Cognition 146 (2016) 110–120

Contents lists available at ScienceDirect

Cognition

journal homepage: www.elsevier.com/locate/COGNIT

Oops, scratch that! Monitoring one's own errors during mental calculation

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ARTICLE INFO

Article history:
Received 10 July 2014
Revised 23 July 2015
Accepted 6 September 2015

Keywords:
Error monitoring
Error detection
Feeling of error
Confidence
Metacognition
Metacognitive feeling
Number bisection task

ABSTRACT

The feeling of error (FOE) is the subjective experience that something went wrong during a reasoning or calculation task. The main goal of the present study was to assess the accuracy of the FOE in the context of mental mathematical calculation. We used the number bisection task (NBT) to evoke this metacognitive feeling and assessed it by asking participants if they felt they have committed an error after solving the task. In the NBT participants have to determine whether the number presented in the middle of a triplet corresponds to the arithmetic mean of the two outer numbers (e.g., 07_16_25) with a Yes/No answer. Our results show that FOE reports were strongly correlated with arithmetic errors and numerical properties of the NBT, suggesting that the FOE accurately represents the error. This finding indicates that even very fast metacognitive feelings are reliable when it comes to evaluating one's own mental performance. Moreover, our results suggest that the occurrence of FOEs is determined by the fluency with which each triplet was solved and the post-decision evaluation processes that occurred after the NBT was solved. Additionally, we asked participants to report their confidence in the given answer for the cases where they did not report FOEs. Participants reported less confidence for the (objectively) incorrect answers than for the (objectively) correct ones, suggesting that in cases where they did not have a conscious FOE they still were able to implicitly detect their errors. Remarkably, confidence was also determined by the fluency of the NBT.

1. Introduction

When solving math problems such as multiplication or division, people sometimes get the (gut) feeling that their calculations have gone wrong and that, therefore, they should not endorse the output of their mental calculation. This feeling appears as a spontaneous phenomenal experience that points to the fact that the calculation might be mistaken and motivates the reasoner to revise what she has been doing. Everyday observation suggests that this phenomenon is not restricted to the classroom; it generalizes to all contexts where people carry out mental actions, such as making mental rotations when calculating their way from one point to another by using a map, deciding between two possible actions, reasoning about the probability of an event, or mentally calculating how much money they spent in the last week. In situations like these, people sometimes report experiencing a "feeling of error" (henceforth FOE) that alerts them about a possible mistake in their mental processing. The subjective experience that something went wrong is assumed to arise during or right after the mental action and is fundamental for further correction and improvement in calculating and reasoning.

The FOE has been classified as a metacognitive or epistemic feeling in the literature on metacognition (Arango-Muñoz, 2014; Gangemi & Bourgeois-Gironde, 2014; Thompson & Johnson, 2014). Accordingly, the FOE is conceived as a phenomenal experience directed toward a mental state, process or disposition, that motivates certain behaviors such as changing the strategy or checking the outcome of a mental action (for an overview see Arango-Muñoz & Michaelian, 2014; De Sousa, 2009; Moulin & Souchay, 2013). Metacognitive feelings are particularly interesting because they make people aware of mental conditions that they would not notice in the absence of such feelings. For instance, in the case of the tip-of-the-tongue phenomenon, the feeling points to the agent that she is in possession of a piece of information although she has no access to it in her memory, and so motivates the individual to keep trying to remember (Brown & McNeill,

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http://dx.doi.org/10.1016/j.cognition.2015.09.005
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1966; Schwartz, 2001; Schwartz & Metcalfe, 2011; see Brown, 2012 for a recent review).

Most of the empirical studies working on metacognitive feelings and reasoning have focused on positive feelings whereby the person detects a correct answer. For example, Boekaerts and Rozendaal (2010) assessed students' confidence in a mathematical task where students had to report their confidence on a 10 point scale before and after they had produced the solution to two types of mathematical problems: computation and application problems.[1] Predominantly, they found effects of the type of mathematical problem (computation and application problem) and the time of measurement (before or after solving the problem) on the accuracy of the confidence. Similarly, the feeling of rightness (henceforth FOR) has been addressed by Thompson, Prowse Turner, and Pennycook (2011); they investigated the FOR after individuals solved conditional reasoning and syllogistic problems. Participants had to provide an initial, intuitive response to the reasoning problem, as well as a retrospective evaluation of their intuitive answer based on their FOR. The authors reported a negative correlation between the FOR and the reaction time of the initial intuitive response, such that fluent processing (as indicated by shorter reaction times) was associated with a higher FOR.

On the other hand, the studies addressing performance monitoring by negative feelings, like the feeling of error, have followed two different traditions. One focuses on error detection and error awareness of bodily actions (see Wessel, 2012 for a review), and the other focuses on the metacognitive feeling of error related to reasoning (Gangemi & Bourgeois-Gironde, 2014; Thompson & Johnson, 2014). The first tradition uses behavioral paradigms such as the Go/No-Go (Dhar, Wiersema, & Pourtois, 2011; Murphy, Robertson, Allen, Hester, & O'Connell, 2012), the flanker task (Hughes & Yeung, 2011; Scheffers & Coles, 2000) and the antisaccade paradigm (Endrass, Franke, & Kathmann, 2005; Nieuwenhuis, Ridderinkhof, Blom, Band, & Kok, 2001) to study the detection and awareness of erroneous bodily movements. Often, these researchers are also interested in determining whether the electrophysiological indices of cortical error processing (i.e., error related negativity (ERN) or the error positivity (Pe)) are associated with error awareness (Boldt & Yeung, 2015; Steinhauser & Yeung, 2010). In contrast, the second tradition, focuses on the detection and awareness of erroneous mental reasoning episodes, and therefore uses logical, probabilistic and mathematical reasoning tasks (De Neys, 2012; De Neys, Cromheeke, & Osman, 2011; De Neys & Glumicic, 2008; Gangemi & Bourgeois-Gironde, 2014).

