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an error has occurred (Davies, Segalowitz, Dywan, & Pailing, 2001; Kaiser, Barker, Haenschel, Baldeweg, & Gruzelier, 1997; Nieuwenhuuis, 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 “no-go” 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 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

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 μV for exploratory correct moves and 0.12 μV 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. Fontal-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

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; Nieuwenhuuis 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; Nieuwenhuuis 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.

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