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Impact of decision and action outcomes on subsequent decision and action behaviours in humans

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Abstract

Speed–accuracy trade-off adjustments in decision-making have been mainly studied separately from those in motor control. In the wild, however, animals coordinate their decision and action, often deciding while acting. Recent behavioural studies support this view, indicating that animals, including humans, trade decision time for movement time to maximize their global rate of reward during experimental sessions. Besides, it is well established that choice outcomes impact subsequent decisions. Crucially though, whether and how a decision outcome also influences the subsequent motor performance, and whether and how the outcome of a movement influences the next decision, is unclear. Here, we address these questions by analysing trial-to-trial changes of choice and motor behaviours in healthy human participants instructed to perform successive perceptual decisions expressed with reaching movements whose duration was either weakly or strongly constrained in separate tasks. Results indicate that after a wrong decision, subjects who were weakly constrained in their action duration decided more slowly and more accurately. Interestingly, they also shortened their subsequent movement duration by moving faster. Conversely, we found that errors of constrained movements influenced not only the speed and the amplitude of the following movement but those of the decision too. If the movement had to be slowed down, the decision that precedes that movement was accelerated and vice versa. Together, these results indicate that from one trial to the next, humans seek to determine a behavioural duration as a whole instead of optimizing each of the decision and action speed–accuracy trade-offs independently of each other.

KEYWORDS
arm movement, decision-making, motor control, post-outcome adjustment, reward rate

Abbreviations: Amp, amplitude; DD, decision duration; DR, delayed-reaching; MD, movement duration; PES, post-error slowing; PV, peak velocity; SAT, speed–accuracy trade-off; *SD*, standard deviation; SP, success probability.

David Thura and Amélie J. Reynaud contributed equally to this work.

1 | INTRODUCTION

Choosing one action among several options and executing that action are usually considered as two distinct functions, most often studied separately from each other (e.g., Franklin & Wolpert, 2011; Ratcliff et al., 2016). However, recent behavioural studies indicate that decision and action show a high level of integration during goal-oriented behaviour (Choi et al., 2014; Cos et al., 2011; Hagura et al., 2017; Haith et al., 2012; Morel et al., 2017; Pierrieau et al., 2021; Reynaud et al., 2020; Saleri Lunazzi et al., 2021; Servant et al., 2021; Shadmehr & Ahmed, 2020; Shadmehr et al., 2010, 2019; Spieser et al., 2017; Thura, 2020; Yoon et al., 2018). For example, human subjects decide faster and less accurately to focus on their actions when the motor context in which a choice is made is demanding (Reynaud et al., 2020). Similarly, when the temporal cost of a movement is significantly larger than usual, humans often reduce the duration of their decisions to limit the impact of these time-consuming movements (Saleri Lunazzi et al., 2021). Conversely, if the sensory evidence guiding the choice is weak and the deliberation takes time, humans and monkeys shorten the duration of the movement expressing that choice (Herz et al., 2022; Thura, 2020; Thura et al., 2014). When faced with multiple successive choices, individuals thus seem to be primarily concerned about determining a global behaviour duration rather than optimizing decision and action durations separately, even if the resulting decision or movement accuracy must slightly suffer. This 'holistic–heuristic' policy may serve what matters the most for decision-makers engaged in such a scenario, the rate of reward (Balci et al., 2011; Carland et al., 2019; Thura, 2021).

Importantly, most of the adjustments mentioned above occur between blocks of tens to hundreds of trials, depending on stable contexts encouraging a fixed speed–accuracy trade-off (SAT). But can these adjustments also occur on shorter timescales, from trial to trial, depending on local decisional and motor performance?

Performance history is known to exert a large influence on subsequent behaviour (e.g., Danielmeier & Ullsperger, 2011; Jentzsch & Dudschig, 2009; Urai et al., 2019). The most well-known post-outcome adjustment is a reduction of behaviour speed after committing an error, namely, post-error slowing (PES) (Dutilh et al., 2012; Rabbitt & Rodgers, 1977). PES is sometimes accompanied by changes in accuracy, although conditions leading to PES-related increase or decrease of accuracy are still unclear (Danielmeier & Ullsperger, 2011; Fievez et al., 2022). Notably, post-outcome adjustments have been mostly described as the effect of a choice on the decisional performance in the following trial (Dutilh et al., 2012; Laming, 1979; Rabbitt & Rodgers, 1977; Thura et al., 2017; Urai et al., 2019), but the influence of a movement outcome on the motor performance in the following trial did not receive the same attention (Ceccarini & Castiello, 2018). Moreover, the consequences of either a decision or a motor outcome on *both* subsequent decision and movement have never been investigated. These are important questions to address in order to further evaluate the level of integration of the decision and the action functions during goal-directed behaviour.

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In the present report, we first test the general hypothesis that coordinated decision and movement adjustments occur from trial to trial, depending on the local decisional and motor performance of the decision-maker. We predict that any adjustment due to a decision or a motor outcome will be integrated and shared across the decision and the movement made in the next trial. That is, a decision error will affect *both* the decision and the movement in the following trial, and, conversely, a movement error will impact *both* the movement and the decision in the next trial. To test this hypothesis, we first analysed a dataset from one recent study of our group (Experiment 1) during which human subjects made successive perceptual decisions between reaching movements (Reynaud et al., 2020; Thura, 2020). In this experiment, participants were faced with changing sensory evidence favouring one of two possible targets and

could invest up to 3 s in the decision process. They then had up to 800 ms to execute the reaching movement expressing a choice.

Because our previous results strongly indicate that human subjects coordinate the duration of their decision and movement in order to optimize their rate of reward (Saleri Lunazzi et al., 2021), we also make the more specific hypothesis that the type of error that induces the largest adjustment of behaviour in the subsequent trial is an error of duration. This hypothesis predicts that post-error adjustments will mainly occur with errors of duration, if participants are 'free' to adjust their decision and/or movement durations (MDs) in the following trial. To test this hypothesis, we analysed a second experimental dataset from our group (Experiment 2) in which the decision component of the task was similar compared to Experiment 1, but in which the allowed duration of reaching movement was strictly constrained, resulting in numerous 'too long' (in duration) and 'too short' (in duration) movements made by the participants.

2 | EXPERIMENT 1: POST-OUTCOME ADJUSTMENTS OF DECISION AND MOTOR BEHAVIOURS DURING A PERCEPTUAL DECISION-MAKING TASK

2.1 | Material and methods

2.1.1 | Participants

Twenty subjects (ages: 20–41; 16 females and 4 males; 18 right-handed) performed this experiment. All gave their consent orally before starting the experiment. The ethics committee of Inserm (IRB00003888) approved the protocol on 19 March 2019. Each participant performed two experimental sessions and received monetary compensation (€20) for completing each session.

2.1.2 | Dataset

The decision and motor behaviours of these subjects have been described in two recent publications reporting the effects of the decisional context on movement properties (Thura, 2020) and the effects of the motor context on decision strategies (Reynaud et al., 2020). In these reports, subjects' behavioural adjustments are described either within a given trial (i.e., the relation between a decision duration [DD] and the duration of the movement produced to express that decision) or between specific conditions designed to set stable decision or motor speed–accuracy contexts in blocks of tens of trials. Here, we aim at describing adjustments of subjects' behaviour from trial to trial, depending on their decision and/or motor performance.

2.1.3 | Setup and tasks

The subjects sat in an armchair and made planar reaching movements using a handle held in their dominant hand (Figure 1a). A digitizing tablet (GTCO CalComp) continuously recorded the handle horizontal and vertical positions (100 Hz with .013-cm accuracy). Target stimuli and cursor feedback were projected by an LCD monitor onto a half-silvered mirror suspended 26 cm above and parallel to the digitizer plane, creating the illusion that targets floated on the plane of the tablet. Participants were faced with a visual display (Figure 1b) consisting of three blue circles (the decision circles) placed horizontally at a distance of 6 cm from each other. In the central blue circle, 15 tokens were randomly arranged. Positioned below, three black circles, organized horizontally too, defined the movement targets. Although the central black circle radius was kept constant at .75 cm, the size of the two lateral black circles and their distance from the central circle could vary, set to either .75 or 1.5 cm of radius and either 6 or 12 cm of distance from the central circle, in distinct blocks of trials (as mentioned above, effects of target size/position on subjects' behaviour are not included in the present report).

