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Neurophysiological responses to gun-shooting errors

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ABSTRACT

The present study investigated the neural responses to errors in a shooting game – and how these neural responses may relate to behavioral performance – by examining the ERP components related to error detection (error-related negativity; ERN) and error awareness (error-related positivity; Pe). The participants completed a Shooter go/no-go task, which required them to shoot at armed targets using a gaming gun, and avoid shooting innocent non-targets. The amplitude of the ERN and Pe was greater for shooting errors than correct shooting responses. The ERN and Pe amplitudes elicited by incorrect shooting appeared to have good internal reliability. The ERN and Pe amplitudes elicited by shooting behaviors also predicted better behavioral sensitivity towards shoot/don't-shoot stimuli. These results suggest that it is possible to obtain online brain response measures to shooting responses and that neural responses to shooting are predictive of behavioral responses.

1. Introduction

The ability to detect and process errors is important in our lives, as this allows us to appropriately respond to and learn from them. A considerable amount of research in cognitive neuroscience has been dedicated to understanding how our brains respond to errors, and how these brain responses predict behavior. In the present research, we were interested in examining errors related to gun-shooting. Because shooting errors can result in harming another person, people should therefore be motivated to be accurate in their shooting decisions. However, shooting behavior is relatively understudied in neuroscience, with basic questions still being unexplored. For example, can shooting a target elicit measurable brain responses? Would these neural responses be related to behavioral responses?

The present study aimed to investigate these questions using a shooting paradigm. Specifically, we wanted to establish, from a methodological angle, whether reliable neural responses to shooting errors can be produced in a novel Shooter go/no-go task. As well, we wanted to examine whether the neural responses to shooting errors may be related to behavioral task performance. We examined two event-related potential (ERP) components that are integral to the detection and processing of errors: error-related negativity (ERN) and error-related positivity (Pe) (e.g., Hajcak, 2012; Falkenstein et al., 2000).

1.1. ERN and Pe

The ERN is a negative-going waveform occurring approximately 50–100 ms after a response is made (Gehring et al., 1993). Consistently elicited by incorrect responses across different types of tasks, the ERN is believed to reflect the neural system for performance monitoring (Gehring et al., 2012). Originating in the ACC (Dehaene et al., 1994), it is thought to reflect the detection and monitoring of conflict, error, and uncertainty (Botvinick et al., 2001; Holroyd and Coles, 2002; Ridderinkhof et al., 2004; Yeung et al., 2004). Increasing evidence also suggests that the ERN may be sensitive to the affective and motivational significance of errors (Hajcak, 2012; Legault and Inzlicht, 2013; Riesel et al., 2012). For example, individuals who experience more negative affect or for whom errors are more aversive tend to produce greater ERN responses to errors (Hajcak et al., 2004; Riesel et al., 2012). On the other hand, if people are given the opportunity to reduce their error-related anxiety (e.g., by misattributing their arousal to a benign source), they show reduced ERN amplitudes compared to those not given such an opportunity (Inzlicht and Al-Khindi, 2012). Thus, in addition to error detection and monitoring, the ERN may also reflect the affective relevance of errors.

In contrast, the Pe is a positive-going waveform that occurs approximately 200 to 400 ms post-response (Overbeek et al., 2005). While debates still exist surrounding the exact functional significance and interpretation of the Pe, a prominent view is that the Pe is associated with the awareness of errors (Nieuwenhuis et al., 2001; Overbeek et al., 2005). Unlike the ERN, Pe responses appear to be elicited only after perceived errors, which suggests that this component is involved in processes related to the actual awareness or conscious recognition of errors (Nieuwenhuis et al., 2001). Evidence suggests that in addition to the ACC, the Pe is also generated from the posterior cingulate–

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precuneus, a region that is associated with post-error processing, as well as self-awareness (O'Connell et al., 2007). It has also been suggested that the Pe may reflect a special type of the P3b component that is associated with the motivational significance of an error (Overbeek et al., 2005).

In sum, while both the ERN and Pe are elicited by error responses, they are believed to reflect separate aspects of error processing (Falkenstein et al., 2000; Overbeek et al., 2005). The ERN is thought to be involved in error detection and is associated with affective responses towards errors, whereas the Pe is thought to be reflective of conscious error awareness and recognition.

1.2. Neural responses to gun shooting

In the present study, we investigated the neural correlates in response to shooting a gaming gun at stimuli targets. Shooting a gun, both in real life and in a video game setting, can be a highly motivating task. Shooting accuracy has socially relevant consequences, and therefore people should want to avoid incorrectly shooting somebody, as doing so may result in harming an innocent person. To our knowledge, there has been very little research examining the neural responses to gun-shooting behaviors. There is preliminary evidence suggesting that the ability to distinguish between targets in a shooting task is related to P200 and N200 amplitudes (Correll et al., 2006). Other work using go/no-go tasks in which participants responded with a gaming gun has found that errors of commission (i.e., incorrect responding on no-go trials) elicited greater ERN and Pe amplitudes (Bediou et al., 2012).

