly learning to perform the task, we wish to determine what the markers of this learning might be. Since the experiment uses the exact same task as Reber and Kotovsky (1997), which showed with verbal protocol analysis that subjects have no conscious awareness of move correctness or any other aspect of the task, we assumed that subjects would lack explicit knowledge for our study as well. Verbal protocols were not collected for this study since they would disrupt the collection of EEG data. Of particular interest is whether and at what stage in processing the brain is able to detect whether a move is correct (towards the goal) or incorrect (away from the goal). If differences are found

between correct and incorrect responses during the exploratory phase, this will suggest that information is present as to the problem solution even before the final path. Our study is focused solely on implicit knowledge of whether a move is correct or incorrect and not directly on implicit knowledge of the task (that is, knowledge of the abstract rules governing when the top of a box will be open or closed). Because earlier work by Reber and Kotovsky (1997) using this same paradigm has established that subjects have no useful conscious knowledge about any aspect of the task, we do not see how knowledge of this more abstract sort could be ascertained. One could attempt to analyze illegal move attempts by subjects (that is, attempts to move a ball in or out of its box when the top is closed, which leads to no change in the stimulus pattern). However, subjects make relatively few of these sorts of illegal moves, and they are in any case indistinguishable from cases where the wrong button is mistakenly pressed.

Given the relative lack of neuroimaging work on non-conscious problem-solving, it is difficult to predict beforehand what ERP components should be relevant. If differences are indeed found between exploratory correct and exploratory incorrect moves, they should show up in components typically associated with error-monitoring. Most ERP research on error-monitoring has focused on the ERN and, to a lesser extent, the error positivity component. The ERN (for error-related negativity) is a negative component maximally active in medial frontal areas between 50 and 100 ms following a response (see Taylor, Stern, & Gehring, 2007 for a review). It has been variously associated with conflict processing (Botvinick, Braver, Barch, Carter, & Cohen, 2001), reinforcement learning (Holroyd & Coles, 2002), and registering the emotional significance of an error (Luu, Tucker, Derryberry, Reed, & Poulsen, 2003) and may play a role in the balls-and-boxes task. A less well understood component important in error-monitoring is the error positivity component (abbreviated Pe), a diffuse positive deflection maximal between 200 and 400 ms (Falkenstein, Hohnsbein, & Hoormann, 1991; Overbeek, Nieuwenhuis, & Ridderinkhof, 2005). The Pe is most often associated with conscious detection that

an error has occurred (Davies, Segalowitz, Dywan, & Pailing, 2001; Kaiser, Barker, Haenschel, Baldeweg, & Gruzelier, 1997; Nieuwenhuis, Ridderinkhof, Blom, Band, & Kok, 2001; Taylor et al., 2007), although an alternative view emphasizes the importance of the Pe in registering the emotional and motivational salience of the error (Falkenstein, Hoormann, Christ, & Hohnsbein, 2000; van Boxtel, van der Molen, & Jennings, 2005; Van Veen & Carter, 2002). To the extent that this view of the Pe is accurate, we might also expect the Pe to be involved in the balls-and-boxes task, especially since emotional processes are known to be important in other forms of non-conscious decision-making (e.g. Bechara, 2001; Damasio, 1996). Finally, a component referred to as a nogo P3 appears during oddball when a distracter appears indicating a “nogo” trial (Kok, 1986; Pfefferbaum, Ford, Weller, & Kopell, 1985). This component is typically maximal over central-parietal areas and is thought to be associated with inhibition of subject responses (Azizian, Freitas, Watson, & Squires, 2006; Falkenstein et al., 2000; Polich, 2007; Salisbury, Griggs, Shenton, & McCarley, 2004).

In short, we have several tentative predictions for what should be expected based on the literature. The data from neuropsychology studies suggest that frontal ERP components should be most predictive of ability to solve the task, since as noted previously, damage to the frontal lobes leads to impairments in non-conscious problem-solving generally. We are particularly interested in the contrast between responses to exploratory correct and exploratory incorrect trials and would predict differences in the ERP components associated with error processing. Finally, we wish to look at individual differences in the ERP components. It is known that there is wide variation in the number of moves subjects require to solve the balls-and-boxes task. However, it is unclear from behavioral data alone what allows some individuals to solve the task more quickly than others. We believe ERP analysis can shed light on this issue. If it turns out, for example that an N1 component is larger for fast solvers than slow ones, this would suggest that differences in attentional shifts can explain at least some of the variance in individual performance during this task.