These two traditions have developed their own methods, paradigms and models in parallel without any interaction. One of the aims of this paper is to bridge this gap by integrating elements from the two perspectives. On the one hand, following the error detection tradition, we chose a speeded button press task (Murphy et al., 2012; Rabbitt, 1966) in which a mathematical task was embedded. On the other hand, the mathematical task was chosen to evoke reasoning errors, as has been done in the metacognitive error awareness literature (De Neys, 2012; Gangemi & Bourgeois-Gironde, 2014). These factors allowed a close examination of participants' behavior related to error monitoring, thereby merging the two traditions. The novelty of this approach is that it incorporates reasoning and/or mental calculation errors in the framework of error detection, which has traditionally focused on action or motor errors. Furthermore, following the metacognitive tradition, we additionally asked for introspective reports about the feelings that accompanied the task (Koriat, 2000, 2007; Reder & Ritter, 1992; Gangemi et al., 2014) and used established measures, such as the Gamma correlation, to assess the accuracy of the feelings (Koren, Seidman, Goldsmith, & Harvey, 2006; Nelson, 1984). In line with both traditions, we also asked participants to rate their confidence (Boldt & Yeung, 2015; Scheffers & Coles, 2000; Yeung & Summerfield, 2012).

With this integrative goal in mind, we considered three specific aims and three hypotheses. First, we wanted to determine the accuracy of the FOE. Based on previous studies on metamemory (Koriat, 2000; Paynter, Reder, & Kieffaber, 2009; Reder & Ritter, 1992) and metareasoning studies (Gangemi & Bourgeois-Gironde, 2014), we hypothesized that: (1) the FOE in a reasoning task is a reliable signal of error (as is the case in error detection on motor tasks). That is, we expect that participants would mainly report having a FOE after having committed a mistake in their calculation.

Second, we were interested in defining the determinants of the FOE. Two main factors that have been proposed in the literature as determinants of metacognitive feelings were considered with this goal: fluency and post-decision evaluation. In the tradition of metacognitive studies, fluency refers to the ease with which a piece of information is processed and/or comes to the mind (Oppenheimer, 2008; Schwarz, 2010), for example, the speed with which an item is retrieved from memory (Benjamin, Bjork, & Schwartz, 1998; Koriat & Ma'ayan, 2005, see Koriat, 2007 for a review). Accordingly, if fluency plays a role in the FOE reports, then there should be a higher probability of no-FOE reports for fluent calculations, and higher probability of FOE reports for disfluent calculations (Jiang & Hong, 2014; Thompson, 2009; Thompson et al., 2011). Therefore, we hypothesized that: (2.1) if the FOE is determined by fluency processing, participants will report less FOEs on fluent trials as compared to disfluent trials. The second factor that has been proposed as a determinant of metacognitive feelings is post-decision evaluation process. Metacognitive tradition on error monitoring specifies that this process occurs after acting or making a decision and serves in evaluating the likelihood that the decision or action will result in a favorable or unfavorable outcome (Vickers & Lee, 1998, 2000). According to Vickers and Lee (1998, 2000), metacognitive feelings of confidence and error are the product of an accumulator system that progressively and continuously accumulates and evaluates evidence in favor of or against the initial response (see Yeung & Summerfield, 2012 for a review). In other words, participants keep considering the problem and checking their answer after giving the answer to the problem, and this post-evaluation leads to error detection and subsequent behavioral slowdown, even in the absence of feedback (Rabbitt, 1966). The behavioral slowdown is not restricted to the primary task (e.g., the mathematical task in our experimental design), but it can generalize and affect other immediately following tasks, as has been demonstrated by recent studies (Cho, Orr, Cohen, & Carter, 2009; Forster & Cho, 2014; Notebaert & Verguts, 2011). Thus, given that error detection is normally followed by a slowdown in the subsequent behavior, the reaction time of the FOE report (the task that immediately follows the mathematical calculation in our experimental design) can be used as an index of a continued post-decision evaluation process. Based on these considerations, we hypothesized that: (2.2) if the FOE is determined by a post-decision evaluation, we expect to find that participants take longer to report whether or not they had a FOE in the mathematical task after having committed an error, compared to when they had made no error; we also expect participants to take longer to report FOEs than to report no-FOEs.

Our third and last aim was to explore the extent to which participants were sensitive to their missed errors, that is, participants' sensitivity to the errors they fail to report (i.e., after no-FOE report).

[1] An example of an application problem: "The Mount Everest has the highest mountaintop on earth. Its height is 8848 m above sea level. The lowest point of the earth's crust is in the Pacific Ocean at 11,034 m below sea level. What is the difference between the highest and the lowest points on earth?". An example of a computation problem: "68.2 − 4.73 = ...?".