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Error detection across the adult lifespan: Electrophysiological evidence for age-related deficits

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A R T I C L E I N F O

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A B S T R A C T

With increasing age, cognitive control processes steadily decline. Prior research suggests that healthy older adults have a generally intact performance monitoring system, but show specific deficits in error awareness, i.e., the ability to detect committed errors. We examined the neural processing of errors across the adult lifespan (69 participants; age range 20–72 years) by analysing the error (-related) negativity (Ne/ERN) and the error positivity (Pe) using an adapted version of the Go/Nogo task.

At a stable overall error rate, higher age was associated with a greater proportion of undetected errors. While the Ne/ERN was associated with the processing of errors in general, the Pe amplitude was modulated by detected errors only. Furthermore, the Pe amplitude for detected errors was significantly smaller in older adults, in contrast to the Ne/ERN amplitude which did not show age-related changes. Structural path models suggested that through those age-related changes in Pe amplitude, an indirect effect on the performance was observed.

Our results confirm and extend previous extreme-group based findings about specific deficits in error detection associated with higher age using age as a continuous predictor. Age-related reductions in Pe amplitude, associated with more undetected errors, are independent of early error processing, as evidenced by the preserved Ne/ERN.

Introduction

With increasing age, cognitive control steadily declines (Harada et al., 2013; Salthouse et al., 2003). One specific aspect of cognitive control is the ability to successfully stop a planned movement, i.e., motor inhibition. Although aging has been associated with weakened cognitive control (Falkenstein et al., 2002; Grady and Craik, 2000; Kramer et al., 1999; Phillips and Andres, 2010), which consequently should result in a larger error rate, older adults tend to be more accurate than young participants on experimental tasks requiring motor inhibition (Hsieh and Fang, 2012; Schreiber et al., 2011; Staub et al., 2014). This phenomenon has been explained to result from an adapted speed-accuracy trade off in older adults: several studies reported a shift from being fast to being as accurate as possible with increasing age (Falkenstein et al., 2001; Nieuwenhuis et al., 2002). This explanation might, however, be too simple since recent studies suggested that older adults allocate more resources than young participants to a general performance monitoring system (Hester et al., 2004; Nielson et al., 2002; Turner and Spreng, 2012), which may also explain the observed reduced error rate. As a drawback of this compensatory activity, fewer resources would be available for sub-functions of the performance monitoring system, for instance error processing and error awareness (Schreiber et al., 2011). Thus, although older adults conduct fewer errors overall in comparison to younger adults, a greater portion of those errors may remain unrecognized by the older participants (Harty et al., 2013; Rabbitt, 1990; Schreiber et al., 2012).

In the first 100 ms after committing an error, a negative component can be observed in the event-related brain potential (ERP), which is called error negativity (Ne) (Falkenstein et al., 1991) or error-related negativity (ERN) (Gehring et al., 1993), originating in the anterior cingulate cortex (Dehaene et al., 1994). According to the main theories of Ne/ERN (for a review see Taylor et al. (2007)), the component reflects the need to update the performance monitoring system in order to adjust future behaviour and to prevent further errors (Ridderinkhof et al., 2004). Three recent studies consistently showed that a necessary prerequisite for the occurrence of the Ne/ERN is a thorough processing of both the target stimulus and the (erroneous) response (Charles et al.,

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2013; Gibbons et al., 2011; Woodman, 2010). However, the question whether error awareness, i.e., a conscious detection of the error, is mandatory for the development of the Ne/ERN is currently under debate (Wessel, 2012).

A second error-related component, the so called error positivity (Pe; (Falkenstein et al., 1994, 1991)), which emerges approximately 200 to 300 ms after the Ne/ERN and originates from more posterior parts of the cingulate cortex, has consistently been associated with error awareness (Endrass et al., 2012; Grützmann et al., 2014; Nieuwenhuis et al., 2001). For instance, Endrass et al. (2012) investigated error awareness in young adults and concluded that the Pe amplitude was significantly larger for consciously detected (aware) errors compared to unaware (undetected) errors, while the Ne/ERN amplitude was not modulated by awareness. That is, the Ne/ERN amplitude was similar for both, aware and unaware errors (Nieuwenhuis et al., 2001; O'Connell et al., 2007). Although the majority of studies reports comparable Ne/ERN amplitudes for aware and unaware errors (Dhar et al., 2011; Endrass et al., 2012, 2007, 2005; Grützmann et al., 2014; Hughes and Yeung, 2011; Nieuwenhuis et al., 2001; O'Connell et al., 2007, 2009; Pavone et al., 2009; Shalgi et al., 2009; Shalgi and Deouell, 2012), evidence for higher Ne/ERN amplitudes after aware errors is recently accumulating (Hewig et al., 2011; Maier et al., 2008; Navarro-Cebrian et al., 2013; Scheffers and Coles, 2000; Steinhauser and Yeung, 2010; Wessel et al., 2011; Woodman, 2010).

Age-related effects on Ne/ERN amplitude are well investigated. While some studies reported similar amplitudes across age groups (Capuana et al., 2012; Eppinger et al., 2008; Hsieh and Fang, 2012; Larson et al., 2016; Pietschmann et al., 2011a, 2011b; Thurm et al., 2013), most studies report smaller Ne/ERN amplitudes for older adults (Band and Kok, 2000; Endrass et al., 2012; Falkenstein et al., 2001; Hoffmann and Falkenstein, 2011; Kolev et al., 2009; Kolev et al., 2005; Mathalon et al., 2003; Mathewson et al., 2005; Nieuwenhuis et al., 2002; Schreiber et al., 2012; Themanson et al., 2006). However, only few studies investigated age-related effects on the Pe amplitude after errors, and these studies consistently concluded that the Pe is significantly reduced in older adults (Capuana et al., 2012; Larson et al., 2016; Mathewson et al., 2005).

