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RESEARCH NOTE

Absent minded but accurate: delaying responses increases accuracy but decreases error awareness

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Abstract Previous work has suggested that conscious error awareness may fluctuate with levels of attention. Here, we explore this relationship by showing that error awareness can be impaired when exogenous support to attentional systems is reduced by decreasing task demands. Twenty participants performed a manual Go/No-Go response-inhibition task optimized to examine error awareness. In one condition (Immediate), participants were asked to respond as quickly and as accurately as possible to each Go stimulus, and in the other condition (Delayed) they were asked to time their responses to the offset of the stimulus, thereby decreasing task difficulty and imposing a more automated response set. As expected, speeding increased the error rate. However, contrary to the expectation (and to participants' subjective reports) that speeding would impair awareness of performance, we found the opposite to be true: errors were more likely to be unnoticed when the task was easier. We suggest that this tradeoff reflects two qualitatively different types of errors arising from the different cognitive demands of the Immediate and Delayed conditions. We propose that unaware errors reflect pure lapses of sustained attention and are therefore more susceptible to changes in task demands, while aware errors mostly reflect failures to inhibit responses, and are therefore most susceptible to increased response speed.

Keywords Error awareness · Sustained attention · Speed–accuracy tradeoff

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Introduction

A vast literature has been directed towards understanding how the brain processes errors. However, only a few studies have made the distinction between error detection in the brain and conscious error awareness. Recently, it has been shown that awareness of errors leads to a specific pattern of neural activity and influences post-error corrective behavior (Nieuwenhuis et al. 2001; O'Connell et al. 2007). Clinical evidence implicates the frontal lobes in error awareness, as damage to this region has been associated with decreased awareness of one's deficits, including a tendency to be unaware of errors during neuropsychological tasks (Hart et al. 1998; O'Keeffe et al. 2007). Reduced awareness of one's deficits predicts behavioral disturbances in brain injured populations and has also been related to poor rehabilitation outcome (Prigatano and Schacter 1991). Consequently, there is an imperative for more studies that can elucidate the neuropsychological processes underlying error awareness. Here we explore error awareness by investigating its relationship to sustained attention.

Error processing is typically assessed using response inhibition Go/No-Go tasks in which participants must withhold a prepotent response to an unexpected No-Go stimulus. However, these tasks also engage other cognitive systems including sensory processing, working memory and sustained attention (e.g. Bekker et al. 2005). Sustained attention is defined as the ability to self-sustain mindful, conscious processing of stimuli whose repetitive, non-arousing qualities would otherwise lead to habituation and distraction to other stimuli (Robertson et al. 1997). In response inhibition tasks, if the stimuli are clearly presented (and are unambiguous) and the task itself is relatively undemanding, two qualitatively different types of commission errors (making a response to a No-Go stimulus) can be made. The first is a response inhibition error, that is, a failure to withhold a response initiated because of the regularity of the Go response and the unexpected occurrence of the No-Go trial. This has been described in terms of a horse-race model whereby the inhibition process races with the conflicting response process (Logan et al. 1997). Whichever process is completed first determines whether the response will be executed or not. As a result, the faster a participant initiates their Go responses, the more difficult it becomes to withhold that response on the appearance of the No-Go stimulus, an effect known as the speed–accuracy tradeoff. The second type of error on a Go/No-Go task is a failure of sustained attention. That is, the appropriate stimulus-response mappings have become de-activated over time, such that a No-Go stimulus fails to activate the withhold response resulting in an error of commission. A challenge for neuropsychologists who are interested in understanding why cognitive systems fail, is to differentiate between these two types of errors.

O'Connell et al. (2007) used the error awareness task (EAT) to measure error awareness in healthy participants. The EAT is a motor Go/No-Go response inhibition task in which participants are presented with a serial stream of single color words. Participants were trained to respond to each of the words with a single button press *timed to the offset of the word*, and to withhold this response if the same word is presented on consecutive trials or if the word and font color did not match. This kind of "response-locking" has been shown to reduce inter-individual variability and eliminate speed–accuracy tradeoffs (Stuss et al. 2003). Participants were additionally instructed to press an "awareness button" following a false press on No-Go trials. Delaying response until stimulus offset allowed ruling out the possibility that certain undetected errors could be attributed to an overemphasis on speed over accuracy. An unpublished observation in our lab from a different group of participants suggested that when this response-locking requirement was eliminated and participants were told that speed and accuracy were equally important, the number of errors greatly increased (reflecting the normal speed–accuracy tradeoff), but error awareness appeared to increase as well.