However, the past research was limited in that they either did not investigate error-related neural responses to shooting mistakes (e.g., Correll et al., 2006), or only made use of simplistic stimuli (e.g., different colored shapes) as shooting targets (e.g., Bediou et al., 2012). Our research aimed to extend on past work by examining the neural responses to errors in a Shooter-type go/no-go task, which used more realistic shooting targets (i.e., armed versus unarmed people), in addition to trigger-pulling response methods. By using more complex shooting targets such as images of people holding guns (compared to simple shapes or letters), as well as requiring the participants to respond via shooting a gaming gun at the targets (compared to using button or key presses), this task then incorporates elements commonly found in real-life shooting or gaming situations. Thus, methodologically, the paradigm of the present study is more realistic to real-life shooting or gaming behaviors compared to traditional tasks (e.g., Flanker, Stroop), and may offer greater external validity in task design. Furthermore, by establishing the reliability of the amplitudes of the ERN/Pe obtained in the present Shooter task, it would allow this task to be a valid measure for future neuroscience research into shooting errors.

1.3. Present research

We examined the neural responses to shooting errors using a Shooter go/no-go paradigm, which instructed the participants to pull the trigger on a gaming gun to shoot armed targets, but to avoid shooting unarmed non-targets. This Shooter task simulates more real-life gaming or even shooting behaviors in both the task design (i.e., using images of individuals holding a gun) and response requirement (i.e., pulling a trigger on a gaming gun to "shoot" a target and to withhold pulling the trigger when seeing non-targets).

We suspect that one of the central characteristics of gun shooting is cognitive conflict (Botvinick et al., 2001), and that incorrectly shooting a non-target should elicit conflict and negative affect. We therefore hypothesize that errors in shooting responses should elicit greater ERN and Pe responses than accurate shooting.

2. Method

2.1. Participants

The participants were 53 first-year psychology undergraduate students (35 males) at the University of Toronto Scarborough, who participated for course credits. The participants' mean age was 19.22 years ($SD = 2.72$ years). Data from 14 participants were excluded from analyses due to low error rate (i.e., fewer than six errors; Olvet and Hajcak, 2009; $n = 6$), equipment/software malfunction ($n = 3$), and poor recording quality (i.e., high artifact rate; $n = 5$),[1] leaving a total of 39 participants for analyses.

2.2. Materials

2.2.1. Shooter go/no-go task

A Shooter go/no-go task was constructed based on the design of the shooter task used by Correll et al. (2002). This task resembled a video game, in which a series of stimuli images were presented on the computer screen. Each image consisted of a male target superimposed on a background. The male target was shown to be either holding a gun (black or silver colored) or a similarly colored harmless object (e.g., camera, wallet, cell phone, soda can). The task made use of 20 different target models (10 White males, 10 African–American males[2]). Each target model appeared four times in the task, twice holding guns and twice holding harmless objects. Thus, there were a total of 40 different images of targets holding guns (20 images with White males, 20 with African–American males), and 40 images of targets holding harmless objects (20 images with White males, 20 with African–American males; for further details regarding specifications of the background and target images, see Correll et al., 2002).

The participants were instructed to shoot ("go") targets holding a gun, but to withhold from shooting ("no-go") non-targets holding a harmless object. Shooting responses were made by pulling the trigger on a G-Mate-PC/USB gaming gun, and don't-shoot responses were made by withholding the pulling of the trigger. The gaming gun was hand-held freely by the participant for the duration of the task, which usually lasted around 10 minutes. The participants were instructed to hold the gun as naturally and comfortably as they could, while ensuring that the gun is pointed at the computer screen. Participants were given breaks between each block of the task, during which they could relax.

A total of 300 trials were used in the task (240 shoot, 60 don't-shoot), separated into six blocks of 50 trials each. The number of shoot and don't-shoot trials were identical in each block (40 shoot, 10 don't-shoot). The shoot and don't-shoot stimuli images were randomized, although the task specified an equal number of White and African–American targets for both the shoot and don't-shoot trials for each block. This 80:20 go to no-go ratio was used, in order to ensure that the go responses will become habitual, whereas the no-go responses will need to be suppressed. A practice session consisting of 20 trials, using different stimuli images than the actual task, preceded the 300 trials.

