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BRIEF REPORT

Your error in my hand: An investigation of observational posterror slowing

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Abstract
For human beings, monitoring others' errors is essential for efficient goal-directed behavior. Indeed, the mere observation of other individuals' errors provides a rich source of information that can be used to avoid potential errors and improve our performance without direct experience. Recent studies have outlined that vicarious experience of errors influences the observer's overt behavior. This observational posterror slowing (oPES) is supposed to reflect a strategic increase in control aimed at reducing the probability of an error. Because the consequences of error observation have been exclusively investigated by means of arbitrary button-press responses, which limit the investigation to premovement processes, it is unclear whether the observation of an error also influences the online control of goal-directed actions. In the present study, for the first time, we investigated the effect of error observation on the reach-to-grasp movement by means of kinematical analysis. The results revealed that error-observation effects are not confined to premovement processes—they also strategically affect spatial movement trajectories. Our findings add substantially to previous literature, showing that the oPES spreads to movement execution when a more realistic, ecologically valid task is employed.

Keywords Posterror slowing · Error observation · Kinematics · Reach to grasp

Error is a constant companion in any daily life activity. Some errors allow us to learn something new, others cause us nothing other than annoyance or frustration, and, in some circumstances, errors can even lead to devastating consequences. For this reason, the ability to monitor actions and adaptively react to one's own errors is of outstanding importance for human beings. Our social nature leads us to monitor the behavior of others, which provides a rich source of information that we can use to avoid potential errors and improve our performance without direct experience.

Recently, some evoked related potential (ERP) studies have shown that when participants monitor errors made by other individuals, a negative-going ERP component, similar to error-related negativity (ERN), can be recorded in the observer (oERN; Bates, Patel, & Liddle, 2005; van Schie, Mars, Coles, & Bekkering, 2004). The neural generator of the oERN is supposed to be the anterior cingulate cortex (ACC), which gives rise to the ERN (van Schie et al., 2004). The evidence suggesting the existence of similar brain activity for error commission and error observation has been supported by some fMRI investigations with specific reference to the medial prefrontal areas (e.g., de Bruijn, de Lange, von Cramon, & Ullsperger, 2009).

Similarly, behavioral studies suggest that adaptations following self-generated and observed errors are driven by analogous mechanisms (Schuch & Tipper, 2007; Núñez Castellar, Notebaert, Van den Bossche, & Fias, 2011). This body of work capitalized on one of the most studied markers of error reactivity, namely the posterror slowing (PES; Rabbitt, 1966). The PES effect consists in an increase in response latencies on the trials following an error, and it has been interpreted as an adaptive adjustment aimed at taking extra time to plan the action and prevent future errors (but see Notebaert et al., 2009). As proposed by theories such as the conflict monitoring (Botvinick, Braver, Barch, Carter, & Cohen, 2001), the inhibition (Marco-Pallarés, Camara, Münte, & Rodríguez-Fornells,

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2008), and the reinforcement learning (Holroyd & Coles, 2002), PES is the product of an error-monitoring system, serving the purpose to implement a more cautious response strategy to reduce the probability of future errors.

A recent development in PES research is that this effect is also present after error observation (observational PES; oPES), providing supporting evidence for the existence of a "mirror" error-monitor system, which may be a key mechanism for the acquisition of learned behaviors on the basis of the actions of others (Schuch & Tipper, 2007). Recent studies, however, have questioned the idea that the oPES is the consequence of simulation of the other person's error processing (Schuch & Tipper, 2007). For instance, Núñez Castellar et al., (2011) showed that the oPES is also present when participants were asked to monitor a computer's performance, demonstrating that the slowing after an observed error occurs even when neither visible behavior to imitate nor high-level processes can be simulated.