In the present study, we tested these observations in a within-subject experiment, where each participant performed the EAT in a response-locked condition (Delayed) and a speeded condition (Immediate). Accuracy was emphasized in both conditions. Specifically, we tested the hypothesis that error awareness, more than error rate, reflects failures of sustained attention. Previous studies have shown that making a Go/No-Go task less demanding increased its sensitivity to fluctuations of sustained attention (Manly et al. 2003). We reasoned that if error awareness is dependent on sustained attention then decreasing the difficulty of the EAT (by delaying responses) should lead to a *decrease* in the total number of errors made relative to the more demanding Immediate condition, but also to an *increase* in the rate of unaware errors.

Methods

Participants

Twenty-one participants were tested initially, but the data of one participant was excluded from analysis due to a complete lack of unaware errors in either condition. The 20 remaining participants were 15 females and 5 males (11 right handed), aged 18–36 (mean 21.95, SD = 5.2). All participants had reportedly normal or corrected-to-normal vision and no history of neurological disorders. They were all fluent English speakers and reported no reading disabilities. The participants were paid or given course credits to participate in the study. Informed consent was obtained after the experimental procedures were explained. All procedures were approved by the ethical review board of the School of Psychology, Trinity College Dublin.

Procedure

We used the error awareness task (EAT) developed by Hester et al. (2005). The EAT is a Go/No-Go response inhibition task in which participants are presented with a serial stream of color words. Participants were asked to press the Go button for every color word that appeared on the screen, except when either of two conditions arose: if the color word and its font color did not match (Incongruent No-Go) or for the second word if the same word was repeated on two consecutive trials (Repeat No-Go). In case of a commission error (failure to withhold a response to either of these No-Go scenarios) participants were trained to press a second "awareness button" on the next Go trial after the error instead of the standard Go response, indicating that they have noticed their error. Each block consisted of 225 trials, of which 200 were Go stimuli and 25 No-Go stimuli (13 Repeat No-Go and 12 Incongruent No-Go or vice versa). All stimuli were presented for 600 ms followed by an ISI of 900 ms and appeared above a white fixation cross on a grey background at a distance of approximately 100 cm from the participant's head. Six different color words (Red, Blue, Green, White, Yellow, Purple) and font colors were used, presented using a 64pt font on the center of a 16 × 12″ monitor.

Participants performed five consecutive blocks of each experimental condition, which differed only in terms of the instructions given. In the "Immediate" condition, participants were told to respond as fast as possible for each Go stimulus, while withholding responses to the No-Go stimuli. Both speed and accuracy were equally stressed. In the "Delayed" condition, participants were not instructed to speed, but rather to time their responses to the offset (i.e. disappearance) of each Go stimulus. They were told that as the words are displayed at a constant rate, they could adjust their response rate to the rhythm of the trial offsets. Accuracy and time-locking of responses were equally emphasized. The order of conditions was counterbalanced across participants. Participants used their right thumb to make both Go and "aware" responses using a 2-button gamepad. Each session was preceded by two practice blocks consisting of 18 stimuli. Following the testing session, participants filled in a questionnaire in which they rated task difficulty and their perceived accuracy and awareness of errors.

Analysis

Go responses were considered correct if they occurred between 0 and 1,500 ms from the stimulus onset. Reaction time outliers (greater than ±3 SD from the mean) were removed. An aware error was defined as any No-Go commission error after which participants pressed the awareness button on the same or next trial. Other commission errors were classified as unaware errors.

