How do we know what we are doing?: Time, Intention and Awareness of Action

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Abstract

Time is a fundamental dimension of consciousness. Many studies of the "sense of agency" have investigated whether we attribute actions to ourselves based on a conscious experience of intention occurring prior to action, or based on a reconstruction after the action itself has occurred. Here we ask the same question about a lower-level aspect of action experience, namely awareness of the detailed spatial form of a simple movement. Subjects reached for a target, which unpredictably jumped to the side on some trials. Participants (1) expressed their expectancy of a target shift during the upcoming movement, (2) pointed at the target as quickly and accurately as possible before returning to the start position, making a visuomotor adjustment to the target shift if required and (3) reproduced the spatial path of the movement they had just made, as accurately as possible, to give an indication of their awareness of the pointing movement. We analysed the spatial disparity between the initial and the reproduced movements on those with a target shift. A negative disparity value, or undershoot, suggests that motor awareness merely reflects a sluggish record of coordinated motor performance, while a positive value, or overshoot, suggests that participants' intention to point to the shifting target contributes more to their awareness of action than their actual pointing movement. Undershoot and overshoot thus measure the reconstructive (motoric) and the preconstuctive (intentional) aspects of action awareness, respectively. We found that trials on which subjects strongly expected a target shift showed greater overshoot and less undershoot than trials with lower expectancy. Conscious expectancy therefore strongly influences the experience of the detailed motor parameters of our actions. Further, a delay inserted either between the expectancy judgement and the pointing movement, or between the pointing movement and the reproduction of the movement, had no effect on visuomotor adjustment but strongly influenced action awareness. Delays during either interval boosted undershoots, suggesting increased reliance on a time-limited sensory memory for action. The experience of action is thus strongly influenced by prior thoughts and expectations, but only over a short time period. Thus, awareness of our actions is a dynamic and relatively flexible mixture of what we intend to do, and what our motor system actually does.

1. Introduction

Action awareness involves knowing what we are doing. We often have conscious experience of thinking about actions, and of controlling them, even in advance of actually moving. That is, there is a direct relationship between our intention to act and our conscious experience of acting. However, conscious intention may inform us about our actions only late in their temporal development (Libet et al., 1983), and perhaps not at all in the case of 'automatic' actions.

1.1. Dissociation Between Conscious Experience and Motor Control

Several studies have shown that conscious perceptual experience and motor control can be dissociated. In the double-step reaching task (e.g., Castiello, Paulignan, & Jeannerod, 1991; Johnson, van Beers, & Haggard, 2002), the target of a reaching or grasping movement is unpredictably shifted during the course of movement. This produces corrections of the trajectory within 100-150 ms (Carlton, 1981; Day & Lyon, 2000; Paulignan, MacKenzie, Marteniuk, & Jeannerod, 1990; Paulignan, Marteniuk, MacKenzie, & Jeannerod, 1991; Prablanc & Martin, 1992; Soechting & Lacquantini, 1983; Zelaznik, Hawkins, & Kisselburgh, 1983). Interestingly, these adjustments may occur independently of the conscious visual experience of perceiving the target moving. For example, Goodale et al. (1986) observed successful visuomotor adjustment in a pointing experiment in which the target occasionally jumped several degrees while the jump remained itself remained unnoticed by the participants. Pélisson, Prablanc, Goodale, & Jeannerod's (1986) improved on this design by triggering the target shift during a voluntary saccade, thus ensuring that it was not consciously detected. Successful visuomotor adjustments were nevertheless observed. Fourneret and Jeannerod (1998) found that subjects adjusted their reaching movements in response to spatially distorted visual feedback about hand-movement trajectory. Their participants remained unaware that the direction of their movement differed from what they saw, for angular distortions up to 15 degrees. Other experiments compared the latency of visuomotor adjustments with the latency of conscious detection of target shifts. Castiello, Paulignan, and Jeannerod (1991) found that awareness of an unexpected target jump occurred some 300 ms after the motor system had initiated an appropriate movement correction. They suggested that the neural pathways underlying visuomotor adjustment and conscious awareness were dissociable, and had different time constants.

These studies distinguish between *motor* performance, and *visual* awareness. In contrast, Johnson et al. (2002) investigated the relation between the ability to make visuomotor adjustments, and the conscious experience of the adjusted movement itself. Participants made rapid pointing movements with blocked instructions to follow the target (pointing condition), or to move in the opposite direction (anti-pointing condition) if it jumped. After each movement, participants reproduced the spatial path of the movement just made, this time without any time constraint. The gap between the spatial path of the original pointing movement and the spatial path of the reproduced movement was used as a measure of motor awareness. In the pointing condition, participants showed reduced and delayed motor awareness: they reproduced the curved movement path evoked by the target shift both later and with lower amplitude than the adjustment executed in the original pointing movement. In the anti-pointing condition, however, participants' corrections did not exhibit this dissociation between performance and motor awareness. Instead, the reproduced movements indicated that participants overestimated the speed and strength of the antipoint responses in the original pointing movements. Their motor awareness thus appeared to be influenced by the antipointing response that they should have made, or perhaps expected to make, and not by the weaker and slower response that they had actually made.

1.2. Dissociating Conscious Expectancy from Behaviour

In many cases, such as the anti-pointing task described above, action awareness may depend on what we expect to occur, rather than on the physical movement of our body. This idea finds supporting arguments in studies dedicated to the dissociation between conscious expectancy and conditioning (Perruchet, 1985; Perruchet, Cleeremans, & Destrebecqz, 2006). When two events, E1 and E2, appear repeatedly in succession, the presentation of E1 tends to improve or modify the behavioral response to E2. Classical conditioning is perhaps the best-known example of such a priming effect. Crucially, this has been interpreted in two contrasting ways. First, the occurrence of E1 may generate a conscious expectancy of E2 (e.g., Bolles, 1972; Lovibond & Shanks, 2002; Tolman, 1932), which is in turn assumed to facilitate responding to the occurrence of E2. Second, classical conditioning has also been explained in terms of automatic activation: E1 facilitates the response to E2 as a mandatory consequence of their having been repeatedly associated in the past. Automatic activation, in this context, is therefore assumed to reflect previous experience with the association**,** independently of the agent's conscious expectancy for E2.