To date, the oPES has been exclusively investigated by means of speeded reaction time (RT) tasks, measuring arbitrary button-press responses. However, as pointed out by Gehring, Liu Orr, and Carp (2011), most daily life movements have a slower time course than speeded RT response, and more realistic and ecologically valid tasks may afford a better opportunity to investigate the consequences of errors. Moreover, it is helpful to keep in mind that, as RTs limit the investigation to premovement processes (Haith, Pakpoor, & Krakauer, 2016), the influence of error observation on movement execution is yet an unexplored field.

With this in mind, the aim of the present study is twofold. To examine the oPES in the context of realistic goal-directed movements and to explore, for the first time, kinematical reorganization following the observation of an erroneous movement. The task required that participants and a confederate alternated in reaching out and grasping a steel sphere positioned on a wooden support. They were asked to perform the movement as naturally and accurately as possible, without knocking over the wooden support (i.e., the error). If oPES is evident not only at premovement level but also during action execution, then we expect changes in kinematic parameterization as to reduce the probability of making an error in subsequent movements.

Methods and materials

Participants

Fourteen participants (mean age = 22.8 years, *SD* = 3.05 years, eight males) were recruited from the student population of the University of Padua. All participants were naïve with respect to the purpose of the study, right-handed (Oldfield, 1971), and had normal or corrected-to-normal vision. The experimental procedure was approved by the Institutional Review Board at the University of Padua and was in accordance with the declaration of Helsinki. We did not perform a power analysis to determine the sample size, because we employed an original task which, for the first time, allows us to determine the influence of error observation on kinematics. Thus, running a power analysis is not recommended because it may lead to arbitrary decisions concerning sample size.

Apparatus

Figure 1a represents the experimental setup. Two participants took part in the experiment. A participant naïve as to the purpose of the experiment (i.e., real participant) and a confederate (i.e., a coexperimenter pretending to be a naïve participant). They were seated on height-adjustable chairs, opposite to each other, their thoraxes pressed gently against the front edge of the table (90 × 90 cm), and their feet were supported. The viewing distance from the target was held constant with the use of an adjustable head-chin rest. The target object was placed in the middle of the table, 45 cm away from the edge of the table and along the midsagittal plane of the participants. The target was a steel sphere (0.5 cm Ø), positioned on a wooden support (0.9 × 20 cm). To control stimulus presentation time, both participants and the confederate wore visual occlusion spectacles (PLATO, Translucent Technologies, Inc.), preventing vision during the intertrial interval, by changing from a transparent to an opaque state. Before each trial, they rested their hand upon a starting switch (11 × 8 cm), placed 22 cm away from the edge of the table. A small container (11 × 8 cm) was placed 4 cm in front of a starting switch.

Kinematic recording

Movements were recorded by means of a 3D-optoelectronic SMART-D system (Bioengineering Technology & Systems, B|T|S|), equipped with six infrared cameras (sampling rate 140 Hz) placed in a semicircle at a distance of 1.2 m from the table (see Fig. 1b). Reflective passive markers (0.25 cm Ø) were fastened using double-sided tape to (a) the wrist, (b) the tip of the index finger, and (c) the tip of the thumb of the participants' and the confederate's right hand. Before data collection, the camera position, roll angle, zoom, focus, threshold, and brightness were adjusted to optimize marker tracking. Static and dynamic calibration was then performed. The static calibration was performed by means of a three-axes frame of five markers at known distances from each other, placed in the middle of the table. For the dynamic calibration, a three-marker wand was moved throughout the workspace of interest for 60 s. Coordinates of the markers were reconstructed with an accuracy of .2 mm over the field of view. The standard