In the task (Figure 1b), implemented by means of LABVIEW 2018 (National Instruments), subjects initiated a trial by holding the handle into the black central circle (starting position) for 500 ms. Tokens then started to jump, one by one, every 200 ms, in one of the two possible lateral blue circles. Subjects had to decide which of the two lateral blue circles would receive the majority of the tokens at the end of the trial. They reported their decisions by moving the handle into the lateral movement target corresponding to the side of the chosen decision circle. Crucially, participants were allowed to make and report their choice at any time between the first and last token jumps. Once a target was reached, the remaining tokens jumped more quickly to their final circles (Figure 1c, grey line), implicitly encouraging subjects to decide before all tokens had jumped to save time and increase their rate of reward at the session level. In separate blocks of trials, tokens could speed up either a lot (a jump every 20 ms) or a little (a jump every 150 ms). The block-related effects are not included in the present report.

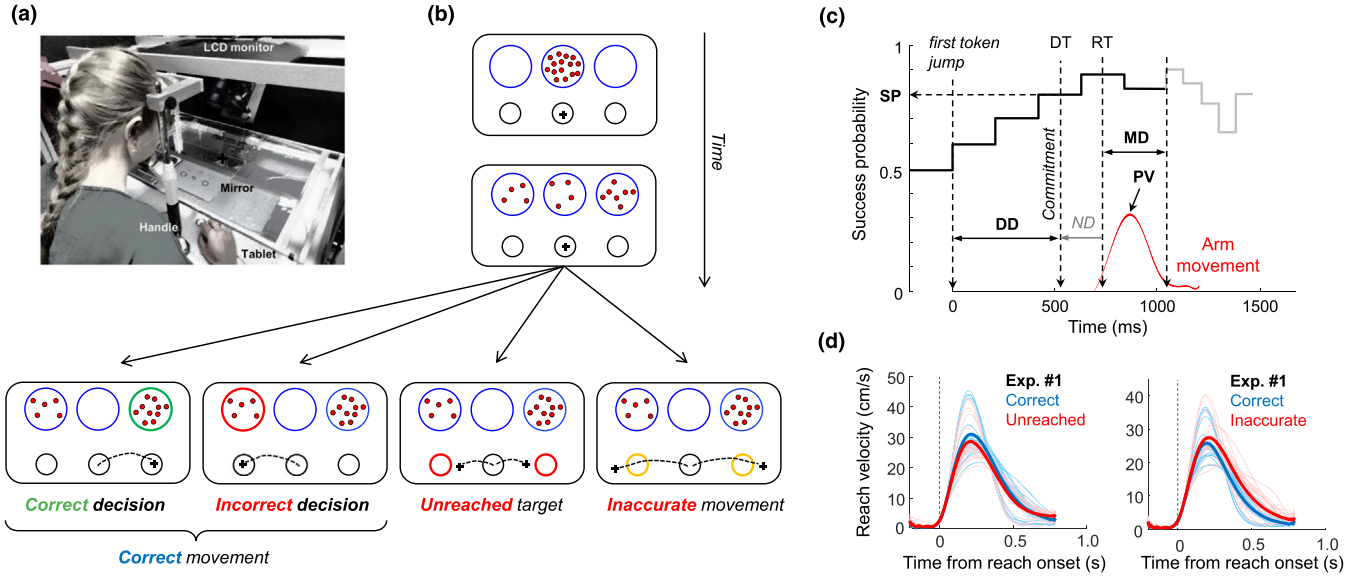

FIGURE 1 Methods. (a) Experimental apparatus (identical in Experiments 1 and 2). (b) Time course of a trial in the decision task of Experiment 1. Tokens jump one by one from the central decision circle to one of the two lateral ones. Subjects move a handle from a central movement target to one of the two lateral ones to express their choice. All the decision and action outcomes are illustrated in the bottom panels (please refer to the main text for details). (c) Temporal profile of success probability (SP) in one example trial of the decision task of Experiments 1 and 2. At the beginning of the trial, each target has the same SP (.5). When the first token jumps into one of the two potential targets (the most leftward vertical dotted line), the SP of that target increases to ∼.6. SP then evolves with each jump. Subjects execute a reaching movement (red trace) to report their choice. Kinematic data allow us to compute movement duration (MD) and movement peak velocity (PV). Non-decisional (ND) delays, determined in a separate reaction time task, allow us to estimate the decision duration (DD) and SP at decision time (DT). Only 10 out of 15 jumps are illustrated on this SP profile. (d) Participants' average reach velocity profiles in Experiment 1, aligned on reaching movement onset. Correct and 'unreached' movements are compared in the left panel; correct and 'inaccurate' movements are compared in the right panel. Data are restricted to trials performed in the long/small motor condition of Experiment 1 (please see the main text for details).

In this task, subjects had up to 800 ms to reach a target and report their choices. If no target was reached within 800 ms, trials were classified as 'unreached' trials, regardless of the direction of the movement with respect to the starting position. If the subject reached a target but failed to stop in it within 800 ms, the trial was classified as an 'inaccurate' trial, regardless of the choice made, correct or incorrect (Figure 1b, bottom panels).

At the end of each trial, a visual feedback about decision success or failure (the chosen decision circle turning either green or red, respectively) was provided to the subject after the last token jump, assuming a correct movement. A movement error was indicated by visual feedback, the chosen movement target turned orange in 'inaccurate' trials, and the two movement targets turned red in 'unreached' trials.

Finally, subjects also performed a simple delayed-reaching (DR) task in each of the two sessions. This DR task was identical to the choice task described above, except that there was only one lateral decision circle displayed at the beginning of the trial (either at the right or at the left side of the central circle with 50% probability). All tokens moved from the central circle to this unique circle at a GO signal occurring after a variable delay (1000 ± 150 ms). The DR task was used to estimate the sum of the delays attributable to response initiation (i.e., non-decision delays). The goal for each subject was to perform in each of the two sessions 100 correct DR task trials and 320 correct choice task trials, indirectly motivating them to optimize successes per unit of time.

2.1.4 | Subsets of trials based on decision and movement outcomes

For this experiment, we defined two subsets of trials based on decision outcomes: (1) 'correct decision' trials, when the subject chose the correct target and reported her or his choice with a correct movement, and (2) 'incorrect decision' trials, if the participant chose the incorrect target with a correct movement. Note that for these two subsets, wrong movement trials are excluded because no feedback was provided to the subject to indicate whether or not she or he chose the correct target. Instead, a salient

feedback was provided at the end of the trial to indicate the error of movement (see above and Figure 1b).

We defined three other subsets of trials based on movement outcomes: (1) 'correct movement' trials, when the subject adequately reached the correct or the incorrect target; (2) 'unreached' trials, when the subjects failed to reach a target (correct or incorrect) before the end of the MD deadline (800 ms); and (3) 'inaccurate' trials, when the subjects reached a target (correct or incorrect) but failed to stop in it. As expected, most movement errors (69% ± 9% at the population level, including both unreached and inaccurate movement trials) occurred in the most difficult motor condition of the task, that is, when targets were small and distant from the starting circle. Only trials collected in this motor condition were therefore included in the analyses of the effect of movement errors on participants' subsequent behaviour.

2.1.5 | Data analysis

Data were analysed offline using custom-written MATLAB (MathWorks) and R (https://www.r-project.org/) scripts. Reaching horizontal and vertical positions were first filtered using polynomial filters and then differentiated to obtain a velocity profile. Onset and offset of movements were then determined using a 3.75-cm/s velocity threshold. Reaching MD, peak velocity (PV) and amplitude (Amp) were respectively defined as the duration, the maximum velocity value and the Euclidean distance between movement onset and offset (Figure 1c).