The two interpretations differ radically in terms of their implications for conscious experience. The expectancy view takes conditioning to be dependent on conscious thought, while the priming view claims that conscious awareness is not necessary for conditioning to occur (e.g., Bush & Mosteller, 1951; Clark, Manns, & Squire, 2001; Clark & Squire, 1998; Hull, 1943). These two hypotheses have been difficult to dissociate because most experimental settings involve learning schedules that modulate both automatic priming and conscious expectancy in parallel: Under typical experimental conditions, identical effects are predicted by each view, for repeated associations between two events could result in either or both expectancy-meditated and activation-based facilitation of the processing of E2. As a solution to this problem, Perruchet (1985) proposed a methodology in which automatic priming and conscious expectancy can be opposed in simple conditioning. Here, we adapted this methodology to explore to explore the relationships between expectancy, action and awareness of action. In the following, we briefly summarize Perruchet's method and the main findings obtained through its application.

Insert Table 1 about here

In Perruchet's methodology, the US is presented in 50% of the trials. On each trial, before the CS is displayed, participants have to rate, on a graded scale, their expectancy that the US will be presented on the impending trial. Crucially, the sequence of trials is not random, but structured as shown in Table 1. This design results in the production of both E1-alone sequences and of sequences of E1-E2 pairings of various lengths. Thus, each trial can be described in terms of the nature and the length of the preceding sequence of identical trials. Both the probability of the conditioned response (CR) and subjective expectancy are recorded for each sequential context. In his 1985 work, Perruchet obtained two main results with this method. The first was the observation that recent experience of the occurrence of E2 influenced conscious expectancy of its repetition. Specifically, participants' expectancy for E2 was the highest after a long sequence of E1-alone events and the lowest after a long sequence of E1-E2 pairings. Furthermore, this difference in degree of expectation was a function of the length of the preceding sequence and decreased linearly between these two extreme sequences — a well-known phenomenon called the Gambler's Fallacy (N. H. Anderson, 1960; Burns & Corpus, 2004; Jarvik, 1951; Keren & Lewis, 1994), according to which people mistakenly believe that the probability of occurrence of successive independent random events depends on the recent history of their occurrence (i.e., mistakenly believing that "heads" is made more likely than "tails" after the observation that the past five tosses had each produced "tails").

The second result obtained by Perruchet was the striking observation that the strength of the conditioned response followed a completely different course than that obtained for conscious expectancy. Specifically, eye blink strength *increased* linearly as a function of the number of recent previous occurences of E1-E2 trials, confirming well-documented laws of conditioning and associative memory (e.g., J. R. Anderson, 2000). This result allowed Perruchet to dissociate between the two classes of interpretations described above. Repeated exposure to E1-E2 pairings strengthens behavioural responses to E2 while the very occurrence of such pairings simultaneously decreases conscious expectancy for E2! In other words, conditioning reflects a priming process that can be completely dissociated from conscious expectancy — a result that, when combined with other findings, suggests the involvement of independent processes in the determination of behavioural responses in this paradigm. In a subsequent study, Perruchet et al. replicated these findings with voluntary responses (keypresses in a simple reaction time task), suggesting that the dissociation method designed by Perruchet (1985) is robust and not limited to reflex responses.

1.3. Temporal effects in conditioning

Further research in the conditioning domain suggested that the relation between conscious expectancy and behaviour depends critically on the temporal features of the task. Clark et al. (2001) used Perruchet's experimental approach to compare effects on behaviour of two training conditions: delay conditioning and trace conditioning. In delay conditioning, the CS co-terminates with the US ; in trace conditioning, a 1000 ms trace interval is introduced between CS offset and US onset. Clark et al. found that learned behaviour and conscious expectancy developed in parallel in trace conditioning, but not in delay conditioning. In trace conditioning, awareness of the CS-US relationship is mandatory for conditioning to take place, whereas this is not the case under delay conditioning. The relationship between conscious expextancy and behaviour thus appears to be modulated by temporal factors. One interpretation of Clark et al.'s findings is that awareness is necessary to bridge the temporal gap between the CS and the US; another is that it takes time for conscious expectancy to influence behaviour (Cleeremans, 2005, 2006; Cleeremans & Sarrazin, in press).

In this context, our study drew on both the visuomotor adjustment literature and on the associative priming literature, both reviewed above, to investigate the awareness of action. Thus, we explored whether retrospective awareness of a aiming movement is influenced by prior conscious expectations about the occurrence of a target shift , by the actual details of the movement that was just executed, or by both. To do so, we asked participants, on each trial, (1) to express their expectancy that a target shift would occur during the upcoming movement, (2) to point to a virtual target as quickly and accurately as possible (returning to the start position immediately thereafter), and (3) to reproduce the spatial path of the movement itself.

Thus, for each trial, we have three measures of different aspects of performance, each collected very closely to each other: (1) An expectancy judgment, which measures participant's instantaneous conscious intention prior to movement onset, (2) path execution measures, which characterize the time course and the spatial extent of the actual movement itself, and (3) path reproduction measures, which characterize participant's conscious awareness of the movement they just executed. The first and latter measures inform us about the preconstuctive (intentional) and reconstructive (motoric) aspects of action awareness, respectively, and both can be compared to the actual movement itself.

To manipulate expectancy systematically, the material was organized in just the same way as was Perruchet's material, that is, the sequence of successive trials participants were exposed to contained both long series of trials where a target shift occurs, and long series of trials where no shift occurs. We would thus expect the recent history of shifts to influence expectancy judgments in the same manner as the recent history of reinforcements influences expectancy judgments in the conditioning and simple RT protocols developed by Perruchet, that is, participants should fall for the Gambler's fallacy in their conscious predictions about whether the next trial will contain a target shift or not.

Finally, to explore the effects of temporal factors on our different measures (keeping in spirit with the delay vs. trace conditioning protocols described above), our design included conditions in which a 6-s delay was inserted, either between expectancy judgment and the initial pointing movement, or between the initial pointing movement and the reproduced path.

2. Materials and Method

2.1. Participants

Seven student volunteers were tested on the basis of informed consent and with local ethical committee approval. They were paid 10 € an hour to participate. All were right-handed and they had normal or corrected-to-normal vision as per self-report.