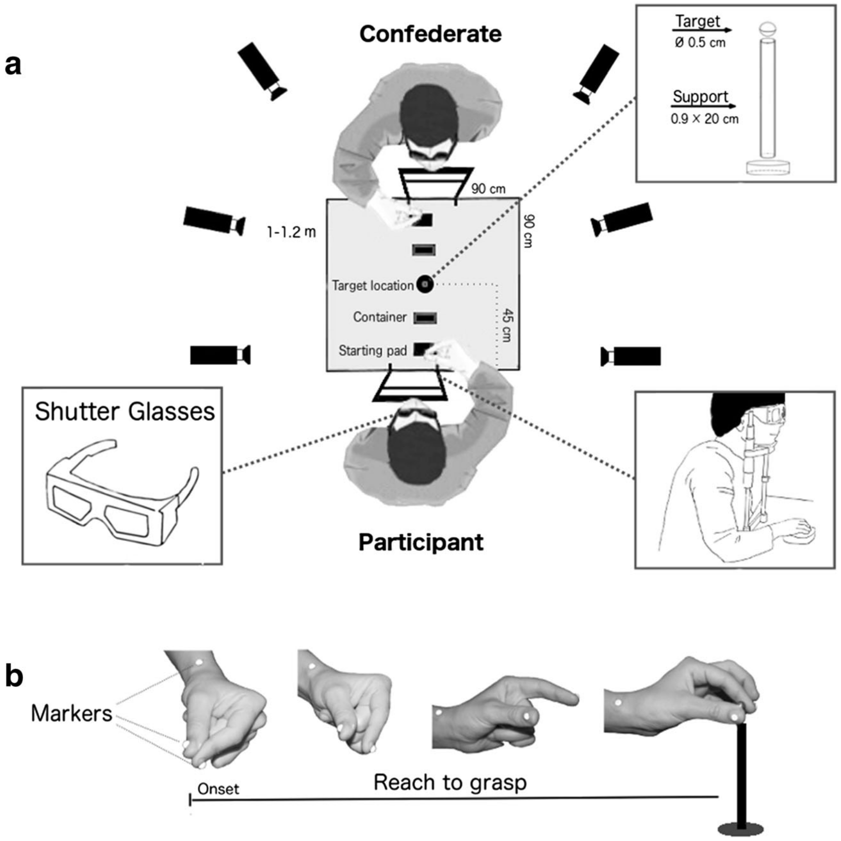

Fig. 1 **a** Graphical representation of the experimental setup. **b** Schematic representation of the reach-to-grasp movement and markers' positioning upon the anatomical landmark of interest

deviation of the reconstruction error was .2 mm for the *x*, *y*, and *z* axes.

Data processing

RT was defined as the time between the opening of the shutter glasses and the release of the starting switch. Kinematical analysis was performed by means of the SMART-D Tracker software package (B|T|S|), which provides a 3-D reconstruction of the marker positions as a function of time. The data were then filtered using a finite impulse response linear filter (transition band = 1 Hz, sharpening variable = 2, cutoff frequency = 10 Hz; D'Amico & Ferrigno, 1992). Movement onset was defined from the tangential speed of the wrist marker using a threshold of 5 mm/s. Movement offset was defined as the time at which the hand made contact with the target, and it was quantified as the time at which the hand opening velocity crossed a threshold (5 mm/s) after reaching its minimum value and remained above it for longer than 500 ms. Rather than using a "fishing expedition" approach, and looking at the many dependent measures kinematic analysis can provide, to test our specific experimental hypothesis, we focused on the maximum height of the wrist trajectory from the working surface. As previously demonstrated, this measure shows consistent differences between situations in which two agents act within the same working space and situations in which agents act in isolation (Becchio, Sartori, Bulgheroni, & Castiello, 2008; Georgiou, Becchio, Glover, & Castiello, 2007; Quesque, Lewkowicz, Delevoye-Turrell, & Coello, 2013). For instance, wrist elevation is modulated according to the type of social interaction occurring between participants and by the level of involvement (e.g., action observation, cooperation, competition). And, of relevance for the present study, higher arm trajectories are evident when people share a reachable space independently from whether the aim to interact is made explicit or not (e.g., Quesque et al., 2013). Furthermore, it should be noted that the modulation of wrist elevation might represent a specific strategy aimed at improving the subsequent performance. An increase in hand elevation may ensure that fingers do not collide with the target or the support—as in our circumstances—during movement execution (Smeets & Brenner, 1999), and may lengthen the time window within which contact points can be established more precisely and firmly (Glover, 2004).