Of course, cognitive control starts already before error commission and two important ERP indicators, the N2 and the P300, reflect putative causes of error commission (e.g., non-successful response inhibition) as well as important neural sources of information for the individual's error detection system. The N2, a negative deflection peaking around 200 ms after stimulus onset, is associated with response inhibition (Falkenstein et al., 1999; Groom and Cragg, 2015) and conflict monitoring (Grützmann et al., 2014). Several studies reported smaller N2 amplitudes in older adults in contrast to younger adults (Czigler et al., 1996; Korsch et al., 2016; Lucci et al., 2013). The P300 peaks approximately 300 ms after stimulus onset and is assumed to signal the need of more attentional resources after a conflict has been detected (Larson et al., 2016; Polich, 1996). More specifically, the P300 is associated with a more thorough stimulus evaluation in order to select an appropriate response (Huster et al., 2014; Polich, 2007), and was shown to be smaller in older participants compared to younger participants (Lucci et al., 2013; Schmiedt-Fehr et al., 2011). Overall, we expected to observe a gradual reduction in the error rate with higher age, accompanied by a higher amount of undetected errors. At the neuronal level, we hypothesized to find smaller amplitudes of all aforementioned components related to error processing with higher age, which we assumed should take place as a gradual process across adult lifespan instead of a sudden decline at a specific age.

Method

Participants

We recruited a sample of 74 healthy participants (31 men, 47 women), aged (mean ± standard deviation [SD]) 42.0 ± 16 years (range: 20–72 years). Five participants (aged 42.6 ± 18 years) had to be excluded due to task performance: one participant responded correctly in less than 10% of the nogo-trials, and four participants failed to signal that they had detected an error (thus we could not rule out that they misunderstood the task instructions). The remaining 69 participants were right-handed [laterality quotient (mean ± SD): 90.5 ± 16.6] according to the Edinburgh Handedness Inventory and had intact colour vision as tested with Ishihara colour plates (mean absolute amount of errors ± SD: 0.8 ± 0.8; (Ishihara, 1994)). None of the participants reported a history of neurological or psychiatric diseases. The Mini Mental State Examination (MMSE; mean ± SD: 29.9 ± 0.3) (Folstein et al., 1975) and the clock drawing test (mean ± SD: 1.1 ± 0.4) (Sunderland et al., 1989) were unremarkable in all participants, thereby excluding relevant general cognitive decline. The Beck's Depression Inventory (BDI; mean ± SD: 4.0 ± 4.0) (Hautzinger, 1991) scores of the participants were in the subclinical range. We used two subgroups to test differences in ERP amplitude (see Section 2.4 for reasoning). The first subgroup consisted of 46 participants who conducted at least six detected errors (mean 43 ± 16 years; 28 men), and 10 participants who conducted at least six undetected errors were included in the second subgroup (mean 60 ± 12 years; 7 men). Prior to the testing session, all participants gave written informed consent. The study was approved by the local ethics committee and conformed to the Declaration of Helsinki.

Objective of the present study

In order to investigate age-related variations in motor inhibition and error processing, we designed a task that allows reliable assessment for participants of all ages. A widely used experimental paradigm to test motor inhibition is the Go/Nogo task (Aron, 2011; Falkenstein et al., 2000; Nee et al., 2007). It consists of two different types of stimuli. Participants are instructed to respond as quickly and as accurately as possible after the presentation of go-stimuli, whereas they are required to withhold a response after seeing nogo-stimuli. Commission errors (i.e., incorrect button presses after nogo-stimuli) serve as indicators of non-successful motor inhibition and can be used for the analysis of error processing.

Previous studies typically investigated age-related effects on error monitoring in a group-based approach (e.g., (Falkenstein et al., 2001; Harty et al., 2013)). However, the categorisation of a continuous parameter such as age—with an arbitrarily chosen cut-off value—usually limits the interpretation of these findings. Hence, we aimed to evaluate previous behavioural findings (e.g., error rate and RT variations) and neurophysiological findings (age related variations in Ne/ERN, Pe, N2 and P300) by investigating a sample of participants with a broad age range (i.e., 20–72 years). Therefore, we used a modified version of a Go/Nogo task to investigate differential effects between correct responses and errors (detected and undetected).

Go/Nogo task and procedure

We adopted typical versions of the Go/Nogo paradigm (i.e., using ‘X’ as go-stimulus and ‘O’ as nogo-stimulus) (Passingham, 1972; Vallesi et al., 2009) by using a colour discrimination task. Nogo-stimuli were shining red, whereas seven similar reddish colours served as go-stimuli (see Fig. 1). Two different approaches of signalling error awareness have been used in previous studies. Half of the studies used a reminder to signal error awareness after each trial in a binary (yes or no) or multiple-choice rating (e.g., yes, no, unsure) (Endrass et al., 2012; Grützmann et al., 2014; Schreiber et al., 2011; Shalgi and Deouell, 2012). In the other studies, participants were instructed to use a separate “awareness button” to indicate the recognition of an error (Murphy et al., 2012; Navarro-Cebrian et al., 2013). We deliberately decided not to use a reminder after each trial, and we also refrained