2.2 Apparatus

The experiment was conducted in a small, dark testing booth. Participants sat at a desk with their right hand resting comfortably on a start button. A video marker was taped over the nail of the right index finger. A Hamamatsu video recorded movement kinematics in the X and Y dimensions at 120 Hz. A black mounting board was positioned vertically in front of the participant, 60 cm from the start button. Virtual images of two red LEDs, located above a semi-reflecting horizontal sheet of glass, were used as the fixation point and the target, respectively. A start button was located 2 cm above the sternum of the participant. The central LED was 40 cm in front of the start button, and served as a fixation point. A second LED 12 cm to the right of the central LED, served as the target LED on shift trials. On 50% of trials, 25 ms after the start button was released, the central LED was turned off and the shift-target LED was turned on at the same moment (see Figure 1).

Insert Figure 1 about here

2.3 Design

The sequence of trials was constructed based on the "randomization with restriction" method described by Nicks (1959). In essence, this method sets up the sequence of trials so that target-shift trials were preceded by runs of 1, 2, 3 or 4 target-shift trials, or by runs of 1, 2, 3 or 4 non-shift trials. Random drawings were taken from a set of runs (block of trials), the numbers and length of which were computed in advance. The resulting sequence included two runs of 4 preceding trials, four runs of 3 trials, eight runs of 2 trials, and sixteen runs of 1 trial (see Table 2), for each of the target-shift and non-shift trial types.

Insert Table 2 about here

We also added three further target-shift trials, one after each longest run of target-shifts and the other at the very end of the experiment, so that the expectancy generated by these long runs could be assessed. The total number of trials experienced by participants in each condition was thus (52*2)+3, that is, 107 trials. A different sequence of runs was generated for each participant.

Conscious expectancy that the target would shift on the next trial was collected using a ramp of 10 LEDs 2 cm apart and situated in front of the participant. At the beginning of each trial, each LEDs was successively illuminated, beginning with the leftmost LED (marked “-”) and proceeding to the rightmost LED (marked “+”), with each LED remaining lit for 0.03 seconds. Participants indicated their expectancy by depressing a pushbutton when the LED that corresponded to their expectancy level (leftmost LED = “I am certain that the next trial will not be shifted”, rightmost LED = “I am certain that the next trial will be shifted”), was illuminated. This arrangement thus approximated a visual analogue scale and made it possible for participants to express fine-grained, almost continuous expectancy judgments. The ramp LEDs were extinguished immediately after the expectancy judgement had been given.

2.4. Procedure

Insert Figure 2 about here

Each trial began with participants indicating their expectancy that the target would shift on the upcoming movement. The target LED was then illuminated after a delay that depends on condition (see below). When the target appeared, participants reached out and touched the target LED as quickly and accurately as possible, and subsequently returned to the start button. Participants were informed that the target LED would jump to the right side on half the trials. They were instructed to move fast and accurately, and to follow the target on such target-shift trials. The end of the movement was defined as the point at which the velocity of the finger fell below 5 cm/s. For each target-shift trial, we identified the initial movement direction (in degrees) and the time of adjustment (in seconds). Initial movement direction was determined by fitting a straight-line to the first 150 ms of the movement. Time of adjustment was identified as the time at which the absolute discrepancy (i.e., the perpendicular distance) between the X coordinates of the actual trajectory and the fitted straight-line first exceeded four times the mean absolute discrepancy measured during the first 150 ms of the movement.

After having executed the movement, participants were then asked to reproduce its spatial path as accurately as possible (see Figure 2). Participants were informed that the accuracy of temporal reproduction was unimportant. Both the target and shifted LEDs were off during reproduction. To initiate reproduction, participants were instructed to wait for two peripheral LEDs (located 30 cm to either side of the central LED and horizontally aligned with the target and shifted LEDs) to be illuminated.

Peripheral LEDs were both turned off when the reproduction movement had been terminated.

2.5. Experimental conditions

Each participant performed the task in 3 conditions that differed from each other by the presence of delays between the three stages of each trial (expectancy judgment, movement execution, path reproduction). In the *no-delay condition*, there was a 300-ms delay between the expectancy judgment and the onset of the central LED, and a 500-ms delay between the end of the initial movement and the beginning of path reproduction. In this condition, expectancy judgments and path reproduction were thus both tightly linked in time to the pointing movement executed during the same trial. In the *delay before target onset* condition, the interval between expectancy judgement and the onset of the central LED was 6000 ms. In the *delayed reproduction* condition, the interval between expectancy judgement and the execution of the pointing movement remained at 300 ms, but the interval between the return to the start button after the initial movement and the onset of path reproduction was increased to 6000 ms. The three delay conditions were tested in separate blocks, and in random order.

2.6. Spatial Re-Sampling and Error Estimation

Insert Figure 3 about here

Initial and reproduced paths could be of different temporal durations. We therefore resampled the paths as follows. First, the start and end of each pair of initial and reproduced movements were identified. The two resulting trajectories were time-normalized to one hundred time points using spline interpolation of the original time-series. The coordinates of the first and last points of the initial trajectory were used to rotate both movements so that the start and end points had equal Y coordinates. The visuomotor adjustment to the target shift then corresponds to the displacement in the X coordinate. Further, the disparity in the X dimension between original and reproduced movements gives an indication of motor awareness. For example, if the participant makes a successful visuomotor adjustment to the target shift, but is completely unaware that they have made it, then the reproduced path will proceed to the central target, and lie to the left of the original path. We call this an undershoot of action awareness, and accordingly give a negative sign to our disparity measure. Conversely, if the subject actually fails to adjust to the target shift in the original movement, but subsequently estimates that they had made a strong adjustment, then the reproduced path will lie to the right of the original path. We call this an overshoot in action awareness, and accordingly give a positive sign to our disparity measure. Disparity measures of action awareness reflect two different influences on action awareness, have quite different psychological interpretations and are therefore handled as separate dependent variables. Undershoot indicates that motor awareness contains only a sluggish, reduced record of actual performance (see Figure 3a). Overshoot indicates that motor awareness is dominated by the movement towards the target that the participant presumably intended to make, but did not (Figure 3b). A given trial could contain both undershoot and overshoot, perhaps during different phases of the movement (see Figure 4). To prevent these from cancelling each other out, we separately integrated the undershoot and overshoot errors along the length of each trajectory, to give each trial both an undershoot and an overshoot score. We then treated these as distinct dependent variables in the subsequent analyses.