Decision duration (DD) was computed as the duration between the first token jump and the time at which subjects committed to their choice (Figure 1c). To estimate this commitment time in each trial, we detected the time of movement onset as mentioned above, defining the subject's reaction time in that trial, and subtracted from it her or his mean sensorimotor delays estimated based on her or his reaction times in the DR task performed the same day and in the same condition.

To assess the influence of sensory evidence on subjects' choices, we computed the success probability (SP) profile of each trial experienced by participants with respect to the chosen target, as well as their decision SP at the time of commitment time (Figure 1c), using Equation (1). For instance, for a total of 15 tokens, if at a particular moment in time the target chosen by the subject contains N_{chosen} tokens, whereas the other target contains N_{other} tokens, and there are N_C tokens remaining in the centre, then the probability that the chosen target will ultimately be the correct one, that is, the subject's SP at a particular time is as follows:

$$p(\text{Chosen}|N_{chosen},N_{other},N_C)=\frac{N_C!}{2^{N_C}}\sum_{k=0}^{\min(N_C,7-N_{other})}\frac{1}{k!(N_C-k)!} \quad (1)$$

To ensure that the difficulty of decisions was homogeneous among subjects and between the experimental conditions, we controlled the sequence of trials experienced by each participant. Especially, we interspersed among fully random trials (~20% of the trials in which each token is 50% likely to jump into the right or the left lateral circle) three special types of trials, easy, ambiguous and misleading, characterized by particular temporal profiles of SP. Subjects were not told about the existence of these trials (please refer to Reynaud et al., 2020, for a detailed description of these trial types and their proportions in the task).

To assess the impact of the outcome of each trial i on the decision and motor behaviour of trial $i+1$, we calculated the difference of movement PV (ΔPV), duration (ΔMD) and amplitude (ΔAmp) and the difference of DD (ΔDD) and SP (ΔSP) between them (e.g., $\Delta PV = PV_{i+1} - PV_i$). We then calculated for each subject the average of each variable with respect to trial i outcome.

2.1.6 | Statistics

To determine whether the behavioural adjustment from one trial to the next (ΔPV, ΔMD, ΔAmp, ΔDD and ΔSP) differs significantly from 0 in the different outcome conditions at the population level, we used one-sample Wilcoxon signed-rank tests. In addition, we calculated the effect size for each post-outcome adjustment by dividing the Z value of the Wilcoxon signed-rank tests by the square root of the sample size. Paired Wilcoxon signed-rank tests were used to compare the movement parameters (MD, PV and Amp) between correct and erroneous movement trials. Levene's tests were used to assess whether the distributions of the post-correct and post-error behavioural variables have different variances. To test the difference between the average SP profiles of two trial subsets (e.g., correct decision trials vs. post-correct decision trials), we performed chi-squared tests, with the distance between the two profiles (1 and 2) from token jump (j) #1 to #15 computed as the following chi-squared metric:

$$\chi^2=\sum_{j=1}^{15}\frac{\left(y_{1,j}-y_{2,j}\right)^2}{\sigma_j^2} \quad (2)$$

where y_1 and y_2 are the two SP profiles averaged across subjects and σ_j^2 is the mean squared variance of the SP profiles, such as $\sigma_j^2 = \frac{1}{2}\left(\sigma_{1,j}^2 + \sigma_{2,j}^2\right)$. For all statistical tests, the significance level is set to .05. Unless stated otherwise, data are reported as medians (±standard deviations [*SD*s]) across the population.

2.2 | Results

2.2.1 | Effect of a decision outcome on the next decision and on the next movement

We first describe the impact of the decision outcome (correct or incorrect choice) on participants' subsequent decisional behaviour. As shown in Figure 2a, ΔDDs were significantly higher than zero at the population level following an incorrect choice (median $\Delta DD \pm SD = +71 \pm 93$ ms, one-sample Wilcoxon rank-sum test: $Z = -2.4$, $p < .05$), meaning that subjects' DDs were significantly increased following an incorrect choice. This slowdown of decision-making was observed despite that trials following an incorrect choice were easier than these incorrect trials, as can be seen on the averaged SP profiles of the two trial subsets (chi-squared test: $\chi^2(14) = 3054.6$, $p < .05$, Figure 2a, top right panel; Figure S1A illustrates the SP profiles of the same trials computed with respect to the correct target). As a consequence, when subjects' SPs at decision time are compared between incorrect decision and post-incorrect decision trials, SPs are increased following incorrect decisions ($\Delta SP = +.09 \pm .03$, $Z = -4.8$, $p < .001$; Figure 2a, middle panel). By contrast, no significant difference of DD (median $\Delta DD = -2 \pm 21$ ms, $Z = -.75$, $p = .45$) was observed following a correct decision. Together, this first analysis demonstrates that subjects used a PES strategy to decide in this task. Interestingly, subjects did not adjust their DD following a correct trial despite that these trials were on average more difficult ($\chi^2(14) = 325.3$, $p < .05$; Figure 2a, bottom right panel). Participants' SP thus slightly decreased after a correct choice ($\Delta SP = -.02 \pm .01$, $Z = -4.76$, $p < .001$; Figure 2a, middle panel), indicating that they committed to a decision with less sensory evidence after a correct trial.

We next investigate whether or not a decision outcome also impacts motor behaviour. We found that

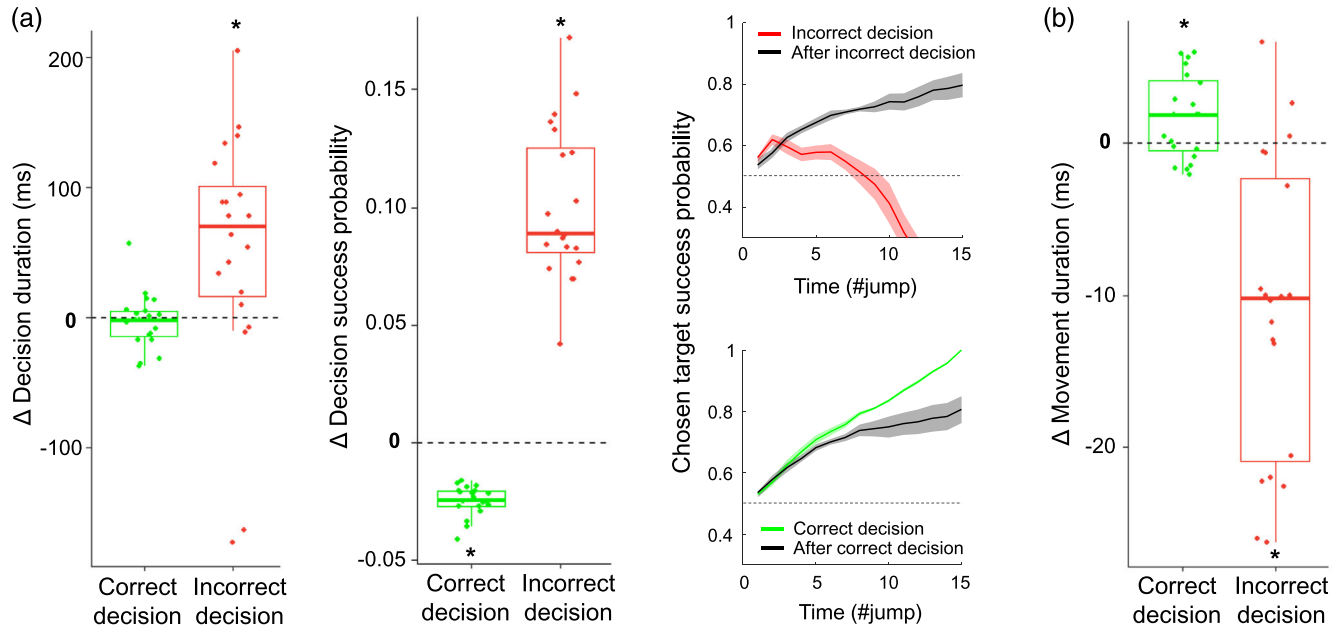

FIGURE 2 Effect of a decision outcome on the next decision and on the next movement in Experiment 1. (a) *Left and middle panels*: Δ decision duration (left) and Δ success probability (middle) after a correct decision (green) and after an incorrect decision (red). In the box plot, dots represent the mean Δ for each participant, the horizontal bold line within the box marks the population median, boundaries of the box indicate the 25th and 75th percentiles of population distribution, and whiskers above and below the box indicate the maximum and the minimum of the distribution, excluding the outliers. If Δ is positive, there is a post-outcome increase for a given metric X ($X_{i+1} - X_i > 0$), whereas a negative Δ value indicates a decrease of this metric. *Right panel, top*: Comparison of the average ± *SD* success probability profiles between trials whose decision was incorrect (red line) and trials following an incorrect choice (black line), computed across subjects with respect to the target they chose. *Right panel, bottom*: Same comparison between correct decision trials (green line) and trials following a correct decision (black line). (b) Same analysis as in (a), left panel, for the post-decision outcome adjustments computed for movement duration. *p value < .05.