Each trial began with a fixation cross that appeared onscreen from between 300 to 600 ms. The image stimulus then appeared for 600 ms, during which the participants could make the shoot/don't-shoot response. The image disappeared from the screen either after 600 ms has passed without any responses from the participant, or after a shoot response was made. Finally, a blank screen was presented

[1] The somewhat high number of participants excluded due to poor ERP recording quality was attributed to the recording amplifier experiencing technical difficulties. However, these exclusions were made a priori before examining the data statistically, and are not selective exclusions.

[2] The original Shooter task was used by Correll et al. (2002) to examine differential responses to White and African–American targets. However, the current study was unable to examine the role of ethnicity, due to the low number of participants who made sufficient number of errors per target-race category.

for a duration ranging from 150 to 300 ms. If a participant responded incorrectly on a don't-shoot trial, the feedback message "You just murdered someone innocent!" was shown for 500 ms.

2.3. Procedure

After providing informed consent, participants completed the Shooter go/no-go task, during which their brain activities were recorded using electroencephalogram (EEG). Upon completion of the study, participants were debriefed and compensated.

2.3.1. Electrophysiological recording and processing

EEG was recorded from 32 tin electrodes in a stretch Lycra cap (Electro-Cap International, Eaton, OH). Vertical eye movements (VEOG) were monitored via a supra- to sub-orbital bipolar montage. EEG and VEOG were digitized at 512 Hz using the ASA acquisition hardware (Advanced Neuro Technology B.V., Enschede, The Netherlands), with digital average-ear reference and forehead ground. Electrode impedances were kept below 5 kΩ for the recordings. EEG was analyzed with Brain Vision Analyzer 2.0 (Brain Products GmbH, Munich, Germany). Continuous EEG was corrected for VEOG artifacts (Gratton et al., 1983) and frequencies below 0.1 Hz and above 30 Hz were digitally filtered offline (FFT implemented, 24 dB slope). An automatic procedure was employed to detect and reject artifacts. The criteria applied were a voltage step of more than 15 μV between sample points, a voltage difference of 150 μV within 150 ms intervals, voltages above 85 μV and below -85 μV, and a maximum voltage difference of less than 1 μV within 100 ms intervals. These intervals were rejected from individual channels in each trial.

For the ERN and Pe, correct go and incorrect no-go trials were separately averaged with an epoch of 200 ms pre-response to 800 ms post-response. The signal was baseline corrected by subtracting the average voltage occurring 200 to 50 ms pre-response. The ERN was quantified as the mean amplitude between 0 and 100 ms post-response at the frontal midline electrode FCz. The Pe was quantified as the mean amplitude between 200 and 400 ms post-response at the posterior midline electrode Pz. These time interval and electrode site selections are consistent with past work (e.g., Olvet and Hajcak, 2009; Riesel et al., 2012).

2.4. Data analyses

Internal reliability was assessed by examining split-half reliability, intraclass correlation coefficient (ICC), and Cronbach's alpha. To assess split-half reliability, we separated the Shooter task data into two subsets via odd and even error trials. We then calculated Pearson's correlations between these two subsets. For the ICC, we selected a two-way mixed model with absolute agreement. In terms of interpreting the ICC, it is suggested that values <0.40 are considered as poor, 0.40 to 0.59 as fair, 0.60 to 0.74 as good, and 0.75 to 1.00 as excellent (Cicchetti, 2001). Because these metrics were based on half of the total number of trials, Spearman–Brown corrections were applied and reported. Finally, we also calculated Cronbach's alpha for the Shooter task data. In terms of interpreting Cronbach's alpha, values >0.90 suggest excellent reliability, between 0.70 and 0.90 suggest high reliability, between 0.50 and 0.70 suggest moderate reliability, and below 0.50 suggest low reliability (e.g., Meyer et al., 2013, 2014).

These analyses were conducted for both the ERN/Pe raw scores, as well as the ERN/Pe difference scores (by subtracting the correct ERPs from the error ERPs). We conducted the analyses for participants with 4 or more errors ($n = 36$ for ERN, $n = 37$ for Pe), as well as for participants with 6 or more ($n = 30$ for ERN, $n = 31$ for Pe), 8 or more ($n = 22$ for ERN, $n = 25$ for Pe), 10 or more ($n = 15$ for ERN, $n = 18$ for Pe), and 12 or more ($n = 12$ for ERN, $n = 13$ for Pe) errors in both subsets.