Insert Figure 4 about here

2.7 Data Analysis

Only target-shift trials were analysed. Each trial yielded 5 dependent variables: (1) the expectancy that a target shift would occur, (2) the initial movement direction (3) the latency of the adjustment to the target shift (4) the motor awareness undershoot in the reproduced movement, (5) the motor awareness overshoot in the reproduced movement.

3. Results

Results will be presented in three parts. First, we examine the extent to which conscious expectancy judgments are sensitive to the recent occurrence of target shifts, that is, we ask whether people's predictions about what will happen in the next trial follows the Gambler's fallacy. Second, we examine how the initial pointing movement is influenced by the occurrence of a target shift. Finally, we present analyses concerning the "motor awareness gap", that is, the impact of both expectancy and time delays on motor awareness.

3.1. Analysis of Conscious Target Expectancy

This analysis was based on the expectancy judgments expressed prior to each shifted trial, whether they subsequently involved a target shift or not. Conscious expectancy did not differ across the three delay conditions. [$F(2,10) = 0.343$, $p = .717$, n.s.]. However, expectancy for the occurrence of a target shift followed the Gambler's Fallacy: Expectancy decreased [$F(7,35) = 2.418$, $p = .039$] as a function of the length and nature of the preceding run. Specifically, expectancy for a target shift after a series of four no-shift trials was higher than after a series of four shift trials. The relation between expectancy and run length was fairly linear, as expected. These data thus replicate both Perruchet (1985)'s findings with conditioning, and Perruchet, Destrebecqz & Cleeremans (2006)'s results with simple RT.

3.2. Analysis of the Initial Movement

These analyses were performed only for trials that contained a target shift.

Insert Figure 5 about here

3.2.1. Initial Movement Direction

Delays had no effect on initial movement direction [$F(2,10) = 0.208$, $p = .816$, n.s.]. Initial movement direction, unlike conscious expectancy, was not affected by recent experience of a target shift [$F(7, 35) = 0.75$, $p = .632$, n.s.] (Figure 5).

Insert Figure 6 about here

3.2.2. Time of Adjustment

There was no effect of delay on time of visuomotor adjustment to the target shift [*F*(2,10) = 0.352, *p* = .712, n.s.] (see Figure 6). Like initial movement direction, time of adjustment was not influenced by the recent experience of a target shift [*F*(7, 35) = 0.52, *p* = .813, n.s.]. Taken together, these measures thus suggest a dissociation between conscious expectancy and control of the initial movement: People's pointing movements towards a shifted target that occurs after a long series of non-shifted trials or after a long series of shifted trials remain almost identical to each other, in spite of the fact that the shift had either been strongly expected or not, respectively.

3.3. Analysis of Motor Awareness

These analyses were performed only for trials that contained a target shift. Undershoot and overshoot of motor awareness were analysed as parallel dependent variables, using MANOVA. Each participant's expectancy judgements were split at their median to define low and high expectancy. Thus, we here considered expectancy as an independent variable with two levels.

Insert Figure 7 about here

To investigate the effect of expectancy on motor awareness, we compared motor awareness measures for trials drawn from the extreme quartiles of the expectancy distribution. Thus, we compared overshoot/undershoot between the 25% trials which showed lowest expectancy, and the 25% which showed highest expectancy. These very low and very high expectancy trials were defined separately for each subject, on the basis of their individual expectancy ratings. This comparison showed a main effect of expectancy on both undershoot and overshoot; Wilks' Lambda= 0.288, approximated by F4,5=6.192, p=.044 (see Figure 7). Post-hoc univariate tests confirmed an effect for high expectancy to decrease undershoot (i.e., make it closer to 0, p=0.014) and to increase overshoot (p=0.015). Analyses based on tails of the distribution only are vulnerable to type I error due to distortion by a few extreme trials. We therefore repeated the comparison based on a median-split of each subject's data instead of extreme quartiles. This showed a trend in the same direction, with higher expectancy being associated with lower undershoot values and higher overshoot values: Wilks' Lambda=0.38, approximated by F2,5=4.01, p=0.09. The median-split analysis, in turn, is likely to underestimate the true effect, since it treats as categorically different expectancies which may in fact just bracket the median.

Insert Figure 8 about here

There was also a main effect of delay, as shown in figure 8. The standardized MANOVA coefficients were 1.23 and 0.18 for undershoot and overshoot respectively; Wilks' Lambda= 0.42, approximated by F4,22=3.02, p=.04). The coefficients indicate that delay influenced the level of undershoot almost 7 times more strongly than it affected overshoot. Specifically, inserting a delay either between expectancy judgement and the original movement, or between the original movement and its reproduction, lead to a larger undershoot in motor awareness. There was no interaction between the factors of expectancy and delay (p=.16).

4. Discussion

This study was aimed at (1) exploring the content of action awareness, viewed here as a “balancing act” between a sensorimotor rendering of an actual, just-executed movement and an intentional rendering of what is consciously expected to happen, and at (2) showing how temporal factors (i.e., the occurrence of delays between expectancy judgments, action execution, and action reproduction) modulate the content of action awareness. To address these issues, we contrasted actual motor performance with two measures of action awareness; one based on conscious expectancy of the action about to be made, and one based on motor reproduction of the action immediately after it had been made. We obtained three key results.

First, conscious expectancy was dissociated from motor performance: The history of preceding target shifts influenced conscious expectancy for a shift to occur on the current trial, consistently with the Gambler’s Fallacy, but influenced neither initial movement direction nor adjustment time during execution of the action.

Second, expectancy nevertheless clearly influenced motor *awareness*: When subjects expected a target shift, their movement reproductions showed increased overshoot and reduced undershoot relative to when they did not expect a target shift. Since conscious expectancy had no effect on motor performance, this must represent a direct link between expectancy and motor awareness, rather than being mediated by changes in motor performance of the original movement.

Third, the relationship between expectancy and motor awareness was modulated by total elapsed time. Adding a delay between either expectancy judgement and the original pointing movement, or between the original pointing movement and the reproduction, produced increased undershoot in motor awareness. In the following, we explore some implications of these results.