subjects reduced their MD ($\Delta MD = -10 \pm 10$ ms, $Z = -3.9$, $p < .001$; Figure 2b) following incorrect decisions by increasing their movement peak of velocity and reducing their amplitude ($\Delta PV = +.25 \pm .52$ cm/s, $Z = -2.5$, $p < .01$; $\Delta Amp = -.09 \pm .08$ cm, $Z = -3.3$, $p < .001$; Table 1 and Figure S1B). By contrast, their MD was slightly increased ($\Delta MD = +2 \pm 3$ ms, $Z = -2.3$, $p < .05$; Table 1 and Figure S1B) and their peak of velocity and movement amplitude were decreased ($\Delta PV = -.22 \pm .22$ cm/s, $Z = -4.1$, $p < .001$; $\Delta Amp = -.03 \pm .05$ cm, $Z = -2.5$, $p < .01$; Table 1 and Figure S1B) after a correct decision.

2.2.2 | Effect of a movement outcome on the next decision and on the next movement

In trials following a correct movement, subjects increased their movement amplitude ($\Delta Amp = +2.46 \pm .08$ cm, $Z = -4.76$, $p < .001$) and reduced their speed ($\Delta PV = -.39 \pm .29$ cm/s, $Z = -4.35$, $p < .001$), leading to an absence of MD adjustment ($\Delta MD = -2 \pm 6$ ms, $Z = -.71$, $p = .47$; Figure 3a). We observed that following a correct movement, DDs and SPs did not significantly vary as well ($\Delta DD = +2 \pm 14$ ms, $Z = -.97$, $p = .33$; $\Delta SP = 0 \pm .01$, $Z = -.6$, $p = .55$; Table 1 and Figure 3b, left and middle panels).

In Experiment 1, inaccurate movements were on average longer (692.5 ± 95.1 vs. 676 ± 94.4 ms, two-sample Wilcoxon rank-sum test: $Z = -3.5$, $p < .001$), larger in amplitude (12.8 ± .2 vs. 11.8 ± .1 cm, $Z = -4.8$, $p < .001$) and faster (30.7 ± 6.6 vs. 29.4 ± 5.6 cm/s, $Z = -2.5$, $p = .001$) compared to correct movements (Figure 1d, right panel). Subjects adjusted their inaccurate movements in the following trial by reducing their reaching velocity peak ($\Delta PV = -.67 \pm 2.28$ cm/s, $Z = -2.1$, $p < .05$; Table 1 and Figure S1B) and amplitude ($\Delta Amp = -1.2 \pm .3$ cm, $Z = -4.8$, $p < .001$; Table 1 and Figure S1B), leading to a reduction of MD ($\Delta MD = -43 \pm 50$ ms, $Z = -2.6$, $p < .01$; Table 1 and Figure 3a).

Conversely, movements in unreached trials were on average shorter in duration (652 ± 104.3 vs. 676 ± 94.4 ms, $Z = -3.6$, $p < .001$), shorter in amplitude (10.8 ± .5 vs. 11.8 ± .1 cm, $Z = -4.8$, $p < .001$) and slower (27.4 ± 5.1 vs. 29.4 ± 5.6 cm/s, $Z = -4.3$, $p < .001$) compared to correct movements (Figure 1d, left panel). Subjects corrected these unreached movements in the following trial by increasing their reaching velocity peak ($\Delta PV = +2.46 \pm 2.43$ cm/s, $Z = -4.8$, $p < .001$; Table 1 and Figure S1B) and amplitude ($\Delta Amp = +1.0 \pm .5$ cm, $Z = -4.8$, $p < .001$; Table 1 and Figure S1B), leading to slightly longer movements ($\Delta MD = +16$

TABLE 1 Post-outcome adjustments of decision and motor behaviours in Experiment 1.

Experiment 1	Mean number of trials per subject (min–max)	Decision behaviour						Motor behaviour									
		ΔDD (ms)			ΔSP			ΔMD (ms)			ΔPV (cm/s)			ΔAmp (cm)		
		Median	*p* value	Effect size	Median	*p* value	Effect size	Median	*p* value	Effect size	Median	*p* value	Effect size	Median	*p* value	Effect size
After correct decision	618.2 (605–624)	−2	.45	/	−.02	<.001	−.88	2	<.05	.52	−.22	<.001	−.81	−.03	<.01	.56
After incorrect decision	153.5 (93–267)	71	<.05	.53	.09	<.001	.88	−10	<.001	−.78	.25	<.01	.54	−.09	<.001	−.70
After correct movement	193.4 (173–226)	2	.33	/	.00	.55	/	−2	.47	/	−.39	<.001	−.84	2.46	<.001	.88
After inaccurate movement	8.35 (2–14)	−59	.19	/	.03	<.05	/	−43	<.01	−.59	−.67	<.05	−.46	−1.20	<.001	−.88
After unreached movement	35.7 (7–72)	13	.38	/	.00	.8	/	16	<.05	.47	2.46	<.001	.88	1.00	<.001	.88

Note: The *p* values refer to the one-sample Wilcoxon signed-rank tests.