Response Times for correct responses (GoRT), aware errors, and unaware errors were entered into a two-way ANOVA with factors Condition (Immediate, Delayed) and RT type (GoRT, Aware Error RT, Unaware Error RT). Planned comparisons for differences between the RTs in each condition were performed using a one-way ANOVA. Greenhouse–Geisser correction was applied when necessary. Accuracy was calculated as the percentage of correct withholds on No-Go trials. Awareness was calculated as the percentage of aware errors out of all commission errors. The difference between the Immediate and Delayed conditions in GoRT, accuracy, awareness rate and the actual number of unaware errors was tested using paired-sample *t*-tests. We corrected for the multiple comparisons by setting the alpha level at 0.0125 (0.05/4, i.e., Bonferrroni's correction). The differences between post-test questionnaire ratings of perceived performance and the observed behavior were entered into a 2-way ANOVA with factors Condition (Immediate, Delayed) and Measure Type (Observed, Perceived) separately for accuracy and for awareness. Contrasts were performed using paired-samples *t*-tests.

Results

Table 1 describes the results of the two experimental conditions.

As dictated by the task demands, GoRTs, measured from the appearance of the word, were longer in the Delayed condition than in the Immediate condition ($t(19) = 16.97$, $P < 0.001$). Accuracy was significantly lower in the Immediate condition ($t(19) = 12.87$, $P < 0.001$), revealing an expected speed-accuracy tradeoff. Concomitantly, the probability of awareness of errors was greater in the Immediate condition ($t(19) = -8.004$, $P < 0.001$). The absolute number of unaware errors that participants made was also significantly smaller in the Immediate condition (Immediate 4.55, SD 3.9; Delayed 6.85, SD 4.46; $t(19) = 2.88$, $P < 0.0125$). These results point to a new tradeoff: when participants were asked to emphasize speed in addition to accuracy, they made more errors but were more likely to be aware of these errors. When participants delayed their

Table 1 Behavioral results given as mean (SD). Accuracy was calculated as the number of correct withholds on No-Go Trials. Awareness rate was calculated as the number of aware errors out of the total number of commission errors. The scores for perceived accuracy, awareness and task difficulty were calculated from the post-test questionnaires. Task difficulty was rated on a scale of 1 (easy) to 5 (very difficult)

	Immediate condition		Delayed condition	
	Observed	Perceived	Observed	Perceived
Accuracy (% correct)	48.88 (14.86)	50.53 (15.54)	83.88 (13.98)	75.26 (13.49)
Error awareness (% aware)	92.93 (5.31)	76.53 (15.29)	59.09 (18.55)	83.74 (10.56)
Reaction times (ms)				
GoRT	377.84 (46.71)		756.85 (91.59)	
Aware Errors	363.44 (41.27)		741.55 (114.87)	
Unaware Errors	408.15 (77.55)		756.85 (81.17)	
Task difficulty		3.55 (0.83)		2.1 (0.85)

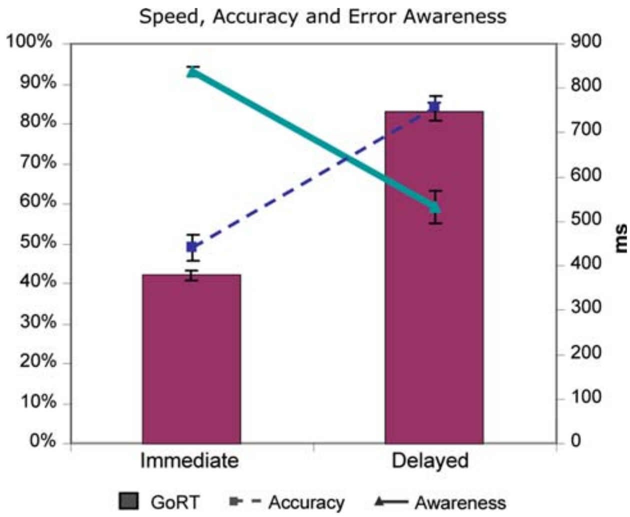

Fig. 1 In the Immediate condition, the participants had faster GoRTs and were less accurate but had higher error-awareness rates. In the Delayed condition, GoRTs were slower and accuracy was higher, but participants were less aware of their errors. *Error bars* indicate standard error

responses to the offset of the stimuli, they were more accurate but *less* likely to be aware of their errors (Fig. 1).