Procedure and design

For each experimental session, two participants came into the lab and were introduced to each other. After receiving the instructions, they sat at a table in front of each other.

Unbeknown to the real participant, the other participant was a confederate. Spontaneous reports provided in postexperimental interviews indicated that participants were completely unaware that the partner was a confederate. Prior to each trial, the shutter goggles worn by the participants and the confederate were set in their opaque state. Both held the ulnar side of the hand upon a starting switch, with the thumb and index finger pinched together (see Fig. 1b). As soon as the shutter goggles opened, one of the two agents was asked to observe the other reaching out and grasping the steel sphere by means of a precision grip (PG; see Fig. 1b) and deposit it into the container. Then, on the following trial, the agent who previously observed the movement performed the action (i.e., execution trials). The "observation" and the "execution" trials were administered in an alternated fashion. The request for the execution trials was to perform the movement as naturally and accurately as possible, to avoid dropping the wooden support. If the wooden support fell down, then the trial was considered incorrect. An experimenter put the steel ball (and the wooden support in the case of error) back in the correct position during the intertrial interval, which varied randomly from 6,500 to 8,500 ms. On the basis of a predetermined random sequence, the confederate made an error rate of about 15% of the total number of trials. The confederate was covertly signaled by the experimenter of when to make an error. Each session consisted of three blocks of 80 trials (40 execution trials and 40 observation trials) separated by a 3-min break. Participants underwent a practice session of 20 trials before the experimental session began. The experiment lasted approximately 90 minutes.

Data analysis

Given the nature of the experimental manipulation, kinematic data were recorded and analyzed only for the "real" participant. Posterror adjustments were computed using the robust method ($\mathrm{PEA}_{\mathrm{robust}}$) proposed by Dutilh et al., (2012). This method compares the participants' performance on trials following (E + 1) and immediately preceding (E − 1) a confederate's error. For comparison purpose, in a similar manner to $\mathrm{PEA}_{\mathrm{robust}}$, we also computed postcorrect adjustments ($\mathrm{PCA}_{\mathrm{robust}}$) considering triplets of correct trials. Posterror analyses were restricted to sequences of trials comprising E − 1 and E + 1 correctly performed trials. Data were analyzed by means of linear mixed-effects (LME) models (for RTs and the maximum height of the wrist trajectory) and generalized mixed-effects (GLME) models with a binomial link function (for error rates; Pinheiro & Bates, 2000). Statistical analysis was performed using the computing environment R (R Core Team, 2012), and the packages lme4 (Bates, Maechler, Bolker, & Walker, 2015) and lmerTest (Kuznetsova, Brockhoff, & Christensen, 2013). For the LME and GLME models used in this study, random effects consisted of Participants and Blocks. The random structure was selected by means of AIC (Akaike's information criterion) weights (Wagenmakers & Farrell, 2004). Models were fitted using maximum likelihood (ML), and *p* values were estimated by likelihood ratio tests of the full model against the null model. For LME and contrasts analyses, we reported Cohen's *d* indices as measure of effect sizes (Cohen, 1988), whereas for GLME analysis we reported the odds ratio statistic (OR; see Szumilas, 2010). All statistical tests were performed by refitting the model after removing outliers with absolute standardized residuals exceeding 2.5 standard deviations (less than ~3.8%). We discarded 25 of the total of 1.680 trials because of technical problems. Visual inspection of residual did not show any obvious deviation from normality and homoscedasticity. To evaluate the relative evidence for the alternative hypothesis (H1) compared with the null hypothesis (H0), we performed statistical comparisons using the Bayesian approach implemented in the BayesFactor package for R (Morey, Rouder, & Jamil, 2014). The default Cauchy distribution centered on zero with rate [r] = 0.707 was used. The conventional cutoff for the interpretation of Bayes factors (Jeffreys, 1961) suggests that a BF greater than three represent a sufficient support for the alternative hypothesis.