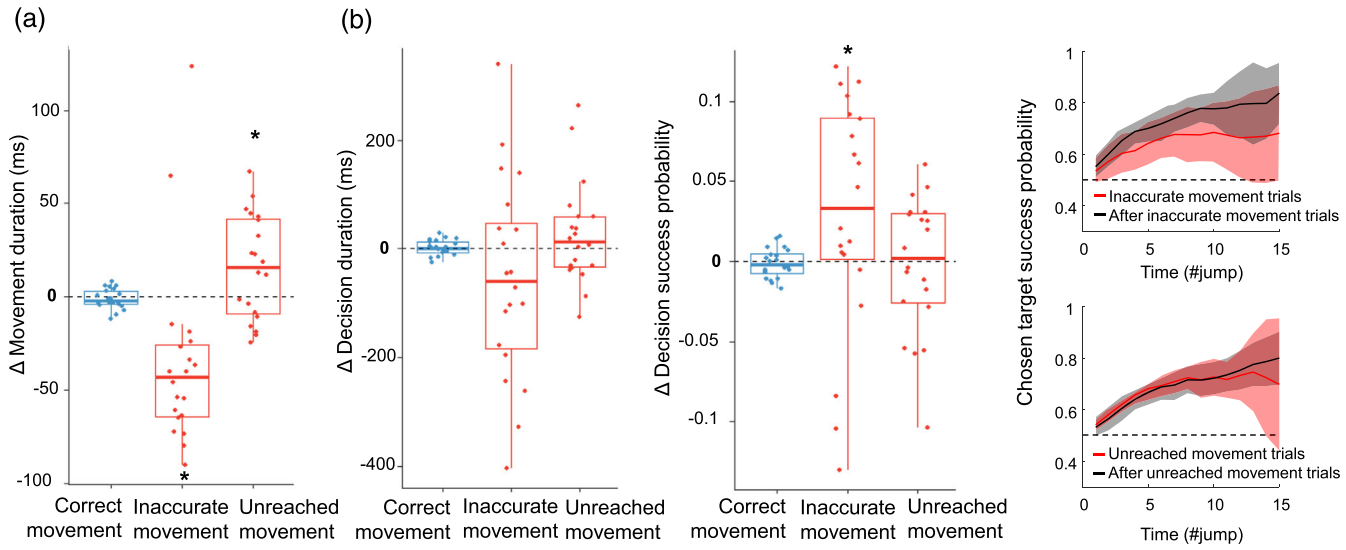

FIGURE 3 Effect of a movement outcome on the next movement and on the next decision in Experiment 1. (a) Δ movement duration after a correct movement (blue) and after an inaccurate or unreached movement (red). Same convention as in Figure 2. (b) *Left and middle panels*: Same analysis as in (a) for the post-motor outcome adjustments computed for decision duration (left) and success probability (middle). *Right panel, top*: Comparison of the average ± *SD* success probability profiles between trials whose movement was inaccurate (red) and trials following an inaccurate movement (black), computed across subjects with respect to the target they chose. *Right panel, bottom*: Comparison of the average ± *SD* success probability profiles between unreached movement trials (red) and trials following an unreached movement (black), computed across subjects with respect to the target they chose. *p value < .05.

± 28 ms, $Z = -2.1$, $p < .05$; Table 1 and Figure 3a) compared to the previous erroneous trials.

These two opposed adjustments of movement parameters following incorrect movements were not accompanied by a significant adjustment of DD (inaccurate: $\Delta DD = -59 \pm 185$ ms, $Z = -1.3$, $p = .19$; unreached: $\Delta DD = +13 \pm 94$ ms, $Z = -.7$, $p = .38$; Table 1 and Figure 3b). We however noticed that the subjects' mean DDs were more variable in trials following an inaccurate or unreached movement compared to trials following a correct movement (*SD*: 184.9 ms for inaccurate, 93.8 ms for unreached and 13.9 ms for correct movements, Levene's test, $F(2) = 16.2$, $p < .0001$).

2.3 | Discussion

This first experiment highlights the well-known post-error slowing (PES) effect, characterized by an increase of DD following an erroneous choice (Danielmeier & Ullsperger, 2011; Jentzsch & Dudschig, 2009; Laming, 1979; Purcell & Kiani, 2016; Rabbitt & Rodgers, 1977; Thura et al., 2017). Interestingly, we show that after a slower choice made in response to a decision error, MD is reduced, indicating that the adjustment due to a decision error impacts both the decision and the movement made in the next trial.

By contrast, the analysis of behavioural adjustments following erroneous movements did not reveal a shared adjustment of decision and movement, only movements being significantly modulated following a wrong movement executed in the previous trial. This absence of effect possibly indicates a specificity of the motor system compared to the decision system. Another possibility however is that movement errors in Experiment 1 do not permit to reveal this effect. First, the number of movement errors was generally low within each subject (Table 1). As a result, the variability in DDs following movement errors was higher than for the correct trials, likely reducing the ability to accurately estimate the influence of these errors on the decision adjustment in the next trial. Moreover, our previous results strongly indicate that human subjects coordinate the duration of their decision and movement in order to optimize their rate of reward (Saleri Lunazzi et al., 2021), leading to the possibility that post-error adjustments mainly occur with errors of duration. Yet movement errors in Experiment 1 were heterogeneous, possibly hiding modulations because of averaging effects. In particular, most of the 'unreached' trials were trials in which subjects failed to reach the target within 800 ms because of too slow movements. These erroneous movements were corrected with faster and shorter ones in the following trial. But there could also be unreached trials in which subjects failed to hit the target after a fast and short movement landing above or below the circle.

In order to more precisely and more specifically assess the impact of MD errors on subjects' subsequent behaviour, we analysed a second dataset from our group (Experiment 2) in which the decision component of the task was similar to the one used in Experiment 1, but in which the allowed duration of reaching movement was strictly constrained, leading to more numerous and more consistent too long (in duration) and too short (in duration) movements.

3 | EXPERIMENT 2: POST-OUTCOME ADJUSTMENTS OF DECISION AND MOTOR BEHAVIOURS DURING PERCEPTUAL DECISION-MAKING TASK WITH CONSTRAINED MOVEMENT DURATION

3.1 | Material and methods

3.1.1 | Participants

Thirty-one subjects (ages: 18–36; 20 females and 11 males; 29 right-handed) performed this experiment. All gave their consent before starting the experiment. The ethics committee of Inserm (IRB00003888) approved the protocol on 19 March 2019. Each participant performed two experimental sessions and received monetary compensation (€15) for completing each session.

3.1.2 | Dataset

The decision and motor behaviours of these subjects have been described in a recent publication reporting the effects of the motor context on decision strategies (Saleri Lunazzi et al., 2021). In this report, subjects' behavioural adjustments are described either within a given trial (i.e., the relation between a DD and the duration of the movement produced to express that decision) or between specific conditions designed to set stable motor speed–accuracy contexts in blocks of tens of trials. Here, we aim at describing adjustments of subjects' behaviour from trial to trial, depending on their decision and/or motor performance.