1. Methods

1.1. Participants

Thirty-two participants (19 males and 13 females) with a median age of 22 were recruited from the Pittsburgh community. Of these participants, 25 were given 15 dollars in compensation. The remaining participants were given research credit.

1.2. Design/materials

The experiment utilized the balls-and-boxes problem developed by Kotovsky and Simon (1990) described earlier.

1.3. Procedure

Participants were seated approximately two feet from a computer screen and made their responses on a button box with five labeled keys each corresponding to one of the five boxes. Participants rested both hands on the button box and moved ball 1 (the leftmost ball) in or out with the ring finger of their left hand, ball 2 with the middle finger of their left hand, ball 3 with the index finger of their left hand, ball 4 with the index finger of their right hand, and ball 5 with the middle finger of their right hand. Instruction screens at the beginning informed subjects that the goal of the puzzle was to get all of the balls out of their boxes, that they would need to complete the task three times, and that a ball could only be moved in or out if the top of its box was open. However (as in earlier versions of the experiment), they were not told the rules for when a box's top would be open or closed. After subjects made a button press, a random 200 ms jitter occurred before the onset of the screen for the next problem state. In the event that the participant mistakenly tried to move a ball in or out if the corresponding box top was closed, no change appeared in the stimulus. These “error” trials were not analyzed, as they occurred very infrequently. Participants were required to solve the problem three times to finish the experiment. After the completion of the first and second runs, a brief two second delay occurred before a screen appeared telling subjects that they would next perform another run of the same task. The screen then moved back to the start state after the participant pressed any of the five buttons. After the completion of

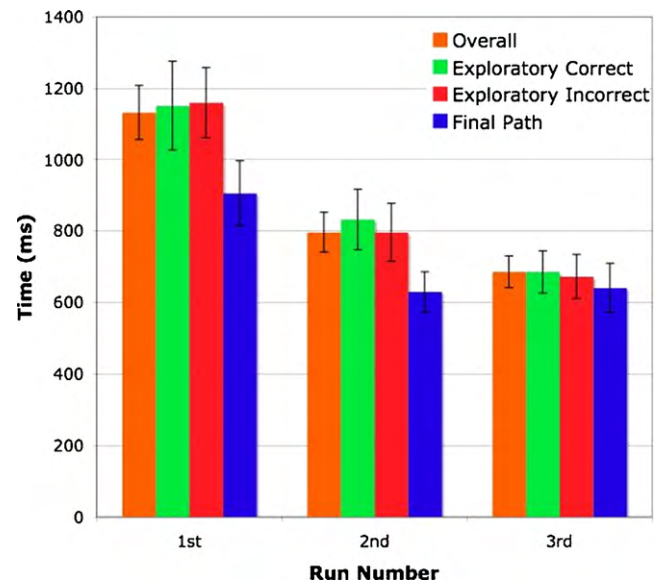


Fig. 2. Move times for different conditions across run numbers. The error bar is one standard error.

the final run, a screen appeared after a two second delay saying the experiment was complete and thanking them for participating. The task took approximately 20 min for all three runs (not counting setup time). After completing the task, subjects were debriefed and given payment or credit.

1.4. 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. 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 0.1–200 Hz. Vertical eye movements were recorded using electrodes placed immediately above and below the orbit of the left eye. Horizontal eye movements 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 1000 ms relative to trial onset (i.e., time of the button press for the response-locked analyses or time of the appearance of the new configuration for the stimulus-locked analyses) for each of the conditions. 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-trial interval. The segmented data were then averaged across trials within participants for each condition and smoothed using a 30 Hz lowpass filter.

2. Results

2.1. Behavioral analysis

The data for average reaction times were analyzed as a function of condition (exploratory correct, exploratory incorrect, and final path) and run number using data from all 32 subjects. All behavioral and ERP analyses reported include 32 subjects unless otherwise noted. Following the definitions employed by Kotovsky and Simon (1990), a move was classified as “final path” if it was part of the last sequence moves prior to goal completion that did not have any intervening incorrect moves. Any moves prior to the final path were classified as “exploratory.” A repeated measures, within-subjects, univariate ANOVA was run using Greenhouse–Geisser corrections when sphericity was violated. Bonferroni corrections were used for multiple comparisons. There was a significant main effect of condition, $F(2, 32) = 8.76$, $MS_e = 48,397$, $p < 0.01$, as well as run number, $F(2, 32) = 36.67$, $MS_e = 63,412$, $p < 0.001$. As shown in Fig. 2, the reac-

tion times were significantly shorter for final path moves compared with exploratory correct moves ($p < 0.05$) and exploratory incorrect moves ($p < 0.05$). However, there were no significant differences in reaction time between exploratory correct and exploratory incorrect moves. The average reaction times also became faster with successive runs, dropping from 1072 ms (S.D. = 427) in the first run to 753 ms (S.D. = 316) in the second to 667 ms (S.D. = 252) in the third, collapsed across the three conditions of exploratory correct, exploratory incorrect and final path. An interaction between condition and run number did not reach significance, $F < 2.5$.