Results

Posterror adjustments after observing an error

Accuracy A GLME analysis, with random intercept for Participants and Blocks, revealed that participant's error rate did not significantly change after observing an error (15.7%) compared with after observing a correct trial (12.5%), $z = 1.604$, $p = .109$, $OR = 1.32$.

Reaction times The mean postcorrect and posterror RT adjustments are shown in Fig. 2a. An LME analysis, with random intercept for Participants and Blocks (modeling intercepts only), revealed a significant difference between postcorrect ($\mathrm{PCA}_{\mathrm{robust}}$ = −9.94 ms ± 5.62) and post-error ($\mathrm{PEA}_{\mathrm{robust}}$ = 36.85 ms ± 13.85) adjustments, $\chi^2 = 10.56$, $p = .001$, BF = 14.8, $d = 0.29$. Contrast analysis showed that $\mathrm{PEA}_{\mathrm{robust}}$ was significantly different from zero, t(954.80) = 2.79, $p = .005$, BF = 3.80, $d = 0.21$.

Maximum height of the trajectory The mean of postcorrect and posterror adjustments of the maximum height of trajectory are shown in Fig. 2b An LME analysis, with random intercept for Participants and Blocks (modeling intercepts only), revealed a significance difference between postcorrect ($\mathrm{PCA}_{\mathrm{robust}}$ = −0.64 mm ± 0.27) and posterror adjustments ($\mathrm{PEA}_{\mathrm{robust}}$ = 2.01 mm ± 0.61), $\chi^{2}_{\_} = 14.503$, $p < .001$, BF = 97.87, $d = 0.33$. Contrast analysis showed that $\mathrm{PEA}_{\mathrm{robust}}$ was

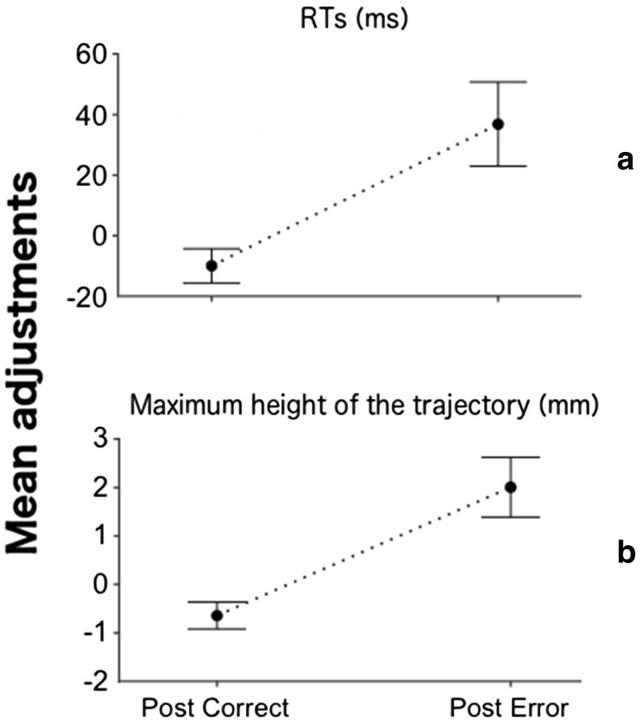

Fig. 2 Mean postcorrect and posterror adjustments in RTs (**a**) and the maximum height of the trajectory (**b**). For RTs, positive values indicate a posterror slowing. For the maximum height of the trajectory, positive values indicate a posterror increase of the amplitude of maximum height reached by the wrist. Vertical bars indicate standard error of the mean

significantly different from zero, t(982) = 3.16, p = .001, BF = 10.34, d = 0.26.