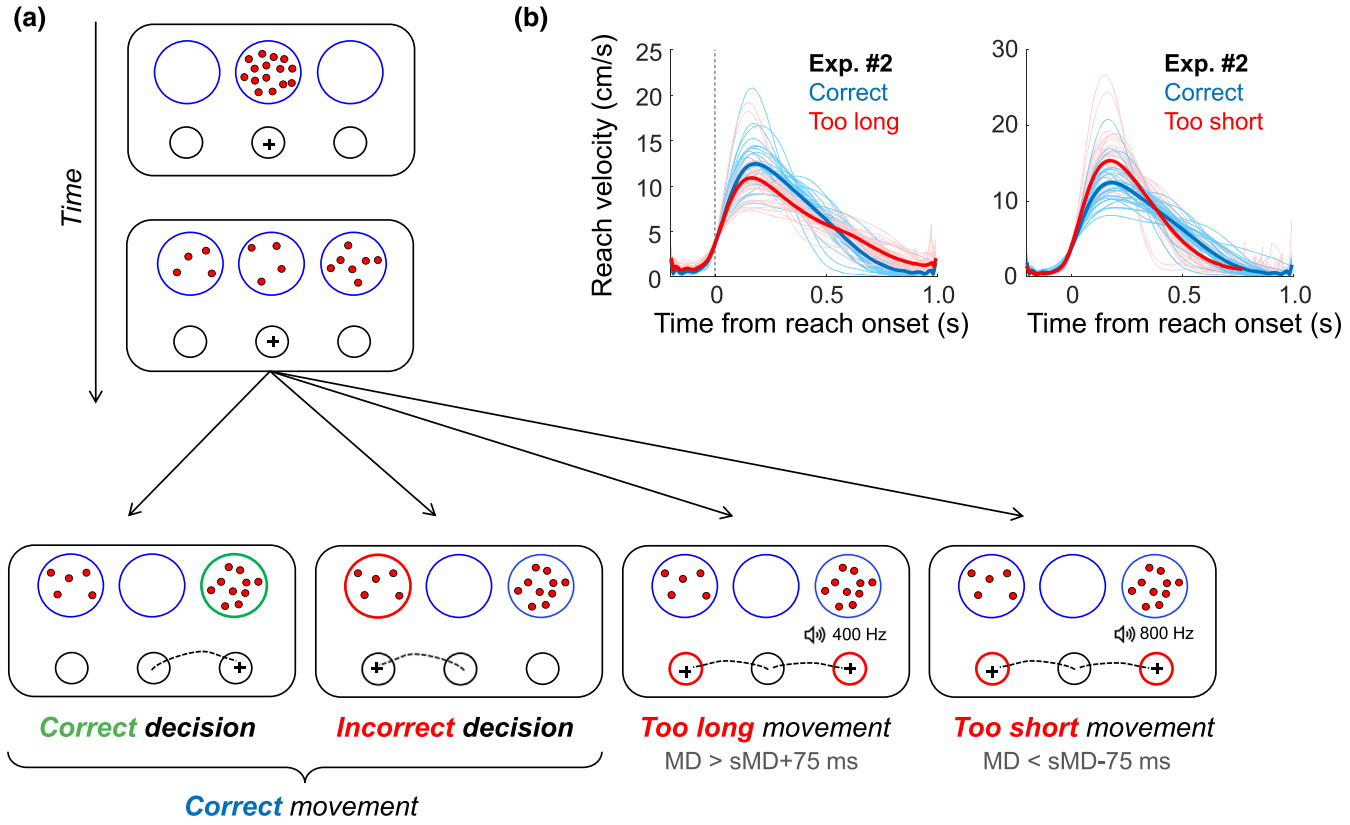

FIGURE 4 (a) Time course of a trial in the decision task of Experiment 2. Tokens jump one by one from the central decision circle to one of the two lateral ones. Subjects move a handle from a central movement target to one of the two lateral ones to express their choices. The possible decision and action outcomes are illustrated in the bottom panels (please refer to the main text for details). MD, movement duration; sMD, spontaneous movement duration. (b) Participants' average reach velocity profiles aligned on movement onset. Correct and 'too long' movements are compared in the left panel. Correct and 'too short' movements are compared in the right panel.

3.1.3 | Setup and tasks

The experimental apparatus (Figure 1a) and visual displays (Figure 4a) used are the same as in Experiment 1, except that the size of the movement targets was set to be 1.5 cm of radius and their distance from the central circle was set to 6 cm. Note that subjects also performed two other motor conditions in distinct blocks of trials, but these blocks, allowing to address questions beyond the scope of the present report, were not included in the present report.

The overall structure of the task was similar to the one used in Experiment 1: Subjects had to decide which of the two lateral blue circles would receive the majority of the tokens at the end of the trial. They could make and report their choices at any time between the first and last token jumps. Once a target was reached, the remaining tokens jumped more quickly to their final circles (a jump every 50 ms).

In Experiment 2, participants were instructed to reach a target within a 75-ms time interval around their spontaneous mean MD, computed for each participant in separate and dedicated trials (25 trials of the DR task; see below). Consequently, if, for a given subject, we estimated a mean spontaneous MD of 400 ms, then this subject had to report each of her or his choice by executing a movement whose duration was strictly bounded between 325 and 475 ms. A trial was thus considered as a movement error trial when the subject did not meet these temporal constraints, even if the correct decision was made. We distinguished 'too short' and 'too long' movement errors (Figure 4a). A movement error was indicated by both a visual feedback and a 500-ms audio feedback (both movement targets turned red, and an 800- or 400-Hz sound indicating that the movement was too short or too long, respectively, was played).

As in Experiment 1, subjects also performed a simple DR task that was identical to the choice task described above, except that there was only one lateral decision circle displayed at the beginning of the trial (either at the right or at the left side of the central circle with 50% probability). All tokens moved from the central circle to this unique circle at a GO signal occurring after a variable delay (1000 ± 150 ms). This DR task was used to estimate the spontaneous MD of each subject and to estimate the sum of the delays attributable to response initiation (i.e., non-decision delays). The goal for each subject was to perform in each of the two sessions 20 correct DR task trials and 80 correct choice task trials, indirectly motivating them to optimize successes per unit of time.

3.1.4 | Subsets of trials based on decision and movement outcomes

As for Experiment 1, we defined two subsets of trials based on decision outcomes: (1) 'correct decision' trials, when the subject chose the correct target and reported her or his choice with a correct movement, and (2) 'incorrect decision' trials, if the participant chose the incorrect target with a correct movement. Note that for these two subsets, wrong movement trials are excluded because no feedback was provided to the subject to indicate whether or not she or he chose the correct target. Instead, a salient feedback was provided at the end of the trial to indicate the movement error (see above and Figure 4a).

The constraints on MD in Experiment 2 allowed us to define three specific subsets of trials based on movement outcomes: (1) 'correct movement' trials, when the subject adequately (i.e., within the instructed time window) reached the correct or the incorrect target, and (2) 'too short movement' trials and (3) 'too long movement' trials, when the subjects reached a target (correct or incorrect) before the minimum instructed duration time and after the maximum instructed duration time, respectively.

3.1.5 | Data analysis

We conducted the same analyses as in Experiment 1.

3.1.6 | Statistics

We performed the same statistical analyses as in Experiment 1.

3.2 | Results

3.2.1 | Effect of a decision outcome on the next decision and on the next movement

We first assessed whether a decision outcome (correct or incorrect choice) influenced the participants' subsequent decisional behaviour. As shown in Figure 5a, subjects did not adjust their DD depending on decision outcome (after incorrect decisions: $\Delta DD = -13 \pm 83$ ms, $Z = -.5$, $p = .59$; after correct decisions: $\Delta DD = +3 \pm 38$ ms, $Z = -1.2$, $p = .22$; Table 2). We observed a decrease and an increase of the SPs following correct and incorrect choices, respectively (after correct decisions: $\Delta SP = -.03 \pm .01$, $Z = -6$, $p < .001$; after incorrect decisions: $\Delta SP =$

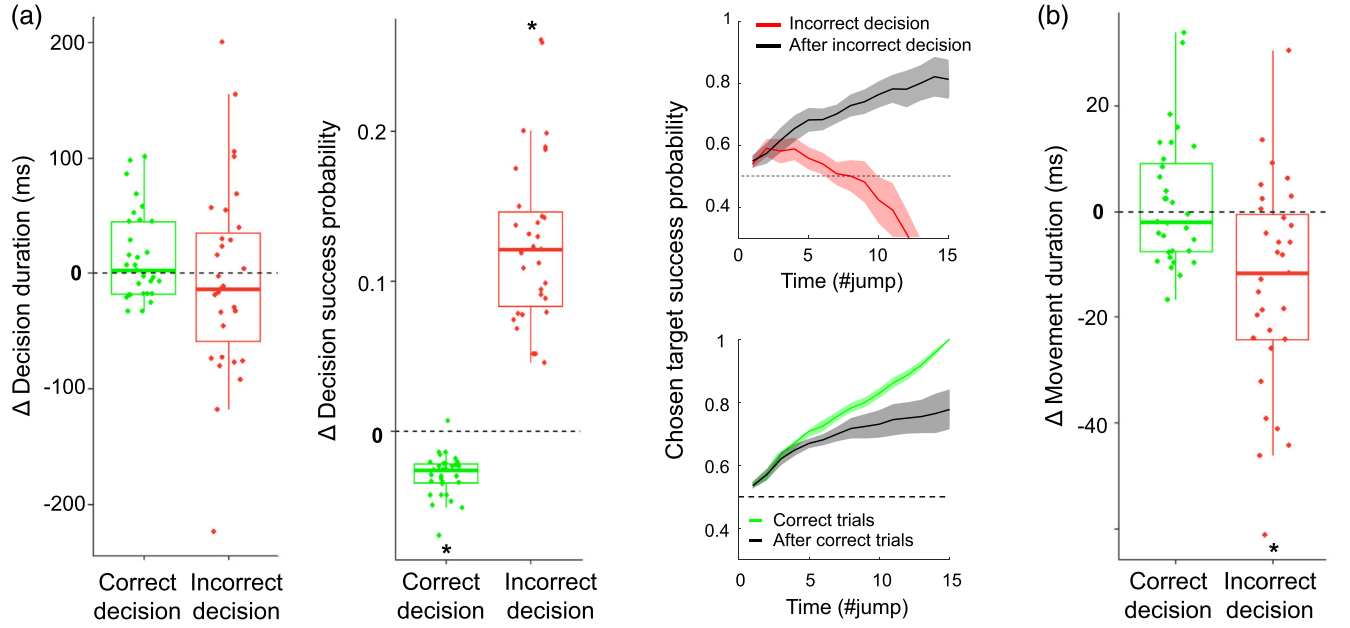

FIGURE 5 Effect of a decision outcome on the next decision and on the next movement in Experiment 2. (a) *Left and middle panels*: Δ decision duration (left) and Δ success probability (middle) after a correct decision (green) and after an incorrect decision (red). Same convention as in Figure 2. *Right panel, top*: Comparison of the average ± *SD* success probability profiles between trials whose decision was incorrect (red) and trials following an incorrect choice (black), computed across subjects with respect to the target they chose. *Right panel, bottom*: Same comparison as above between correct decision trials (green) and trials following a correct decision (black). (b) Same analysis as in (a), left panel, for the post-decision outcome adjustments computed for movement duration. *p value < .05.