3. Results

3.1. Behavioral results

Overall, the participants performed well on the Shooter go/no-go task (see Table 1 for descriptive statistics). Accuracy rates were 84.03% ($SD = 10.09$) for the shoot and 61.67% ($SD = 19.33$) for the don't-shoot trials. The difference in performance between the shoot and don't-shoot trials was significant, $t(38) = 5.37$, $p < 0.001$, such that participants were overall more accurate on the shoot trials. Reaction time data was recorded only for the correct shoot and incorrect don't-shoot responses, as incorrect shoot and correct don't-shoot responses were marked by a lack of a response. The mean reaction time was 449.27 ms ($SD = 33.70$) for correct shoot trials and 429.95 ms ($SD = 37.14$) for incorrect don't-shoot trials. The difference in reaction time between the two trial types was significant, $t(38) = 6.73$, $p < 0.001$, indicating that the participants on average responded quicker on incorrect don't-shoot trials.

Lastly, we calculated the sensitivity index (d′) and response bias (c) in accordance with signal detection theory for the Shooter go/no-go task responses. Higher sensitivity scores indicate better ability at distinguishing between the shoot and don't-shoot cues, and higher bias scores indicate more conservative response bias (i.e., less willing to engage in shoot responses; Macmillan and Creelman, 1991). Better behavioral sensitivity was related to increased accuracy on the don't-shoot trials, $r = 0.73$, $p < 0.001$. More conservative response bias was related to increased accuracy on the don't-shoot trials ($r = 0.92$, $p < 0.001$), but decreased accuracy on the shoot trials ($r = -0.81$, $p < 0.001$).

3.2. Brain activity

3.2.1. Overall ERN and Pe responses

We first examined the participants' overall neural responses to errors across the entire Shooter go/no-go task. In terms of the ERN, as expected, a repeated measures analysis revealed that incorrect shooting responses ($M = -3.37$ μV, $SD = 3.71$ μV) elicited greater ERN amplitudes than correct shooting responses ($M = 3.94$ μV, $SD = 3.69$ μV), $F(1, 38) = 107.89$, $p < 0.001$, $\eta_p^2 = 0.74$ (Fig. 1). Similarly, incorrect shooting ($M = 2.29$ μV, $SD = 6.97$ μV) also elicited greater Pe amplitudes than correct shooting responses ($M = -4.24$ μV, $SD = 6.71$ μV), $F(1, 38) = 35.91$, $p < 0.001$, $\eta_p^2 = 0.49$ (Fig. 2).

In light of recent work suggesting that a minimum of 20 errors are needed in order to obtain a reliable ERN (e.g., Meyer et al., 2014), we conducted the same analyses as above including only the participants who have made 20 or more errors on the Shooter task ($n = 15$). In these analyses, we again found that incorrect shooting responses ($M = -2.69$ μV, $SD = 3.12$ μV) elicited greater ERN amplitudes than correct shooting responses ($M = 3.53$ μV, $SD = 3.86$ μV), $F(1, 14) = 35.88$, $p < 0.001$, $\eta_p^2 = 0.72$. Incorrect shooting responses ($M = 0.17$ μV, $SD = 8.47$ μV) also elicited greater Pe amplitudes than correct shooting responses ($M = -5.21$ μV, $SD = 5.76$ μV), $F(1, 14) = 10.24$, $p = 0.006$, $\eta_p^2 = 0.42$. Thus, overall, it appears that mistakenly shooting

Table 1
Descriptives for the Shooter go/no-go behavioral data.

Variable	Mean (SD)
Correct shoot response percentage	84.03 (10.09)
Incorrect shoot response percentage	15.97 (10.09)
Correct don't-shoot response percentage	61.67 (19.33)
Incorrect don't-shoot response percentage	38.33 (19.33)
Sensitivity (d′)	1.39 (0.45)
Response bias (c)	−0.37 (0.41)
Correct shoot reaction time	449.27 ms (33.70)
Incorrect shoot reaction time	429.95 ms (37.14)

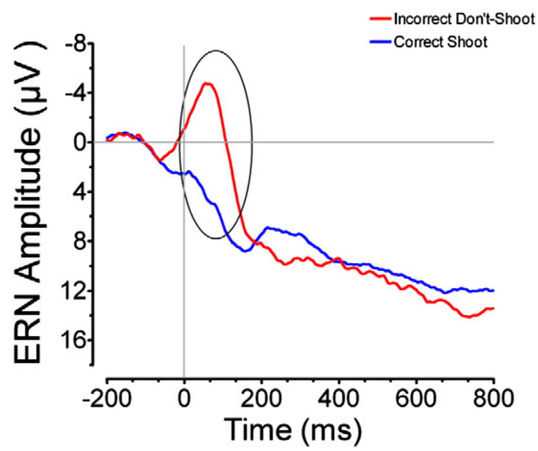

Fig. 1. Grand average ERN amplitudes at electrode site Fcz for incorrect don't-shoot and correct shoot trials.

an innocent person produced greater error-related neural responses compared to correctly shooting an armed person.