There was a significant drop in the number of total moves with increasing run number, changing from an average of 236 (S.D. = 76.3) moves on the first run to 229 (S.D. = 104.4) on the second to 138 (S.D. = 55.2) on the third, $F(2, 62) = 7.82$, $MS_e = 104316$, $p < 0.01$. The number of exploratory moves dropped from 116 (S.D. = 39.3) in the first run to 114 (S.D. = 56.4) in the second to 68 (S.D. = 29.6) in the third. The number of exploratory incorrect moves changed from 95 (S.D. = 35.6) in the first run to 97 (S.D. = 50.5) in the second to 56 (S.D. = 26.4) in the third. The mean number of exploratory correct moves was significantly larger than the mean number of exploratory incorrect moves, $F(1, 31) = 17.5$, $MS_e = 734$, $p < 0.001$. The mean length of the final path increased somewhat from 14.5 moves (S.D. = 1.5) in the first run, to 16.7 (S.D. = 1.6) moves in the second, to 18.7 (S.D. = 1.6) moves in the third. This trend approached but failed to reach significance, $F(2, 62) = 2.5$, $MS_e = 53.4$, $p = 0.086$. The final path results were comparable with the results of Reber and Kotovsky (1997), who showed a mean final path length of 18.4 moves (S.D. = 1.0).

To determine whether there was evidence for implicit learning within the final path, an additional analysis was performed whereby the final path trials for each run and for each subject were divided in half according to distance from the goal. For example, if a particular subject had 12 final path trials in the second run, the six trials closest to the goal for that run would be assigned to the “close to goal state” group, while the others would be assigned to the “far from goal state” group. The reaction times of these two groups were then compared. For the first run, there was no difference in reaction time as a function of how close the final path trial was to the goal, $t < 1.0$. Also, the trend for the first run was towards somewhat slower reaction times for trials close to the goal. However reaction times were reliably faster for final path trials close to the goal for both the second, $t(31) = 2.86$, $p < 0.05$, and third, $t(31) = 3.32$, $p < 0.05$, runs. The reaction times drop from 817 ms (S.D. = 75.2) to 658 ms (S.D. = 47.8) for second run final paths and from 744 ms (S.D. = 69.2) to 597 ms (S.D. = 42.7) for third run final paths. Since analyses of the ERP components discussed in this paper suggest that they do not differ as a function of distance from the goal, we think it is unlikely that this effect directly relates to either of them. Rather we speculate that this speedup reflects a sort of recognition mechanism (presumably implicit since earlier work (Reber & Kotovsky, 1997) suggests no conscious awareness that one is near the goal) that a particular problem state is associated with closeness to the goal.

2.2. ERP analysis

The trials were analyzed based on their earlier classification as exploratory correct, exploratory incorrect, or final path. Stimulus-locked and response-locked waveforms were analyzed separately. There were, however, significant differences in the response-locked waveforms in the period following the response (see Fig. 3). An N1 component was analyzed in the range from 60 to 220 ms based on visual inspection of the waveforms. A P3 component was analyzed in the range from 300 to 495 ms. All analyses of amplitude were based on mean amplitude of the waveform in the given time window. In order to determine where the analyses would be centered,