+.12 ± .06, $Z = -6.1$, $p < .001$; Table 2 and Figure 5a), these adjustments being likely driven by a difference of trial difficulty in these conditions (correct vs. post-correct decisions: $\chi^2(14) = 182.6$, $p < .05$; incorrect vs. post-incorrect decisions: $\chi^2(14) = 1105.5$, $p < .05$, Figure 5a, right panel; Figure S2A illustrates the SP profiles of the same trials computed with respect to the correct target).

We then observed that following incorrect choices, subjects reduced their MD (ΔMD = −12 ± 20 ms, $Z = -3.5$, $p < .001$; Table 2 and Figure 5b) by increasing their peak of velocity and reducing the amplitude of their movements (ΔPV = +.24 ± .40 cm/s, $Z = -3$, $p < .01$; ΔAmp = −.13 ± .14 cm, $Z = -3.1$, $p < .01$; Table 2 and Figure S2B). By contrast, subjects did not adjust their MD after a correct choice (ΔMD = −2 ± 12 ms, $Z = -.2$, $p = .84$; Table 2 and Figure 5b).

3.2.2 | Effect of a movement outcome on the next decision and on the next movement

First, we observed no adjustment of the subjects' behaviour duration following a correct movement. Participants did not adjust their MD (ΔMD = −3 ± 9 ms, $Z = -1.4$, $p = .16$) nor their DD (ΔDD = +7 ± 33 ms, $Z = -1.55$ $p = .12$; Table 2 and Figure 6a,b, left panel).

Too short movements were on average faster (16.3 ± 3.6 vs. 13.1 ± 2.4 cm/s, $Z = -6.1$, $p < .001$) and shorter (516.2 ± 70.9 vs. 591.2 ± 81 ms, $Z = -6.1$, $p < .001$) compared to correct movements (Figure 4b, right panel). As expected, subjects adjusted their movements in the following trial by reducing their velocity peak (ΔPV = −3.1 ± 1.2 cm/s, $Z = -6.1$, $p < .001$; Table 2 and Figure S2B) and increasing their duration (ΔMD = +63 ± 26 ms, $Z = -6.1$, $p < .001$; Table 2 and Figure 6a). Conversely, too long movements were on average slower (11.7 ± 2.5 vs. 13.1 ± 2.4 cm/s, $Z = -5.7$, $p < .001$) and longer (628 ± 79.1 vs. 591.2 ± 81 ms, $Z = -2.4$, $p = .02$) compared to correct movements (Figure 4b, left panel). Subjects thus adjusted their subsequent movements by increasing their velocity peak (ΔPV = +1.3 ± .5 cm/s, $Z = -6.1$, $p < .001$; Table 2 and Figure S2B) and reducing their duration (ΔMD = −20 ± 20 ms, $Z = -5$, $p < .001$; Table 2 and Figure 6a).

We investigated whether these two types of movement error, leading to opposite motor adjustments in the following trial, also impacted the subsequent decision behaviour. We found that subjects reduced their DD following too short movements (ΔDD = −79 ± 86 ms, $Z = -3.9$, $p < .001$; Table 2 and Figure 6b, left panel). Crucially, this adjustment was not due to a difference of decision difficulty between the two trial subsets ($\chi^2(14)$

TABLE 2 Post-outcome adjustments of decision and motor behaviours in Experiment 2.

Experiment 2	Mean number of trials per subject (min–max)	Decision behaviour						Motor behaviour					
		ΔDD (ms)			ΔSP			ΔMD (ms)			ΔPV (cm/s)			ΔAmp (cm)		
		Median	*p* value	Effect size	Median	*p* value	Effect size	Median	*p* value	Effect size	Median	*p* value	Effect size	Median	*p* value	Effect size
After correct decision	156.2 (120–159)	3	.22	/	−.03	<.001	−.87	−2	.84	/	.04	.9	/	−.04	<.001	−.68
After incorrect decision	43.4 (18–74)	−13	.59	/	.12	<.001	.87	−12	<.001	−.59	.24	<.01	.52	−.13	<.01	−.54
After correct movement	199 (173–228)	7	.12	/	.00	.2	/	−3	.16	/	.07	.4	/	−.05	<.001	−.75
After too short movement	49.6 (18–144)	−79	<.001	−.66	−.01	.7	/	63	<.001	.87	−3.1	<.001	−.87	−.35	<.001	−.87
After too long movement	94.7 (21–175)	26	.06	/	−.01	<.05	.06	−20	<.001	.87	1.3	<.001	.87	.30	<.001	.87

Note: The *p* values refer to the one-sample Wilcoxon signed-rank tests.

= 1.2, $p = .99$; Figure 6b, top right panel), and no variation of decision SP ($\Delta SP = -.01 \pm .03$, $Z = -.3$, $p = .7$; Table 2 and Figure 6b, middle panel) was observed. Following too long movements, we observed a trend for subjects to increase their DD ($\Delta DD = +26 \pm 73$ ms, $Z = -1.8$, $p = .06$; Table 2 and Figure 6b, left panel). This effect was accompanied by a slight decrease of SP ($\Delta SP = -.01 \pm .02$, $Z = -2.1$, $p < .05$; Table 2 and Figure 6b, middle panel). Importantly, these adjustments were not due to a difference of decision difficulty between the two trial subsets ($\chi^2(14) = .6$, $p = .99$; Figure 6b, bottom right panel).

4 | GENERAL DISCUSSION

In this study, we investigated the level of integration of decisions and movements from trial to trial, depending on human subjects' decisional and motor performance. First, we found that erroneous decisions influenced the subsequent decision and movement durations in opposite ways, verifying the hypothesis of an integrated adjustment of both durations and actions from trial to trial. Second, by comparing the two experiments, we showed that the interactions between decisions and actions strongly depend on the duration of each process, possibly indicating that from one trial to the next, humans seek at determining a global behavioural duration instead of decision and action durations in isolation.

The post-error slowing (PES) observed in Experiment 1 is a phenomenon commonly reported in the literature (Danielmeier & Ullsperger, 2011; Jentzsch & Dudschig, 2009; Laming, 1979; Purcell & Kiani, 2016; Rabbitt & Rodgers, 1977; Thura et al., 2017), even if post-error speeding has been described as well (e.g., King et al., 2010). PES is often interpreted as an error-induced increase in response caution that allows one to improve subsequent performance (Danielmeier & Ullsperger, 2011; Fievez et al., 2022). Interestingly, after a correct choice, subjects who performed Experiment 1 did not adjust their choice durations, but they committed with less sensory evidence. Because post-correct decision trials were slightly more difficult than correct trials, this result suggests that a successful behaviour increased participants' confidence, possibly promoting risk taking (Bandura & Locke, 2003).