4.1. Conscious Expectancy, Motor Awareness, and Time-Dependency

We have used the ability to reproduce a movement made just previously as a conscious, but non-verbal report of motor awareness (Johnson et al., 2002; Johnson Van Beers and Haggard, 2002). We made an important distinction, on theoretical grounds, between undershoot and overshoot in motor awareness. Undershooting means that participants' reproductions show *less* adjustment to the target shift than the original movement. This implies that awareness of action contains only a sluggish and reduced record of the original coordinated motor performance. For example, the original motor adjustment might rely on fast dorsal stream processes (Milner & Goodale, 1992) while motor awareness might rely on more ventral stream representations of body movement (Dijkerman & De Haan, in press). In contrast, overshoot means that participants' reproductions show *more* adjustment to the target shift than the original movement. In that case, awareness seems to retain a record of a highly efficient adjustment that the participant intended to make, rather than the less efficient one that they actually made. In sum, undershoot in movement reproduction is a marker of sensory-based action awareness, while overshoot is a marker of intention-based action awareness.

Our results show that high expectancy of a target shift tends to suppress undershoot and to increase overshoot, without affecting the original motor performance. Action awareness is therefore penetrable to general cognitive factors in a way that original motor performance is not. If people explicitly judge the target shift to be very likely, then their awareness of the movement more strongly reflects the expected shift, and less strongly reflects the actual movement they made. This result shows that awareness of action is partly an awareness of what we anticipate we will do, as distinct from what we actually did. When the context of action supports strong predictions, then intended or predicted action makes a stronger contribution to action awareness than otherwise. Importantly, in this experiment, these predictions were in fact misguided. Subjective expectancies of target shifts were sensitive to the Gambler's Fallacy, although the actual probability of a target shift was fixed and independent on each new trial.

Furthermore, by introducing a six-second delay between conscious expectancy and the appearance of the central target, or between the initial movement and the reproduced movement, we demonstrated the time-dependent nature of the sensory-driven component of action awareness. As delay increased, undershoot became greater, while overshoot changed much less. Let us first consider the case of delays between expectancy judgment and initial movement. We have already seen that cognitive evaluation associated with expectancy judgment tends to reduce undershoots, but to increase overshoots. The effect of delay shows that this is only so over a relatively short time period. When a time interval is added between explicit prediction and motor reproduction, the dynamic balance shifts away from predictive/intentional contribution to action awareness towards a sensory-based contribution, reflecting actual rather than intended movement. The ability to preconstruct awareness according to an explicit prediction of what we intend to do operates only for a short time. Lengthening the delay makes this preconstruction harder, and produces increased reliance on sensory-based awareness. Our results suggest that expectancy and prediction do structure action awareness, but only over short intervals.

Second, a similar increase in undershoot was found when adding a delay between initial movement and reproduction. We argue that this change reflects the short time-constant of sensorimotor memory. The ‘ventral-stream’ body representation that encodes and memorizes bodily action is only short-lived. Participants generally underestimate the speed and gain of their own performance in visuomotor adjustment tasks (Castiello, Paulignan, & Jeannerod, 1991; Johnson, van Beers, & Haggard, 2002). Here we further show that these estimates are time-sensitive. Sensory access to the details of our actual movements may operate only over the timescale of a few seconds.

To summarize, we suggest that the mind mixes two renderings of an executed movement to create an experience of action. These are an underpowered sensory rendering of what actually happened (measured by undershoot) and an overpowered intentional rendering of what should have happened (measured by overshoot). Action awareness is subject to general cognitive modulation. Conscious cognitive evaluation tends to downplay sensory evidence and boost the contribution of what we intended to do. There is some evidence that 'what should have happened' involves a short-term cognitive prediction: when a delay is introduced, the sensory rendering shows increased contribution, so that conscious experience is more congruent with the subsequent action.

4.2. Dissociation Between Conscious Expectancy and Motor Adjustment

Our study replicated a finding of rapid visuomotor adjustments, which is a now a classic result in the action awareness literature. The adjustment, which is related to the minimum processing time taken by the central nervous system to adapt the reaching movement to a visual perturbation (i.e., a target shift), usually occurs at about 150 ms (Carlton, 1981; Day & Lyon, 2000; Paulignan, MacKenzie, Marteniuk, & Jeannerod, 1990; Paulignan, Marteniuk, MacKenzie, & Jeannerod, 1991; Prablanc & Martin, 1992; Soechting & Lacquantini, 1983; Zelaznik, Hawkins, & Kisselburgh, 1983). It was around 180 ms in our experiment, which is very close to the result usually obtained. Furthermore, the introduction of a delay between conscious expectancy and the appearance of the central target, or between the initial movement and the reproduced movement, did not modify this pattern of results.

Further, neither the direction of the initial movement nor the time of adjustment were influenced by the recent history of target shifts. Indeed, even in conditions where subjects reported a strong expectation that a target shift would occur, they still planned to point toward the central target: The direction of their initial movement did not show anticipatory deviation towards the shifted target. Motor performance thus varied quite independently of conscious expectancy.

In other words, these results indicate a dissociation between conscious expectancy and early adjustment to a visual perturbation. This supports the widely-acknowledged dissociation between consciousness and motor control. Many aspects of motor control take place unconsciously (e.g., Fourneret & Jeannerod, 1998; Goodale, Pelisson, & Prablanc, 1986). Action awareness is partly independent of the motor control circuits of the dorsal visuomotor stream (Milner & Goodale, 1998). We suggest that action awareness involves a balance of influences from conscious intention, expressed here through expectancy judgment, and from sensory-based information arising from a 'ventral-stream' type of representation of body movement (Dijkerman and de Haan, in press). Intentional influences are typically available in advance of action, while sensory-based evidence is only available in a brief time window after action itself. In this sense, our experience of action is both preconstructed and reconstructed. Interestingly, both processes appear to be sensitive to temporal factors, with the result that our experience of action is highly ephemeral.

Recent studies of action awareness have focused on the sense of agency: i.e., the feeling that "I" control my own actions. On one view (Wegner, 2002), agency requires the prior conscious thought of performing an action, appropriately close in time to the action itself. When both these conditions are present, people may believe they have performed an action which was in fact performed by another party, as in the "I-Spy" experiment of Wegner and Wheatley (1999). We have focused here on a rather lower level of action awareness, namely conscious access to information about the detailed motor pattern of an aimed movement. We made no attempt to influence agency, and our participants presumably recognized that their arm movements were their own. Nevertheless, the same principles that determine the sense of agency seem to apply to this lower level of action experience. We suggest that all action experience involves a brief moment of dynamic interplay between thought and sensory evidence.