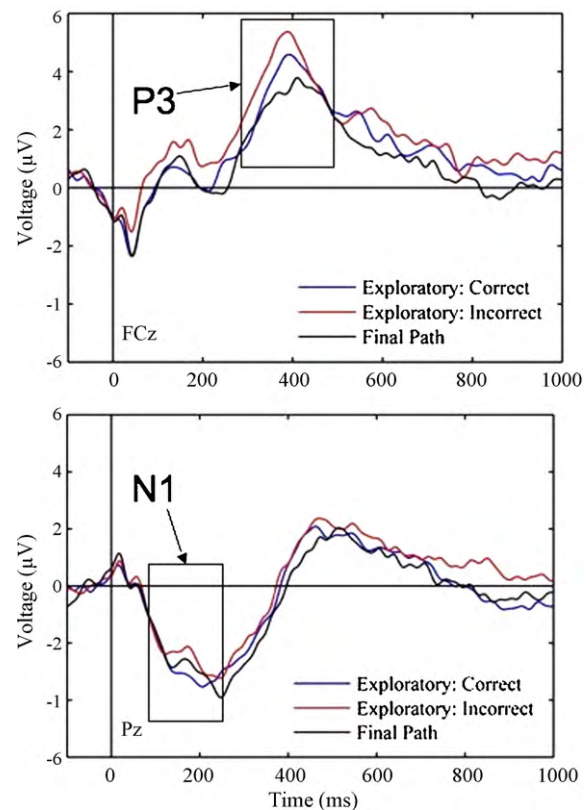


Fig. 3. Response-locked waveforms at FCZ (top) and PZ (bottom) electrodes. X-axis is time in ms.

an initial repeated measures ANOVA was performed to determine where the components were maximal collapsed across conditions (exploratory correct, exploratory incorrect, and final path). The midline electrodes FZ, FCZ, CZ, CPZ, PZ, POZ, and OZ were used for this determination. The N1 component was found to be maximal at the PZ electrode, reaching a maximum of $-2.22 \mu\text{V}$ collapsed across condition. The P3 component was found to be maximal at the FCZ electrode, reaching a maximum of $3.53 \mu\text{V}$ collapsed across condition. On this basis, all further analyses of the N1 component were performed at the PZ electrode and its four neighbors (P3, P4, CPZ, and POZ). Similarly all further analyses of the P3 component were performed at the FCZ electrode and its four neighbors (FC3, FC4, FZ, and CZ).

Univariate repeated measures ANOVAs were next performed for the N1 and P3 components using condition (exploratory correct, exploratory incorrect, or final path) and electrode as factors. For the N1 component, there was no effect of condition in this preliminary analysis, $F < 1.5$. However, there was a main effect of electrode, $F(4, 124) = 11.03$, $MS_e = 2.59$, $p < 0.001$, and a significant interaction of electrode and condition, $F(8, 248) = 3.54$, $MS_e = 0.74$, $p < 0.01$. The N1 component reached a maximum of $-2.34 \mu\text{V}$ at the P4 electrode. For the P3 component, there was both a significant effect of condition, $F(2, 60) = 3.64$, $MS_e = 18.45$, $p < 0.05$, and of electrode, $F(4, 120) = 13.18$, $MS_e = 6.02$, $p < 0.001$. This P3 component was higher in amplitude for exploratory incorrect moves, with approximately equivalent amplitudes for exploratory correct and final path moves (all of which were correct by definition of “final path”). The component reached its highest amplitude of $3.53 \mu\text{V}$ at the FCZ electrode. For these analyses, a few trials were lost due to muscular and ocular artifacts even though these trials had been included in the behavioral analyses. The mean number of trials was therefore 288 for exploratory correct (S.D. = 37.4), to 248 for exploratory incorrect (S.D. = 53.4), to 48 for final path moves (S.D. = 8.2).

To determine if the ERP components were affected by absolute distance from the goal, the exploratory trials were further split on the basis of this factor. Trials were categorized as relatively close to the goal if 18 moves or fewer would be needed to take them to the goal state and as relatively far if more than 18 were required. This cutoff was chosen to ensure approximately equal number of observations for both levels of the distance condition. For both the N1 component, $F < 0.5$, and the P3 component, $F < 0.5$, the effect of distance was clearly not significant. Furthermore, distance from the goal failed to interact with any other factor. The N1 component was again maximal at the P4 electrode, reaching $-2.41 \mu\text{V}$, while the P3 component was again maximal at the FCZ electrode, reaching $4.0 \mu\text{V}$. Next, a correlation analysis was performed whereby the average distance from the goal state was determined for all the trials of each condition (exploratory correct, exploratory incorrect, and final path) for each subject. These average distances were then correlated with N1 and P3 amplitude (collapsed across electrode) for each subject. None of the correlations thus obtained were reliably different from zero (all p -values greater than 0.3).