3.2.2. Reliability analyses

Table 2 displays the corrected split-half reliability, ICC, and Cronbach's alpha for the ERN/Pe raw scores, as well as the ERN/Pe difference scores, for participants with ≥4, ≥6, ≥8, ≥10, and ≥12 error trials on the Shooter go/no-go task. Additionally, we have also included the reliability metrics for the correct-related negativity (CRN; Vidal et al., 2000) raw scores. For the ERN raw scores, the reliability metrics ranged from fair to good for the ICC (from 0.48 to 0.62), and mostly moderate for the Cronbach's alpha (from 0.48 to 0.61). The reliability for the CRN raw scores, however, were considerably better, with the ICC in the excellent (from 0.76 to 0.98) range, and Cronbach's alpha in the high to excellent (from 0.76 to 0.97) ranges. This is likely because of the greater number of trials that contributed to the CRN. The ERN difference scores had somewhat better internal reliability compared to the ERN raw scores, with most metrics ranging from good to excellent for the ICC (from 0.48 to 0.79), and mostly from moderate to high for the Cronbach's alpha (from 0.47 to 0.78). However, as can be seen in Table 2, the reliability properties for the ERN generally improved with increased numbers of errors. These findings corroborate existing work on the internal reliability of the ERN (e.g., Larson et al., 2010; Meyer et al., 2013, 2014; Riesel et al., 2013; Rietdijk et al., 2014). It is interesting to note that, in the present study, we found better reliability metrics for the ERN difference scores compared to the ERN raw scores. This difference in reliability between the raw and difference scores may be due to the fact that the calculation of difference scores takes into account the CRN, in addition to the ERN. This, in turn, may then help to reduce the noise in the ERN difference scores, thus resulting in better reliability properties.

Table 2
Reliability metrics for the ERN, CRN, ΔERN, Pe, and ΔPe amplitudes.

	≥4 Error trials	≥6 Error trials	≥8 Error trials	≥10 Error trials	≥12 Error trials
ERN					
r	0.50*	0.53†	0.59†	0.61	0.59
ICC	0.48*	0.52*	0.60*	0.62*	0.61†
α	0.48	0.51	0.59	0.61	0.59
CRN					
r	0.77***	0.89***	0.97***	0.98***	0.98***
ICC	0.76***	0.88***	0.97***	0.97***	0.98***
α	0.76	0.88	0.97	0.97	0.97
ΔERN					
r	0.47†	0.66**	0.68*	0.78*	0.74*
ICC	0.48*	0.66**	0.69**	0.79**	0.74*
α	0.47	0.65	0.68	0.78	0.74
Pe					
r	0.85***	0.87***	0.94***	0.93***	0.95***
ICC	0.82***	0.84***	0.92***	0.91***	0.93***
α	0.85	0.87	0.94	0.93	0.94
ΔPe					
r	0.85***	0.83***	0.89***	0.87***	0.93***
ICC	0.82***	0.80***	0.87***	0.82***	0.90***
α	0.85	0.83	0.89	0.87	0.92

Note. †$p < 0.10$, *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$; ICC = intraclass correlation coefficient.

On the other hand, the Pe reliability metrics for both raw and difference scores were consistently in the excellent range (≥0.80) for the ICC, and high to excellent range for the Cronbach's alpha (≥0.83), although better reliability was obtained with increased trial count. These results suggest that, a minimum of 10 error trials should be required in order to obtain a reliable ERN on the Shooter go/no-go task. However, reliable Pe responses appeared to be obtained with as few as 4 error trials. Figs. 3 and 4 display the split-half grand average waveforms for the ERN and Pe, respectively.

3.3. Relationship between neural and behavioral responses

We first examined whether the ERN and Pe difference scores on the Shooter go/no-go task were correlated with behavioral performance in general. Better performance on don't-shoot trials were correlated with larger ERN ($r = -0.39$, $p = 0.01$) and Pe ($r = 0.33$, $p = 0.04$) difference amplitudes. ERN and Pe difference amplitudes were unrelated to performance on correct shoot trials (*ps* > 0.60). Since ERN/Pe responses are generally only elicited by incorrect trials, it would make sense that they would only be related to incorrect behavioral performances, i.e., incorrect don't-shoot trials. ERN and Pe difference amplitudes were unrelated to reaction times (*ps* > 0.17).

Next, we performed correlation analyses to examine how the ERN and Pe difference scores were associated with behavioral sensitivity (d') and response bias (c) for the task. Higher behavioral sensitivity scores were correlated with larger (i.e., more negative) ERN ($r = -0.56$, $p < 0.001$) and larger (i.e., more positive) Pe difference amplitudes ($r = 0.41$, $p = 0.01$) on the Shooter task. Response bias was not correlated with either ERN or Pe difference scores (*ps* > 0.18). Table 3 contains the correlations between the ERN, Pe, and behavioral performance for the Shooter task.