The 2-way interaction between Condition and RT Type was not statistically significant ($P = 0.3$), possibly due to the small sets of error RTs (Aware and Unaware). However, planned comparisons for RT Type in each condition showed that in the immediate condition, the difference between GoRTs, aware error RTs and unaware error RTs was significant in a one-way ANOVA ($F(2,34) = 6.41$, $P < 0.05$). Contrasts showed that GoRTs were significantly slower than aware error RTs ($t(17) = 3.44$, $P < 0.005$), and tended to be faster than unaware error RTs ($t(17) = 4.149$, $P = 0.058$). In the Delayed condition, there was no significant difference between GoRTs and error RTs ($F(2,38) < 1$).

On a scale of 1 to 5, participants reported the Immediate condition harder than the Delayed ($t(19) = 6.87$, $P < 0.001$). Two-way ANOVAs with factors Condition and Measure Type performed separately for the dependent variables accuracy and error-awareness showed significant 2-way interactions (Accuracy: $F(1,18) = 8.12$, $P < 0.05$; Awareness: $F(1,18) = 65.39$, $P < 0.001$). Follow-up contrasts showed that in the Immediate condition, participants' estimates did not significantly differ from their measured accuracy ($t(18) = 0.5$, $P = 0.62$), while in the Delayed condition they underestimated their performance ($t(18) = 2.86$, $P < 0.05$). In both conditions participants incorrectly judged their awareness of errors[1], albeit in opposite directions: they reported that they were more aware of errors in the Delayed condition than they actually were ($t(18) = 5.29$, $P < 0.001$) and less aware in the Immediate condition than they actually were ($t(18) = 4.48$, $P < 0.001$). To summarize, participants' ratings of error-awareness were tied to their perceptions of accuracy such that a lower rating of accuracy was accompanied by a lower rating of awareness. Conversely, the performance data showed that higher accuracy was linked to lower awareness of errors.

[1] The internal validity of these estimates was verified by asking participants to list reasons for their unawareness. The most listed reason was a failure to pay attention.

Discussion

Our results indicate that an emphasis on speed led to an increase in the number of errors made, but concomitantly led to a reduction in the number of unaware errors. When participants locked their responses to the offset of the stimuli, their accuracy improved substantially but there was an increase in the number and rate of unaware errors made. As the only difference between the two conditions was the emphasis on immediate or delayed response, we infer that the different conditions placed demands on distinct cognitive processes. In the Delayed condition, asking participants to respond to the offset of each stimulus (600 ms post-presentation) induced a repetitive, monotonous rhythm to the task, which was likely to induce an inattentive response style. In addition, since participants had to withhold their response until stimulus offset, they had more time for stimulus-processing and may have had sufficient time to correct most potential response inhibition errors before these were made. Manly et al. (2003) compared performance of a Go/No-go response inhibition task to a less challenging version, in which the stimuli were presented in a fixed, predictable sequence. They showed that the fixed version was more sensitive to frontal lobe damage than the random version, and also led to increased blood flow in a right hemispheric network that has been closely linked with sustained attention. Functional imaging evidence and lesion studies indicate that sustained attention is subserved by a fronto-parietal cortical network that interacts with subcortical arousal structures (Sturm and Willmes 2001). A number of pharmacological studies have shown that boosting these arousal systems reduces the requirement for mindful, endogenous control of task performance (Arnsten and Contant 1992; Coull et al. 1995; Smith and Nutt 1996). Manly et al. (2003) thus argued that the easier response inhibition task actually increased the demands on sustained attention, as when overall task demands are decreased and the task is less challenging, more endogenous control is required. The Delayed condition in the current study is similar in this respect as it was less challenging (participants rated it as easier, and accuracy levels were higher). In contrast, when speed was emphasized, less endogenous control was needed because of the challenging—and hence alerting—nature of the requirement to prepare to respond quickly.