The setup of the task was such that the new configuration of the stimulus appeared only after a random jitter between 0 and 200 ms following the button press by the participant. This allowed us to collect response-locked and stimulus-locked waveforms separately. Preliminary inspection of the stimulus-locked waveforms seemed to show no significant differences across conditions. An analysis was performed of the stimulus-locked waveforms using the same time windows, electrode sites, and conditions (exploratory correct, exploratory incorrect, and final path) as for the response-locked analyses. For the N1 component, there was a main effect of electrode, $F(4, 124) = 8.20$, $MS_e = 4.93$, $p < 0.01$. However, the N1 component showed no significant effect of condition, $F < 1.0$, and no significant interaction of condition and electrode, $F < 2.0$. The P3 component also showed a main effect of electrode, $F(4, 124) = 3.97$, $MS_e = 3.32$, $p < 0.01$, and reached a maximum of $2.93 \mu\text{V}$ at the FCZ electrode. However, there was again no effect of condition, $F < 1.0$, and no significant interaction of condition and electrode, $F < 1.5$. This shows that the effects we are reporting are primarily associated with the participants' responses rather than changes in the appearance of the stimulus.

To determine whether there was a significant change in the components from one run to the next, a new set of repeated measures ANOVAs were performed with run number as a factor. This analysis was hindered by the fact that subjects often did not have many exploratory moves for the second and third runs. Therefore, the second and third runs were collapsed and then compared against mean amplitudes from the first run. However, five subjects still had to be excluded from these analyses as a result of having made too few exploratory moves in the two later runs. The minimum number of observations needed for each condition for a subject to be included was five. Meeting this threshold was not an issue for the other analyses. Exploratory correct, exploratory incorrect, and final path moves were analyzed, with the same electrodes and time windows as for the previous analyses. Both the N1 component, $F < 1.5$, and the P3 component, $F < 1.5$, did not differ significantly in amplitude between the first run and later runs. This suggests that the ERP components remain relatively stable even as the subject gains greater practice with the task. The N1 component was maximal at P4, reaching $-2.31 \mu\text{V}$, while the P3 was maximal at FCZ, reaching $3.57 \mu\text{V}$. The mean number of exploratory correct trials for these analyses was 227 for the first run (S.D. = 15.5) and 61 for later runs (S.D. = 22.6). The mean number of exploratory incorrect trials was 189 for the first run (S.D. = 14.7) and 59 for later runs (S.D. = 21.4). The mean number of final path trials was 12.4 for the first run (S.D. = 2.9) and 32.3 for the later runs (S.D. = 4.0). Because run number was not a significant factor in these ANOVAs, data were collapsed across run number in all other analyses.

Following this, additional analyses were performed focusing on the exploratory moves. These moves were broken down by whether they were correct or incorrect and whether they were moves into or out of a box. This allowed us to determine whether the effect was driven by whether a move seemed superficially correct (a move out of a box) or whether the move was correct in actuality (moved the solver closer to the goal). There were on average, 56.4 superficially correct moves that were correct in actuality (S.D. = 16.8), 52.6 superficially correct moves that were incorrect in actuality (S.D. = 19.2), 60.4 superficially incorrect moves that were correct in actuality (S.D. = 19.2), and 43.4 superficially incorrect moves that were incorrect in actuality (S.D. = 16.7). For the N1 component, there was no effect of superficial appearance of correctness (i.e., whether the ball was moved in or out of the box), $F < 1.0$, but there was a significant main effect of whether the move was actually correct, $F(1, 30) = 3.77$, $MS_e = 12.38$, $p < 0.05$. There was also a significant main effect of electrode, $F(4, 124) = 9.34$, $MS_e = 5.18$, $p < 0.001$. The N1 component was significantly more negative for exploratory correct moves and showed the most negativity, $-2.35 \mu\text{V}$, at the POZ electrode. No significant interactions were found of superficial correctness with any other factor.

For the P3 component, there was again no effect of superficial appearance of correctness, $F < 1.0$, but there was a significant effect of whether the move was actually correct, $F(1, 30) = 7.12$, $MS_e = 31.15$, $p < 0.05$ such that the component was significantly more positive for exploratory incorrect moves. There was again a main effect of electrode, $F(4, 124) = 7.11$, $MS_e = 23.86$, $p < 0.01$ such that the P3 was highest in amplitude at the FZ electrode ($3.94 \mu\text{V}$). An interaction of correctness and whether the ball was taken in or out of the box approached, but did not reach significance, $F(1, 30) = 3.89$, $MS_e = 21.75$, $p = 0.058$. There appeared to be a larger difference between correct and incorrect amplitudes when balls were put back into a box than when they were taken out. The observed differences in the ERP components could not have been from differential time in the experiment, since a separate analysis showed no significant difference in the average move position of exploratory correct and exploratory incorrect trials, $t < 0.50$.