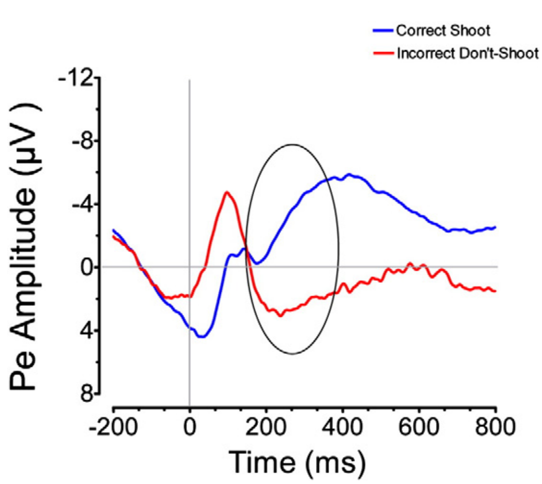

Fig. 2. Grand average Pe amplitudes at electrode site Pz for incorrect don't-shoot and correct shoot trials.

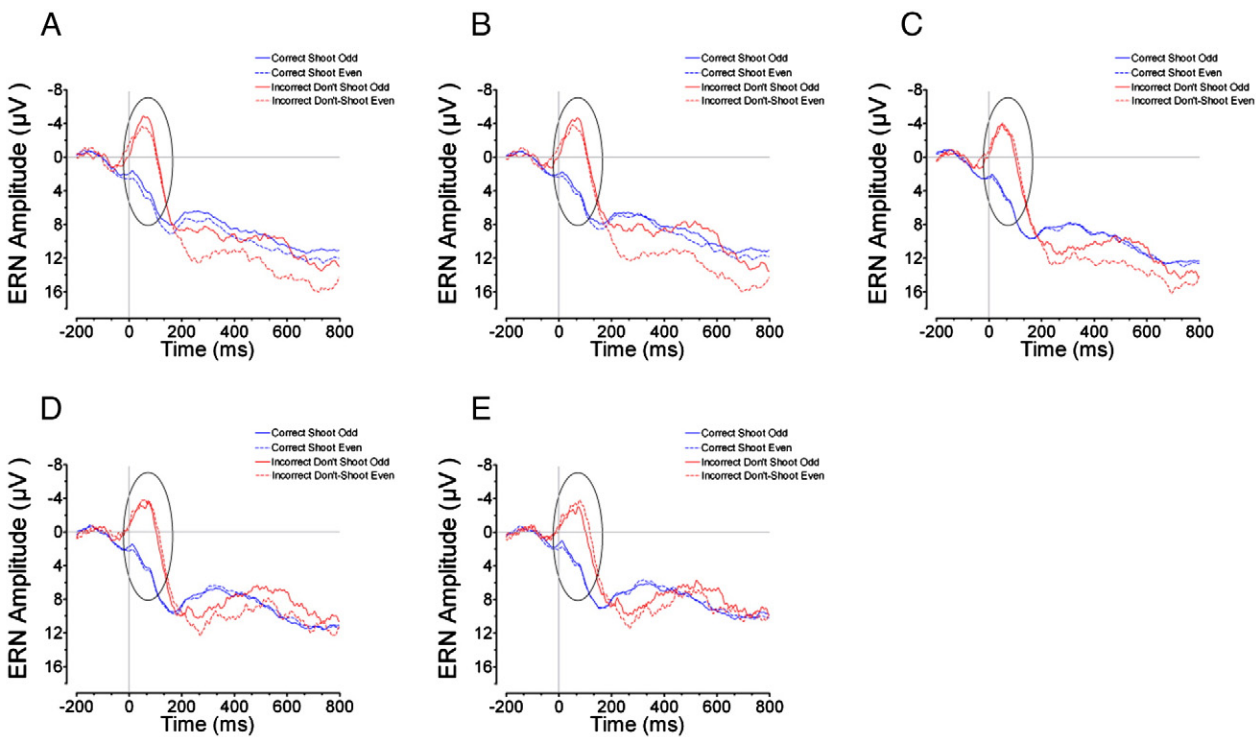

Fig. 3. Split-half grand average ERN amplitudes at electrode site Fcz for incorrect don't-shoot and correct shoot trials for participants with (A) 4 or more errors, (B) 6 or more errors, (C) 8 or more errors, (D) 10 or more errors, and (E) 12 or more errors.