Author Notes

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Figure captions

Figure 1: Experimental setup.

Figure 2: Schematic representation of experimental events across time in each trial.

Figure 3: Calculation of (a) underestimation and (b) overestimation errors in motor awareness.

Figure 4: Average spatial paths for initial and reproduced movements from a typical participant. Data are split at the median level of the participant's prior expectancy that a target shift would occur. Note the dominance of undershoot when reproducing movements on trials with low expectancy (a), and overshoot for trials with high expectancy (b). Note the expanded scale on the X axes.

Figure 5: Mean conscious expectancy ratings for the occurrence of a target shift (on a 10-point scale, left y-axis), and mean initial-movement direction (in degrees, right y-axis), as a function of the preceding run of trials, in each delay condition.

Figure 6: Mean conscious expectancy ratings for the occurrence of a target shift (on a 10-point scale, left y-axis), and mean time of adjustment (in seconds, right y-axis), as a function of the preceding run of trials, in each delay condition.

Figure 7: Mean undershoot (blue) and overshoot (red) reproduction errors (in cm) for

low and high expectancy trials. For a more powerful use of these data, we have chosen to not include the trials that were close to the median, but for instance we have used only the 25% lowest and highest expectation trials.

Figure 8: Mean undershoot (blue) and overshoot (red) reproduction errors (in cm) in each delay condition.

Table 1: Structure of the sequence of trials in the experiment of Perruchet 2006

Table 2: Structure of the sequence of trials in our experiment.

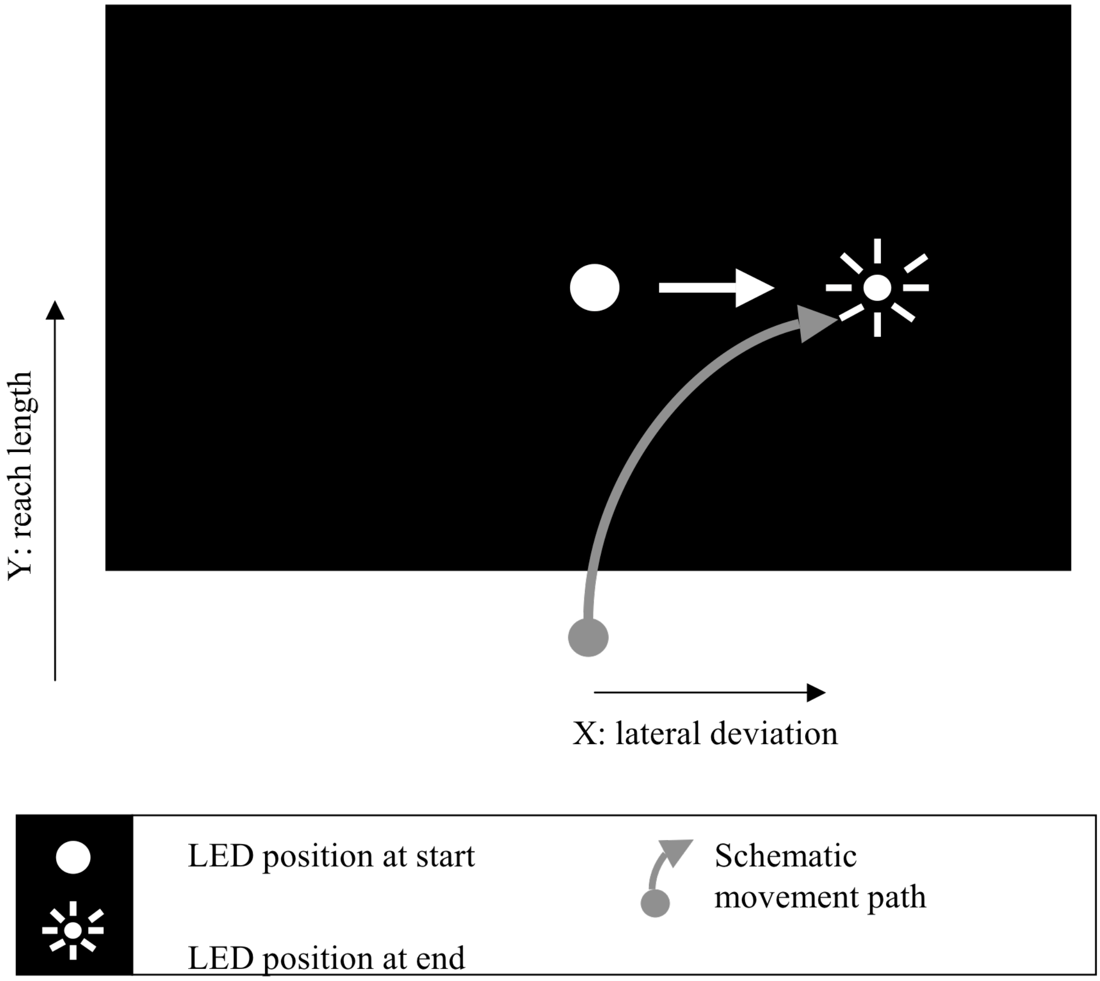

Y: reach length
X: lateral deviation
LED position at start
LED position at end
Schematic movement path