A final set of analyses was performed to determine whether there were individual differences in the ERP waveforms. Subjects were assigned to either a "fast" or "slow" group based on the total number of moves the subject needed to complete the experiment. The sixteen subjects with the most total moves were classified as "slow," while the sixteen subjects with the fewest were classified as "fast." The amplitudes for exploratory correct and exploratory incorrect moves were compared for these two groups. There was no main effect of "slow vs. fast" on amplitude for either the N1 component, $F < 2.0$, or the P3 component, $F < 1.5$. However, an interaction between "slow-fast" and correctness approached significance for the P3 component, $F(1, 30) = 4.01$, $MS_e = 18.52$, $p = 0.054$. It is noteworthy that the trend was towards fast solvers showing greater differences as a function of correctness for both the N1 component and the P3 component, suggesting greater neural information about the correctness of a move for subjects who solved the task quickly.

In addition to the ANOVAs, Pearson's r correlations were performed between the mean amplitudes of the ERP components (collapsed across electrodes) and the total number of moves required to complete the task. These correlations were done separately for the amplitudes of exploratory correct components and the amplitudes of exploratory incorrect components. The correlation between the N1 amplitude and total moves was 0.269 when exploratory correct moves were used for the N1 component and 0.140 when exploratory incorrect moves were used. This means that more negative (and therefore stronger) N1 amplitudes were associated with fewer total moves needed to complete the task. Neither of these correlations, however, was statistically significant. The correlation between the P3 amplitude and total moves

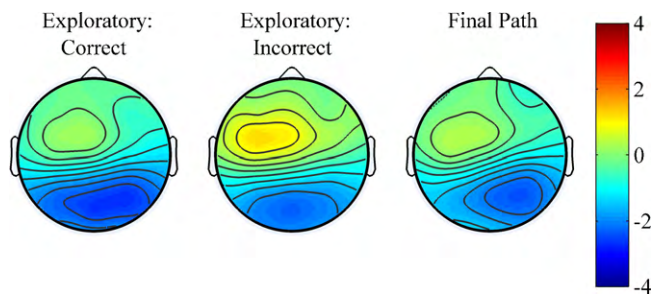


Fig. 4. Headplot of N1 component (average amplitude in μV in the time window from 60 to 220 ms).

was -0.276 when exploratory correct moves were used for the P3 component and -0.372 when exploratory incorrect moves were used. This means that more positive P3 amplitudes were associated with fewer moves needed to solve the task. The correlation between exploratory incorrect P3 amplitudes and total moves was statistically significant, $p < 0.05$.

3. Discussion

Subjects performed three runs of the balls-and-boxes task while ERPs were being recorded. ERP results showed that a response-locked N1 component was weaker in amplitude for exploratory incorrect moves compared with exploratory correct moves. A response-locked P3 component was stronger in amplitude for exploratory incorrect moves. These differences were not simply a result of differential time in the experiment. Further analyses showed that the differences were based on whether the move was correct in actuality rather than whether the move seemed superficially correct on the surface. Stronger exploratory incorrect P3 amplitudes were reliably associated with fewer moves being required to solve the task, and there were non-significant trends towards stronger N1 amplitudes being associated with fewer moves. This shows that neural signals associated with distinguishing correct from incorrect moves were stronger in individuals who were able to solve the task more quickly.

The response-locked N1 component was not expected beforehand. The component clearly did not correspond to an ERN, as it was clearly parietal in its scalp distribution (see Fig. 4) and was in any case larger for exploratory correct than exploratory incorrect moves. Negative parietal and occipital deflections in this time window are most often associated with shifts in visual attention (Herrmann & Knight, 2001; Hillyard, Vogel, & Luck, 1998; Mangun, 1995), suggesting that subjects changed which part of the screen they attended to at the time of a button press. We believe it is unlikely that this component resulted from the change in stimulus appearing on the screen. This is because a 200 ms jitter was used between button press and stimulus onset, and ERP waveforms were generated that were stimulus-locked as well as response-locked. The stimulus-locked waveforms showed no visible difference between exploratory correct and exploratory incorrect moves for any component, and a repeated measures ANOVA confirmed that there was no reliable difference for the N1 component, $F < 1.0$.

It is worth briefly speculating on why an ERN was not observed for this task. At least some theories of the ERN hold that the component corresponds to detection of a mismatch between the response made and a representation of the correct response (e.g. Falkenstein et al., 1990). Since participants probably do not have an especially strong internal model of the correct response (given that they are just learning the task), this could explain why an ERN was not observed.