We propose that the increased number of unaware errors was due to the fact that error awareness is dependant on the same sustained attention system as that required to maintain vigilance for the task. This sustained attention system may be supported by exogenous increases in arousal and by endogenous control (Sturm and Willmes 2001). In the absence of exogenous support, the system has to rely mainly on the latter mechanism, which is prone to occasional lapses. These lapses of attention lead both to errors on the task and failure of being aware to such errors. In support of this view, we have previously reported a correlation between tonic EEG indices of arousal and individual awareness rates on the response-locked version of the EAT (O'Connell et al. 2007). In addition, the same right fronto-parietal system that has been implicated in vigilant or sustained attention (Manly et al. 2003) has also been implicated in aware versus unaware trials in a change blindness paradigm (Beck et al. 2001). In the current experiment therefore, the incidence of unaware errors may be a better indicator of true lapses of sustained attention than the number of overall errors.

A clinical implication of this is that asking participants to lock their responses to the offset of stimuli increases the sensitivity of the task to sustained attention failures, if error awareness is also measured. When introducing "speed" demands into a nominally sustained attention task, any sustained attention deficits may actually be masked by the exogenously alerting effects of the requirement to speed. Traditionally, sustained attention has been examined in the form of a gradual decrease in accuracy arising from reduced arousal over long periods of time (time-on-task decrements), but here we show that the response-locking can isolate genuine sustained attention errors relatively quickly, precluding the need for prolonged sessions. As this can be shown even in healthy participants, it may be even clearer in patient groups with sustained attention deficits. On the other hand, asking participants to speed up seems to be an optimal condition for keeping them alert during the task. The demand for speed acts as a catalyst for engaging attention and improving alertness. This is useful in tasks in which the researcher needs to be sure the participant's attention is focused on the task. In addition, in studies aiming at understanding the mechanisms of error unawareness, employing a less challenging task, although providing less errors overall, will provide a better balance between aware and unaware errors. Moreover, the nature of errors performed in the two tasks is not the same.

We propose that in contrast to unaware errors, aware errors in the present paradigm are mainly response inhibition failures, consistent with the fact that these errors were susceptible to the speed-accuracy tradeoff. Because the task is relatively simple and the stimuli are clearly and unambiguously presented for a relatively long time, it follows that if participants correctly perceive the stimulus but speed causes a response inhibition failure, they should be aware of the error. Indeed, aware errors made on the Immediate condition had significantly shorter RTs than the mean GoRT for that task. This has been a common finding with Go/No-Go tasks and suggests that the erroneous response has been executed before the inhibition process could be completed (Logan et al. 1997). Nevertheless, the exogenous alerting nature of the Immediate condition enhances attention, and this in turn improves action monitoring. Conversely, RTs for unaware errors in both conditions did not differ from the average GoRT, in line with the view that true sustained attention errors occur when participants mindlessly persist with the default Go-press mode. Thus, the present results show that attention not only improves perception of sensory stimuli, but also improves perception of action. Our findings suggest that the level of goal-directed attention may determine whether or not an error will trigger the cascade of events that results in awareness. In support of this view, a study by O'Keeffe et al. (2007) has shown that impulsive errors made by patients with traumatic brain injury were more easily detected than errors resulting from lapses of attention which failed to engage subsequent conscious error-processing.

Another way to induce unawareness in laboratory tasks is through the Inattentional blindness effect (Rock et al. 1992; Simons and Chabris 1999). In these studies, attention is kept away from the pertinent stimuli by having the participant pay attention to something else. Both the Inattentional blindness paradigm and response-locked sustained attention tasks create circumstances in which the participants are not aware of an event that is well above detection threshold and in other circumstances is easily detected. Both these paradigms link unawareness with inattention. Using the more monotonous task as shown here may be a more ecological way of inducing unawareness, by letting the participant's attention naturally drift away. By increasing the amount of unaware errors, we may be able to more successfully tap into sustained attention deficits using various brain imaging methods.

Finally, participants' subjective reports of their performance provided further insights into the reliability of error awareness. Participants thought they were more aware of their errors in the easier, Delayed condition while in reality they were less aware in that condition. This finding suggests that when we are operating in a more automated mode, we might be less aware of our errors than we think we are. This could have important implications for automated sustained attention tasks such as driving and needs to be further explored. In contrast, the comforting fact is that in more demanding conditions, although we may make more errors, these errors are consciously registered, allowing behavioral adaptation and remedial action. Thus, while we may intuitively assume that accuracy and error awareness are positively correlated, as our subjects did, the present study demonstrates that this is not always the case.

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