Figure 1

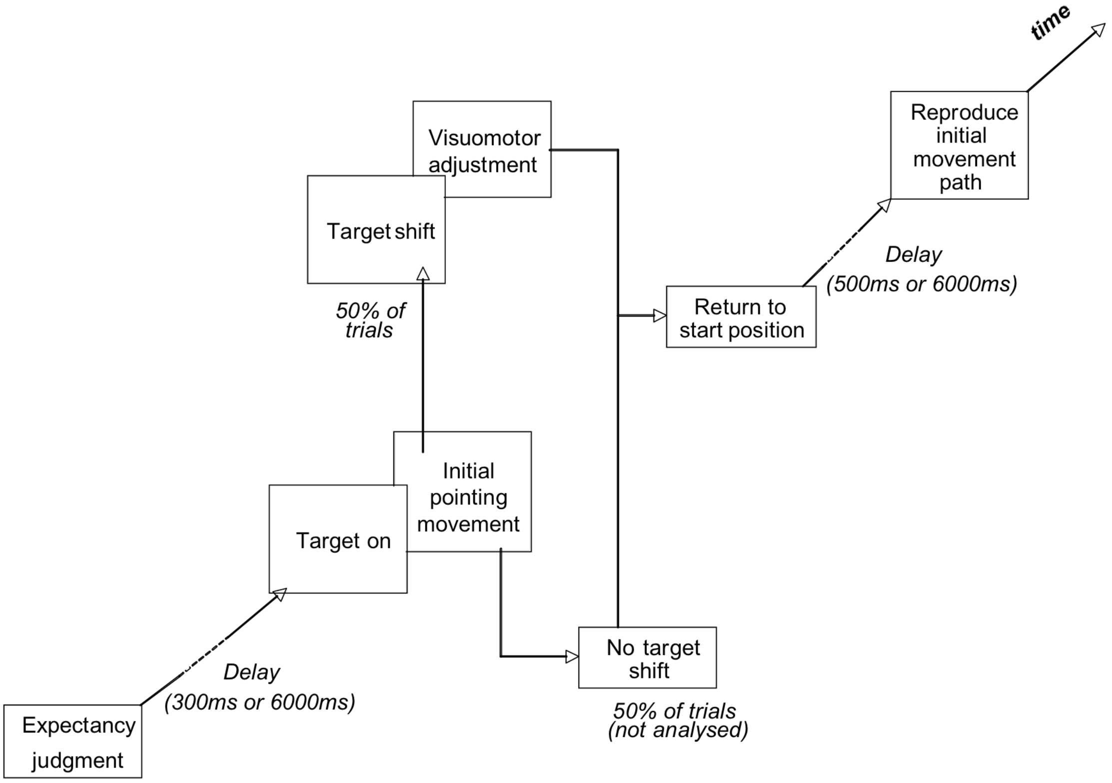
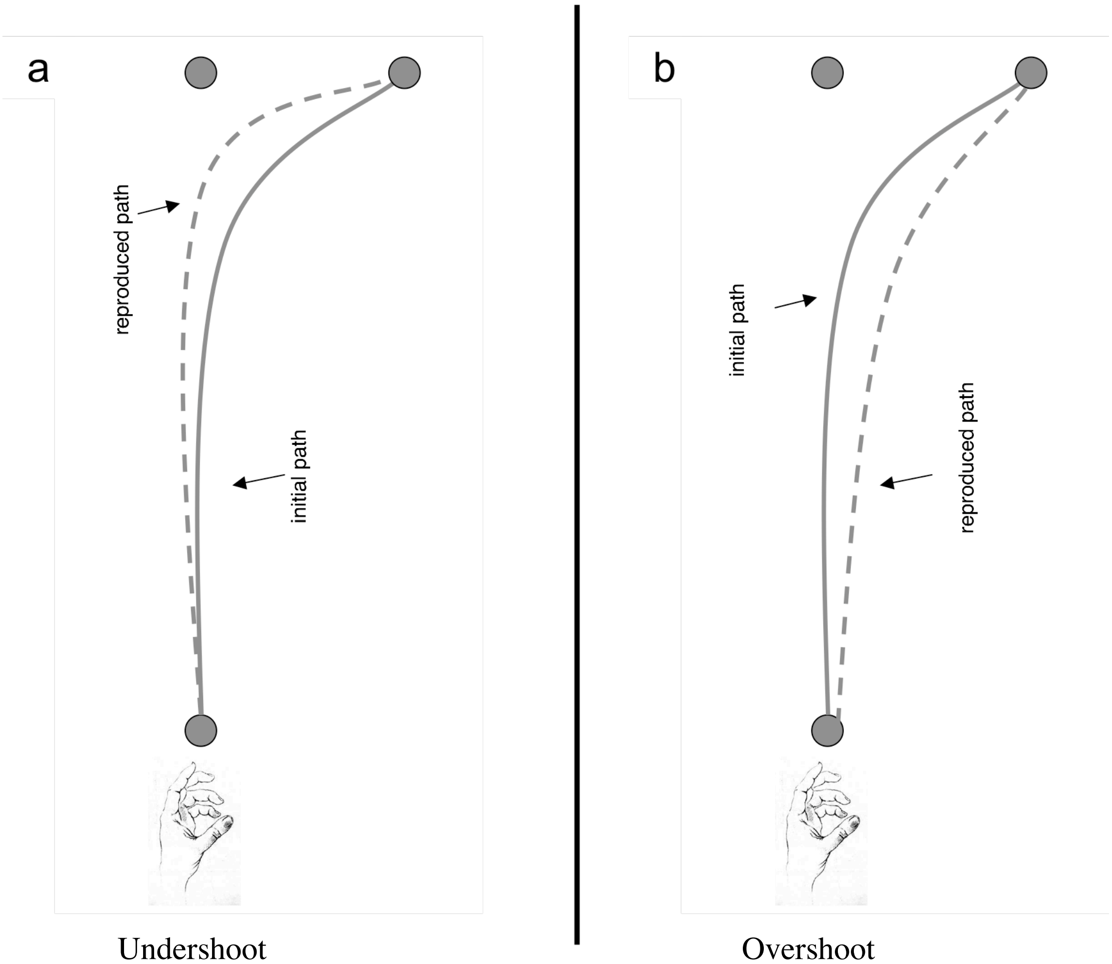

time
Reproduce initial movement path
Visuomotor adjustment
Target shift
50% of trials
Return to start position
Delay
(500ms or 6000ms)
Initial pointing movement
Target on
No target shift
50% of trials
(not analysed)
Delay
(300ms or 6000ms)
Expectancy judgment