Posterror adjustments after own errors

Accuracy The overall error percentage was 20.3%. A GLME analysis, with random intercept for Participants and Blocks, revealed that participant's error rate did not significantly change after an error (24.2%) compared with a correct trial (19.3%), $z = 0.583$, $p = .560$, $OR = 1.09$.

Reaction times The mean postcorrect and posterror RT adjustments are shown in Fig. 3a. An LME analysis, with random intercept for Participants and Blocks (modeling intercepts only), did not show any significant difference between postcorrect ($\mathrm{PCA}_{\mathrm{robust}} = -5.69 \pm 5.59$) and posterror ($\mathrm{PEA}_{\mathrm{robust}} = 5.78 \pm 10.85$) adjustments, $\chi^2 = 0.79$, $p = .373$, BF = 0.14, d = 0.07.

Maximum height of the trajectory The mean of postcorrect and posterror adjustments of the maximum height of trajectory are shown in Fig. 3b. An LME analysis, with random intercept for Participants and Blocks (modeling intercepts only), did not revealed any significance difference between postcorrect ($\mathrm{PCA}_{\mathrm{robust}} = 0.16 \pm 0.30$) and posterror adjustments ($\mathrm{PEA}_{\mathrm{robust}} = -0.05 \pm 0.68$), $\chi^2 = 0.09$, $p = .759$, BF = 0.09, d = 0.02.

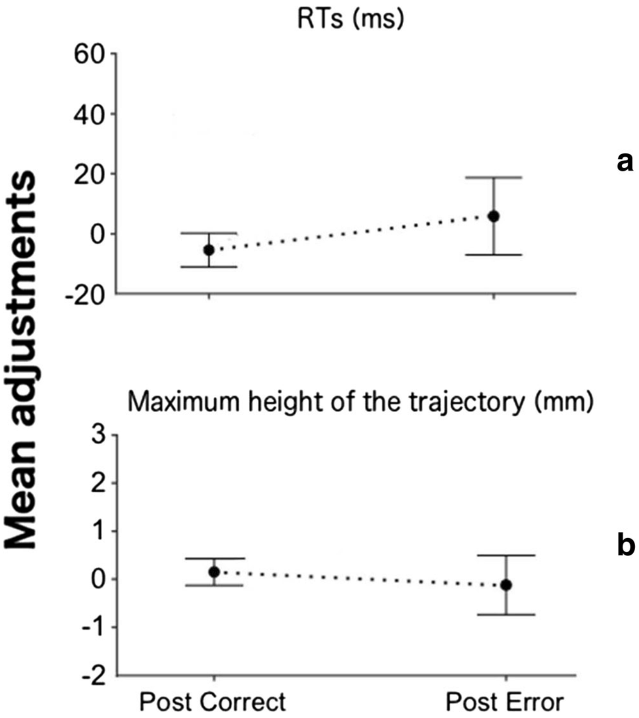

Fig. 3 Mean postcorrect and posterror adjustments in RTs (**a**) and the maximum height of the trajectory (**b**). For RTs, positive values indicate a posterror slowing. For the maximum height of the trajectory, positive values indicate a posterror increase of the amplitude of maximum height reached by the wrist. Vertical bars represent standard error of the mean

Discussion

The goal of the present study was twofold. To investigate whether the oPES is present when a more realistic, ecologically valid task is employed, and whether error observation affects motor execution.

In line with the previous literature, RTs analysis showed that error observation led to a slowdown during the motor preparation phase (Núñez Castellar et al., 2011; Schuch & Tipper, 2007). This finding demonstrates that the oPES is strong empirical evidence, which can also be observed using more realistic and ecologically valid tasks. Interestingly, no evidence of posterror improvement of accuracy (PIA) was found in this study. This result argues against the strict association between oPES and posterror accuracy and supports the hypothesis that the oPES and PIA are dissociated and sensitive to different aspects of the task (Núñez Castellar et al., 2011). With regard to this issue, Núñez Castellar et al., (2011) pointed out that the oPES is modulated by social context (cooperation vs. competition), while posterror accuracy is sensitive to the nature of the agent involved in the interaction (human vs. computer). The relation between PES and PIA has been a topic discussed at length, even in the context of individual task performance, and several studies demonstrated that the PES and PIA do not always occur together and might represent different processes (for a review, see Danielmeier, & Ullsperger, 2011).