The present report reveals the properties of the decision-related PES further by showing that participants did not adjust their DD following a wrong decision when MD was highly constrained (Experiment 2). To explain this observation, it could first be argued that post-decision error trials were overall easier compared to trials in which a decision error occurred. Although possible,

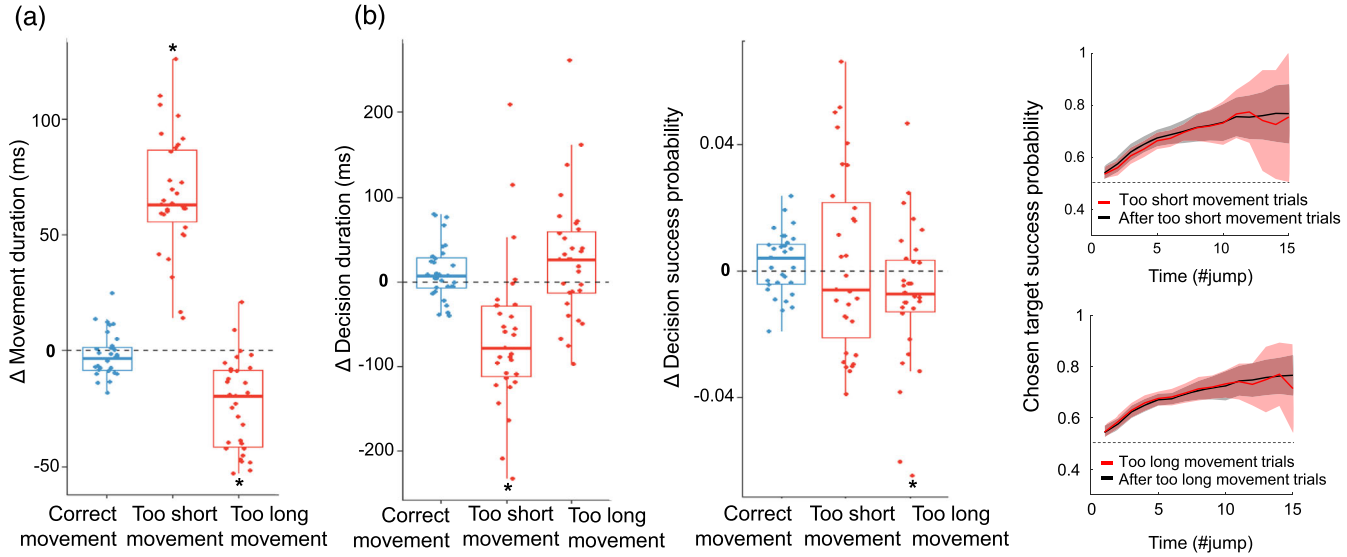

FIGURE 6 Effect of a movement outcome on the next movement and on the next decision in Experiment 2. (a) Δ movement duration after a correct movement (blue) and after too short or too long movements (red). Same convention as in Figure 3. (b) *Left and middle panels*: Same analysis as in (a) for the post-motor outcome adjustments computed for decision duration (left panel) and success probability (middle panel). *Right panel, top*: Comparison of the average ± *SD* success probability profiles between too short movement trials (red) and trials following too short movements (black), computed across subjects with respect to the target they chose. *Right panel, bottom*: Comparison of the average ± *SD* success probability profiles between too long movement trials (red) and trials following too long movements (black), computed across subjects with respect to the target they chose. *p value < .05.

the difference of SP profiles in the two trial subsets was large in both experiments, with consistent higher SP profiles in post-decision error trials compared to decision error trials, suggesting another reason for the lack of PES in the constrained task. Alternatively, it is known that PES partly depends on error frequency (Notebaert et al., 2009), and participants made more errors in Experiment 2 than in Experiment 1. However, errors in Experiment 2 concerned mostly movements, and decision error rates were low in the two tasks (18% ± 4% in Experiment 1; 13% ± 5% in Experiment 2). We thus believe that the lack of decision-related PES in Experiment 2 primarily relates to the strict duration constraints imposed on movements executed by subjects in this task (see below).

We also observed in both experiments the expected post-movement error adjustments in participants' motor behaviour. Generally, effects of behaviour history on subsequent behaviour have been investigated by means of cognitive tasks (Dutilh et al., 2012; Notebaert et al., 2009; Rabbitt & Rodgers, 1977), limiting the analysis to pre-movement processes (but see Ceccarini & Castiello, 2018). The present report describes, to our knowledge, the first analysis addressing the impact of decision *and* action outcomes on *both* the decision and the action executed in the following trial. This is important because in most everyday life choices, decisions and movements expressing these choices are temporally linked, constituting a continuum separating an event from a potential reward (Cisek, 2007). In agreement with this view, recent behavioural studies indicate a high level of integration between choices and movements during goal-oriented behaviour (Choi et al., 2014; Cos et al., 2011; Hagura et al., 2017; Haith et al., 2012; Morel et al., 2017; Pierrieau et al., 2021; Servant et al., 2021; Shadmehr & Ahmed, 2020; Shadmehr et al., 2010, 2019; Spieser et al., 2017; Yoon et al., 2018).

We found that after a slower choice made in response to a decision error, MD, if unconstrained, is reduced. This result is consistent with recent reports in both human and non-human primates showing that within blocks of trials defined by specific SAT properties, long decisions are expressed with vigorous, short movements (Herz et al., 2022; Thura, 2020; Thura et al., 2014). We show here that this policy can be established on a shorter timescale, from trial to trial, based on the subject's previous trial outcomes. Conversely, we found that when participants had to correct a wrong movement, they not only adequately adjusted their movement in the following trial, but they could also alter the duration of the decision made in this following trial, prior to the corrected movement expressing that choice. The comparison between the two experiments suggests that this transfer depends on the robustness and on the size of the motor correction following a movement error. This observation is at first sight consistent with several studies showing that the cost of a movement executed to report a choice influences

that choice in a given trial (Burk et al., 2014; Hagura et al., 2017; Marcos et al., 2015). But it actually goes beyond and demonstrates for the first time the ability of humans to preemptively compensate for a movement correction due to a motor error by altering the deliberation process of the post-error trial, before the execution of the corrected movement.

A possible functional interpretation of the reduction of MD accompanying a decision-related PES in Experiment 1 is that subjects aimed at compensating the extra time devoted to the deliberation by executing faster movements, even if shortening MD usually leads to a slight decrease of accuracy. In ecological scenarios, individuals are indeed often free to adjust the time they invest in deciding versus moving, and movements are parametrized following 'economic' rules (e.g., Shadmehr et al., 2019), allowing to optimize what matters the most for individuals during successive choices, the rate of reward (Balci et al., 2011; Bogacz et al., 2010; Carland et al., 2019).

In agreement with a reward rate maximization account, when a movement was corrected by increasing or decreasing its duration, most participants decreased or increased their DD, respectively, within the same trial. This is consistent with our previous reports in which compensatory effects are described across blocks of tens of trials defined by specific motor SAT constraints (Reynaud et al., 2020; Saleri Lunazzi et al., 2021). This suggests that one can flexibly share temporal resources between the decision and the action processes depending on both global and local contexts, even if these processes must slightly suffer in terms of accuracy (i.e., a 'good enough', or heuristic, approach, Gigerenzer & Gaissmaier, 2011). According to this mechanism, the absence of decision-related PES when MD was strictly constrained (Experiment 2) would mean that subjects anticipated that they could not compensate for a potential extension of their DD following a wrong choice during the movement phase, discouraging them to slow down their decisions after a decision error. Intriguingly, they still produced faster and shorter movements after a wrong choice, indicating here an adjustment of MD that did not depend on the decision leading to this movement. It is possible that in this specific task where movement errors were frequent (∼50%), subjects aimed at limiting the waste of time due to an erroneous trial by moving slightly faster in the next trial despite the strict constraints imposed on MD. Additional experiments will help to better understand the possible specificities related to the different tasks used in this study.

Taken together, the present results indicate that following both decision and movement errors, humans are primarily concerned about determining a behavioural duration as a whole instead of optimizing each of the decision and action SATs independently of each other, probably with the goal of maximizing their success rate.

AUTHOR CONTRIBUTIONS

David Thura: Funding acquisition; conceptualization; investigation; data curation; formal analysis; writing—original draft; writing—review and editing. **Clara Saleri Lunazzi:** Conceptualization; investigation; data curation; formal analysis; writing—original draft; writing—review and editing. **Amélie J. Reynaud:** Conceptualization; data curation; formal analysis; writing—original draft; writing—review and editing.

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CONFLICT OF INTEREST

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

This work's data and codes are freely available at the following URL: https://drive.google.com/drive/folders/1Pi19MlTIidqxGouOLalFP0E2Chx95HrB?usp=sharing.

PEER REVIEW

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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