We are not aware of any prior work directly suggesting a role for the N1 component in high-level problem-solving. However, there is research suggesting that certain patterns of shifts in visual attention, as measured by eye movements, can be useful in solving insight problems (Grant & Spivey, 2003). A particularly interesting study has recently shown that when subjects are given a diagrammatic representation of the tumor and lasers problem, subjects who were allowed to move their eyes had a higher rate of problem-solving success than those asked to maintain fixation (Thomas & Lleras, 2009). The implication was that encouraging shifts in visual attention facilitated the breakup of problem representations causing an impasse, which in turn facilitated insight solutions. Other research using ERP has found higher gamma band activity in parietal-occipital areas being associated with sudden, as opposed to non-sudden solutions, to an insight problem (Sandkuhler & Bhattacharya, 2008). We are hesitant to assert a relation between the current study and research on insight, since we have argued that subjects are not consciously aware of the solution and because the hallmark of insight-based problem-solving is sudden conscious awareness of the solution (Metcalfe & Wiebe, 1987). However, there is an analogy present since subjects suddenly make a large number of correct moves in succession after getting nowhere for an extended period.

One source of information that could lead to an insight-like breakthrough would be attention to the leftmost balls on the screen. The rules of the balls-and-boxes task are such that solving it most efficiently requires a process of subgoaling whereby one first works on getting the leftmost ball out of its box, regardless of the other balls, then focuses on getting the ball that is second from the left out of its box, and so on. This is the optimum strategy because whether a given box is open or shut depends only on the configuration of balls to the right, not on balls to the left (Kotovsky & Simon, 1990). For this reason, any moves in which the subject is focused on getting the leftmost ball out of its box are more likely to be correct than moves in which the subject is not focused on doing this. This would lead one to expect that the N1 component should be more right-lateralized for exploratory correct moves compared with exploratory incorrect moves (since the right hemisphere is associated with processing of information in the left half of the visual field). We believe it is relevant to note that the difference in N1 amplitudes between the P3 and P4 electrodes was $0.40 \mu\text{V}$ for exploratory correct moves and $0.12 \mu\text{V}$ for exploratory incorrect moves (in both cases the N1 was more negative at P4). Unfortunately, a planned comparison of this interaction failed to reach significance, $F < 1.5$. Nonetheless, we believe this may at least partly explain the N1 attentional effect.

The functional significance of the P3 component we observed is ambiguous. Frontal-central P3 components are usually interpreted as either a P3a or 'novelty' P3 component (Polich, 2007). We think this interpretation is unlikely since the P3a and 'novelty' P3 are both associated with responses to stimuli that are relatively infrequent (Polich, 2007). Exploratory incorrect moves constituted 42% of all subject moves, and both exploratory correct and exploratory incorrect moves traversed the same problem states, so there is little reason to see exploratory incorrect moves as appreciably novel. A more plausible explanation is that the P3 corresponded to a nogo P3 component. These are components that appear in response to repeated distracter stimuli when subjects are performing a go/nogo task (Kok, 1986; Pfefferbaum et al., 1985). Unlike P3a and novelty P3 components, these can occur even when targets and distracters are equally likely (Kiehl, Smith, Hare, & Liddle, 2000; Pfefferbaum et al., 1985) (Fig. 5).

The nogo component is generally associated with inhibition of a subject's tendency to make a 'go' response when a stimulus appears (Azizian et al., 2006; Falkenstein et al., 2000; Polich, 2007; Salisbury et al., 2004). For the current study, it may be that

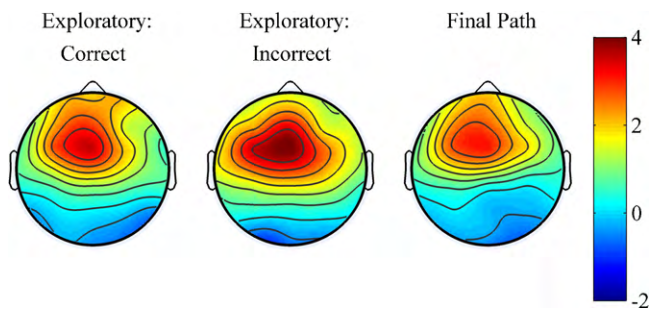


Fig. 5. Headplot of P3 component (average amplitude in μV in the time window from 300 to 495 ms).

the P3 component reflects an (unsuccessful) attempt to inhibit a response that one non-consciously “believes” is probably incorrect. The source of this non-conscious information is unclear, although we can speculate that the incorrect move subjects are making had been previously associated with, for example, later being forced to put several balls back into their boxes. The interpretation of the component as a nogo P3 is complicated however by the scalp distribution information. Nogo P3 components are usually maximal at parietal or central-parietal sites (Polich, 2007; Salisbury et al., 2004), while our P3 was clearly maximal at frontal-central sites. Nonetheless, this is certainly a plausible interpretation of the ERP results.