It is worth noting that accuracy does not tell us anything about the strategy implemented after an error. Rather, it tells us whether this strategy has been successful or not. A potential solution to this issue is the use of kinematical analysis. By investigating how errors influence kinematics parameters, it is possible to investigate the strategy adopted after an error. Crucially, the results of the present study demonstrated that the observation of another person's error does not only influence the observer's overt behavior in terms of RTs but also affects the unfolding of the movement. In particular, we found a posterror increase in wrist elevation, which may be interpreted as a compensatory strategy aimed at grasping the target with a larger safety margin (Smeets & Brenner, 1999). Indeed, an increase in hand elevation ensured that the index finger and thumb did not collide with the target or support during movement execution. Moreover, increasing the height of wrist elevation may serve to improve the quality of visual information by means of which contact points are established. In fact, it should be noted that in the present study, the target was positioned along the midsagittal plane of the participants, and thus the vision of the target was partially covered by fingers during the gripping phase. An increase in wrist elevation may improve visibility of the target during the honing phase, which would allow adjustment of contact points and possibly the applied forces, with the aim to avoid knocking over the support. The motor control system relies on visual and proprioceptive feedback loops, and thus the more information these loops can process, the greater the influence control will exert (Glover, 2004). In this connection, several studies have investigated the effect of object properties and context on the planning of digit placement upon the target (e.g., Lukos, Ansuini, & Santello, 2007). For instance, to prevent object tilt when an object's center of mass is shifted to the right (resulting in a clockwise tilt if uncompensated), subjects adjust the movement by placing the thumb lower than the index finger (Lukos et al., 2007). In this example, digit placement is modulated to ensure successful completion of the task. Our finding of a posterror increase in wrist elevation might signify that the observation of an error elicits strategic adjustments related to finger positioning. Thus, kinematic signatures are capable of automatically influencing an onlooker's action system by allowing motor functional strategies to be transferred.

After making an error, participants did not show any evidence of posterror adjustments on the following execution trial. Recent investigations indicate that PES tends to decay over time (Danielmeier & Ullsperger, 2011; Jentzsch & Dudschig, 2009). In particular, short intertrial intervals (it is; <500 ms) are usually associated with a larger PES, whereas long ITIs (>8,000 ms; Williams, Heathcote, Nesbitt, & Eidels, 2016) tend to elicit a decrease of PES. In our experiment, participants were asked to observe the confederate undertaking the task before they again executed the movement. In these circumstances, the PES might not have survived because of the long interval between execution trials (~16 s). These results are consistent with the previous literature of oPES, suggesting that the aftereffects of the participant's performance tend to weaken when the task requires that the execution of the action is alternated with the observation of another person's action (e.g., Winkel et al., 2009).

Although our understanding of how the human motor system reacts following action observation (for a review, see Heyes, 2011) has often been limited to "successful" actions, we have shown here that this system also considers the outcome of such actions. If the observed action is marred by an error, then onlookers internalize the observed "error" as to put in place error avoidance strategies when the observed action is subsequently performed. In this view, the activated motor representation does not merely reflect an automatic resonance mechanism of motor structures paralleling observed movements. If this were the case, then error observation would inevitably determine an error during execution. Rather, it might reflect the interplay between an initial emulative process, which allows the observer to experience what is being observed, and a subsequent one, which considers the consequences/outcome of the initially observed actions.

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Supplementary material

All relevant data and R scripts are available at https://osf.io/amxfy/.