Larger ERN and Pe difference amplitudes on the Shooter task, then, are related to better abilities to correctly shoot armed targets and to correctly avoid shooting unarmed non-targets. Thus, this pattern of results suggests that better differentiation of neural responses to erroneous versus correct shooting may produce more sensitive behavioral decisions.

4. Discussion

This study examined the neural responses towards errors on a Shooter go/no-go task, a task that simulates real-life shooting behavior. By using stimuli images showing real people holding guns (or harmless objects), as well as using actual trigger pulling response methods, we

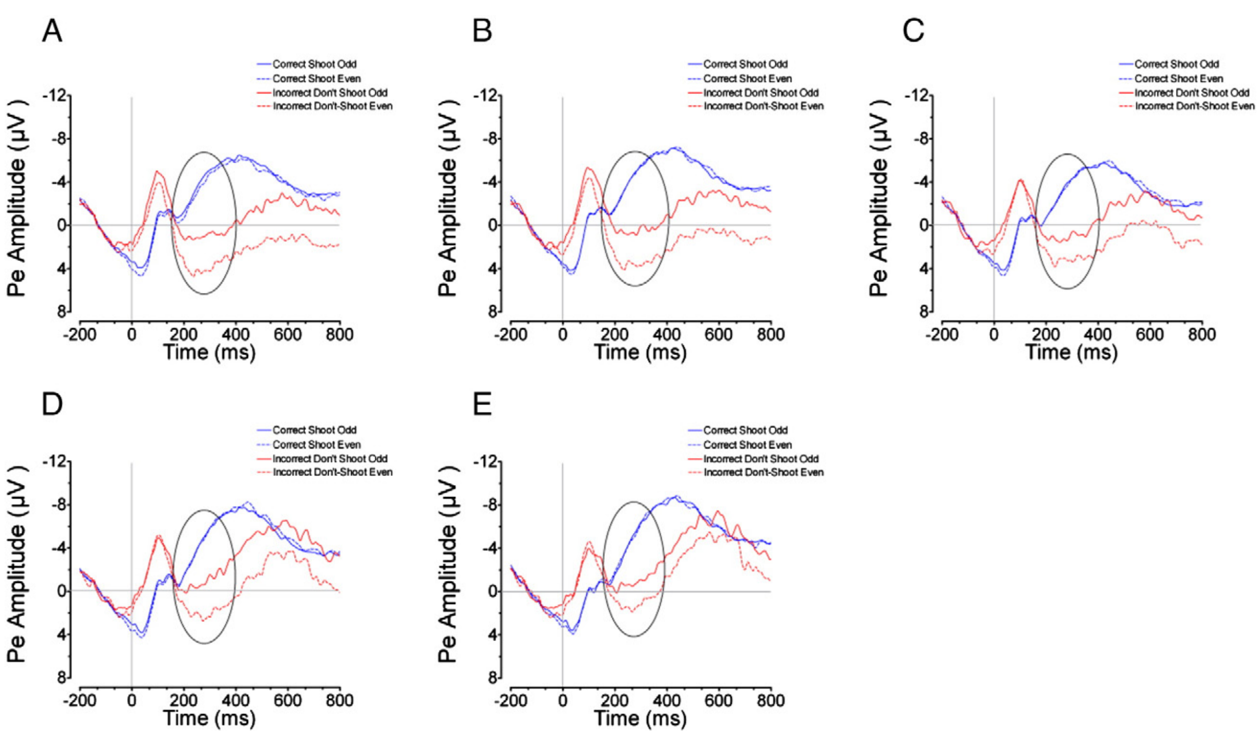

Fig. 4. Split-half grand average Pe amplitudes at electrode site Pz for incorrect don't-shoot and correct shoot trials for participants with (A) 4 or more errors, (B) 6 or more errors, (C) 8 or more errors, (D) 10 or more errors, and (E) 12 or more errors.

Table 3
Correlation matrix between ΔERN, ΔPe, and behavioral responses for the Shooter go/no-go task.

	1.	2.	3.	4.	5.	6.	7.
1. ΔERN							
2. ΔPe	0.01						
3. % Correct shoot	−0.09	0.02					
4. % Incorrect don't-shoot	0.39*	−0.33*	0.51***				
5. Sensitivity (d')	−0.56***	0.41*	0.20	−0.73***			
6. Response bias (c)	−0.22	0.21	−0.81***	−0.92***	0.40*		
7. RT correct shoot	−0.19	0.22	−0.70***	−0.87***	0.42**	0.93***	
8. RT incorrect don't-shoot	−0.19	0.14	−0.56***	−0.75***	0.37*	0.77***	0.88***

Note. *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$; RT = reaction time.