The P3 could also be interpreted as an error positivity (abbreviated Pe) component, although this interpretation is at least equally problematic. First, error positivity components, like nogo P3 components, are usually maximal at parietal sites (Falkenstein et al., 1991; Nieuwenhuis et al., 2001). Second, the predominant view of the error positivity component is that it reflects conscious detection of an error by the subject (Endrass, Reuter, & Kathmann, 2007; Kaiser et al., 1997; Nieuwenhuis et al., 2001; O’Connell et al., 2007). For reasons stated earlier, we think it is highly unlikely that subjects are consciously aware of move correctness or any other aspect of the task. Work by Reber and Kotovsky (1997) using this same task showed that when subjects are asked to give a verbal protocol when performing the balls-and-boxes task, no useful information is present in their statements about any aspect of the task, including the current distance from the goal, the correctness of moves they are making, and the rules for when a box is open or shut. Furthermore, when subjects are given a “move-selection task” after completing the puzzle that asks them to guess whether a hypothetical move will take them closer to or farther from the goal, subjects are at chance in their performance. For these reasons we think it is unlikely that the P3 differences, or any other ERP differences in this study, result from differences in conscious awareness. It is conceivable that the error positivity component serves as a marker of conscious awareness for simple tasks but begins to play a different role when the task becomes more complex, although this is of course highly speculative.

As noted previously, there is an alternative view in the literature emphasizing the role of the error positivity in emotional and motivational processing (Falkenstein et al., 2000; van Boxtel et al., 2005; Van Veen & Carter, 2002). According to this account, the rostral anterior cingulate, which is generally believed to be involved in emotional processing (Bush, Luu, & Posner, 2000), is able to generate error positivity signals that register how emotionally important the error is but need not necessarily correlate with conscious awareness of an error. Support for this view come from dipole source modeling (van Boxtel et al., 2005; Van Veen & Carter, 2002) of the Pe and from evidence that the Pe is reduced when subjects “care less” about having made a mistake (Falkenstein et al., 2000). Therefore, there is reason to believe Pe can serve as

a marker of emotional processing for at least some task types. If the Pe does turn out to serve as a register of emotional salience for complex tasks, it will support the broader view that emotional processing is important for non-conscious decision-making generally (e.g. Bechara, 2001; Damasio et al., 1991; Damasio, 1996). This analysis, however, is posited on the assumption that the P3 component in our analysis is interpreted as an error positivity component, despite the frontal-scalp distribution and the fact that the view of the error positivity as reflecting conscious error detection is the predominant one. In any case more research will need to be done to assess the validity of these claims.

Regardless of whether the P3 component corresponds to a Pe or nogo P3 component, it was clearly frontal in its scalp distribution. This fits well with the neuropsychological research suggesting the frontal lobes are important in non-conscious problem-solving generally (Colvin et al., 2001; Goel & Grafman, 1995; Morris et al., 1997). It has been suggested, based on research with frontal patients, that engagement of the frontal lobes is particularly crucial in allowing subjects to make a “counterintuitive” move that superficially seems to be a step backwards but is actually necessary to reach the goal (Colvin et al., 2001). This again fits well with our observation that effect sizes for the P3 component were larger in magnitude when subjects were placing a ball into a box than when taking one out. Since moves placing a ball into a box are “counterintuitive” in the balls-and-boxes task, it is reasonable that greater differences in frontal processing would be observed for these moves.

In conclusion, ERP evidence showed clear evidence of information about the correctness of a move well before subjects were making progress on the task behaviorally, let alone being able to consciously determine if a move was correct or not. An N1 component suggested that attentional shifts are important in solving the balls-and-boxes task. Scalp distributions of the P3 component were consistent with other evidence suggesting a special role for the frontal lobes in non-conscious problem-solving. We will conclude by noting that there may well be other learning mechanisms present that were not captured by the ERP analyses. The number of moves needed to solve the task clearly dropped with increasing run number, and yet the ERP components identified remained relatively stable across runs. It is therefore conceivable that in addition to the mechanisms we have identified there are other mechanisms that are responsible for better performance in later runs compared with the first run. In any case, we have only scratched the surface of the neural mechanisms of non-conscious problem-solving. Learning more about these mechanisms should be an important focus for cognitive neuroscience in the future.

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