found that erroneously shooting an innocent person elicited significantly greater ERN and Pe amplitudes compared to correctly shooting an armed person. One possible explanation could be that mistakenly shooting an innocent person may be higher in conflict, or perhaps affective distress, than shooting an armed person. The present results are also consistent with the conclusions of past research on error processing and response (e.g., Gehring et al., 2012; Hajcak, 2012; Yeung et al., 2004). Furthermore, the neural responses to errors on the Shooter task appeared to have fairly good internal reliability, as indicated by split-half, ICC, and Cronbach's alpha analyses. These results suggest that, for the Shooter go/no-go task, a minimum of 10 error trials are required in order to obtain good internal reliability for the ERN. Overall, the results suggest that the Shooter task has adequate psychometric properties, and may be used as a more realistic task to assess shooting errors in future neurocognitive research on this topic.

Finally, it is of interest to note that the current study found significant relationships between neural responses to errors and behavioral performance. Greater ERN and Pe difference amplitudes were related to better performance on don't-shoot trials and greater sensitivity scores in terms of behavioral performance on the Shooter task. These results offer preliminary evidence that neural differentiation of shoot/don't-shoot responses may produce better accuracy in withholding incorrect shooting responses, as well as more sensitive behavioral ability to distinguish between shoot versus don't-shoot targets. This finding is noteworthy especially in light of past work showing conflicting findings regarding whether there exists a relationship between the neural and behavioral responses to errors, with some studies showing that higher ERN and Pe amplitudes are associated with lower error rates (e.g., Falkenstein et al., 2000; Hajcak et al., 2003a; Legault et al., 2012), and others finding no relationship between ERN/Pe and behavioral responses (e.g., Mathewson et al., 2005).

4.1. Implications of current findings

The most methodologically important contribution of the current study is that it demonstrated that it is possible to elicit reliable ERN and Pe responses using a more realistic task paradigm. The Shooter go/no-go task in the current study used stimuli images depicting real individuals holding guns, and required the participants to pull an actual trigger on a gaming gun to input responses. This is distinct from most tasks used in the study of the ERN/Pe, which usually adopt more simplistic task designs (e.g., colored shapes or letters as stimuli, button press responses). Therefore, the paradigms of the current study may present as a more advanced methodology for more accurate studies of shooting behaviors.

4.2. Future directions and limitations

By demonstrating that people's brains do indeed produce significant, measurable ERP responses towards shooting responses, and that these ERP responses are correlated with behavioral shooting performance, the current results may stimulate the study of more socially relevant behaviors involving guns. One potential application of the current paradigm would be to investigate whether it could be used to differentiate people in terms of their brain responses to shooting a gun. For example, would specific individual differences that relate to the standard ERN, such as psychopathy (Brazil et al., 2009), anxiety (Hajcak et al., 2003b), or negative affect (Hajcak et al., 2004), also be related to the ERN on the Shooter task? If so, this may help predict whether certain types of individuals should or should not own a gun, or be employed in occupations that require the usage of guns. Future research should examine the individual differences related to gun shooting ERP responses.

One limitation of the current study, however, is that is does not offer any potential mechanisms for why we found a relationship between neural and behavioral responses to shooting errors, especially since past research report somewhat conflicting findings. One possible explanation may be that the decision to shoot another person could be viewed as more socially and motivationally relevant, and people would therefore want to avoid incorrectly shooting or harming someone innocent. Thus, the motivational relevance of the task may in part be responsible for observing an association between neural and behavioral responses to errors. It is also possible, however, that differences in task design, i.e., different stimuli and response methods, between the Shooter go/no-go task and other traditional ERN/Pe tasks (e.g., Flanker, Stroop) also contributed to finding any associations between neural and behavioral responses. More future work is needed to further determine the factors that influence when and why these associations and dissociations exist.

Another important limitation lies in the fact that the ratio of "shoot" versus "don't-shoot" stimuli (80:20) is unrepresentative of "real life" situations, where it is highly uncommon for an average person to be in an environment which contains such a high ratio of armed versus unarmed individuals. Future studies need to employ more realistic "shoot" to "don't-shoot" ratios to provide more accurate investigation into shooting behaviors.

4.3. Conclusion

Using the Shooter go/no-go task, this study examined the reliability of the neural responses towards shooting errors, and whether these neural responses may relate to behavioral performances. The results found that shooting errors elicited greater ERN and Pe amplitudes compared to correct shooting, and that these neural responses showed good reliability. Furthermore, greater ERN/Pe difference amplitudes were related to more accurate behavioral performance and sensitivity. The present results can be seen as a proof of concept: it is possible to measure online brain responses to shooting responses, and as such, this could stimulate more advanced research on shooting behaviors.

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