Figure 2



Undershoot

Overshoot

Figure 3

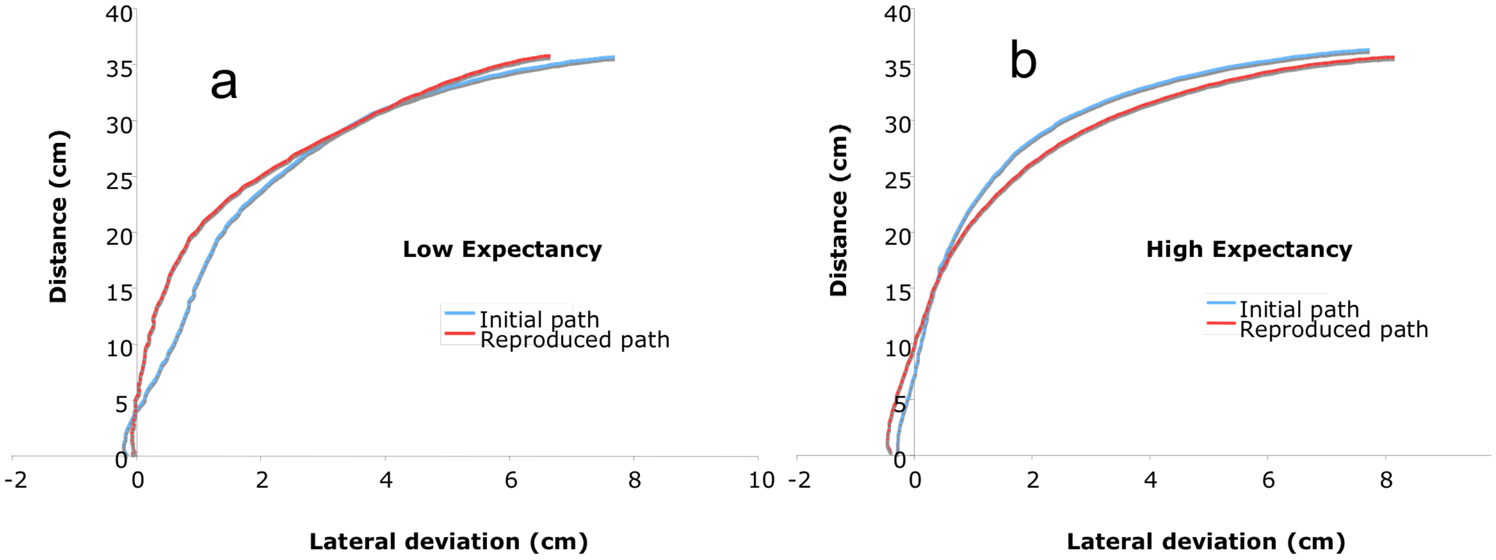

a
Low Expectancy
Initial path
Reproduced path
Distance (cm)
40
35
30
25
20
15
10
5
0
-2
0
2
4
6
8
10
Lateral deviation (cm)
b
High Expectancy
Initial path
Reproduced path
Distance (cm)
40
35
30
25
20
15
10
5
0
-2
0
2
4
6
8
Lateral deviation (cm)

Figure 4

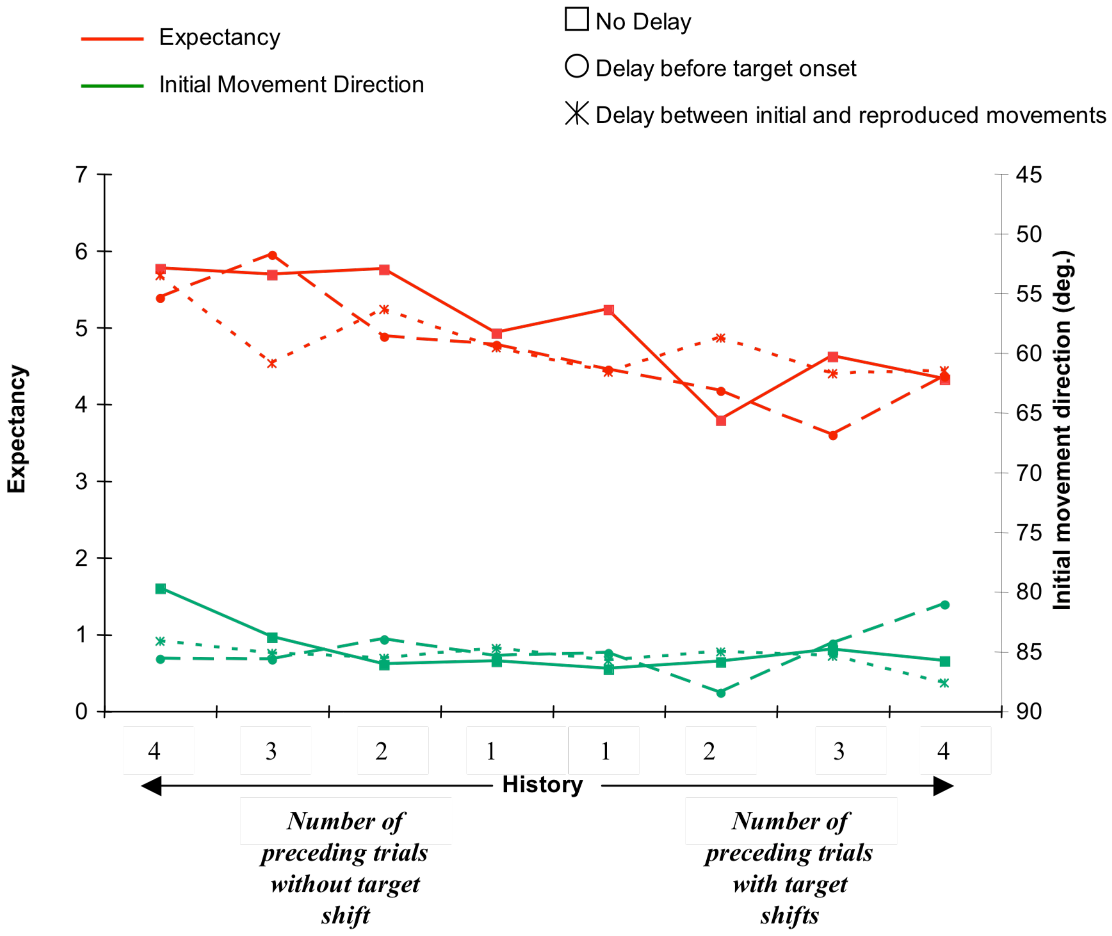

Expectancy
Initial Movement Direction
☐ No Delay
○ Delay before target onset
✳ Delay between initial and reproduced movements
Expectancy
0
1
2
3
4
5
6
7
Initial movement direction (deg.)
45
50
55
60
65
70
75
80
85
90
4
3
2
1
1
2
3
4
History
Number of preceding trials without target shift
Number of preceding trials with target shifts

Figure 5

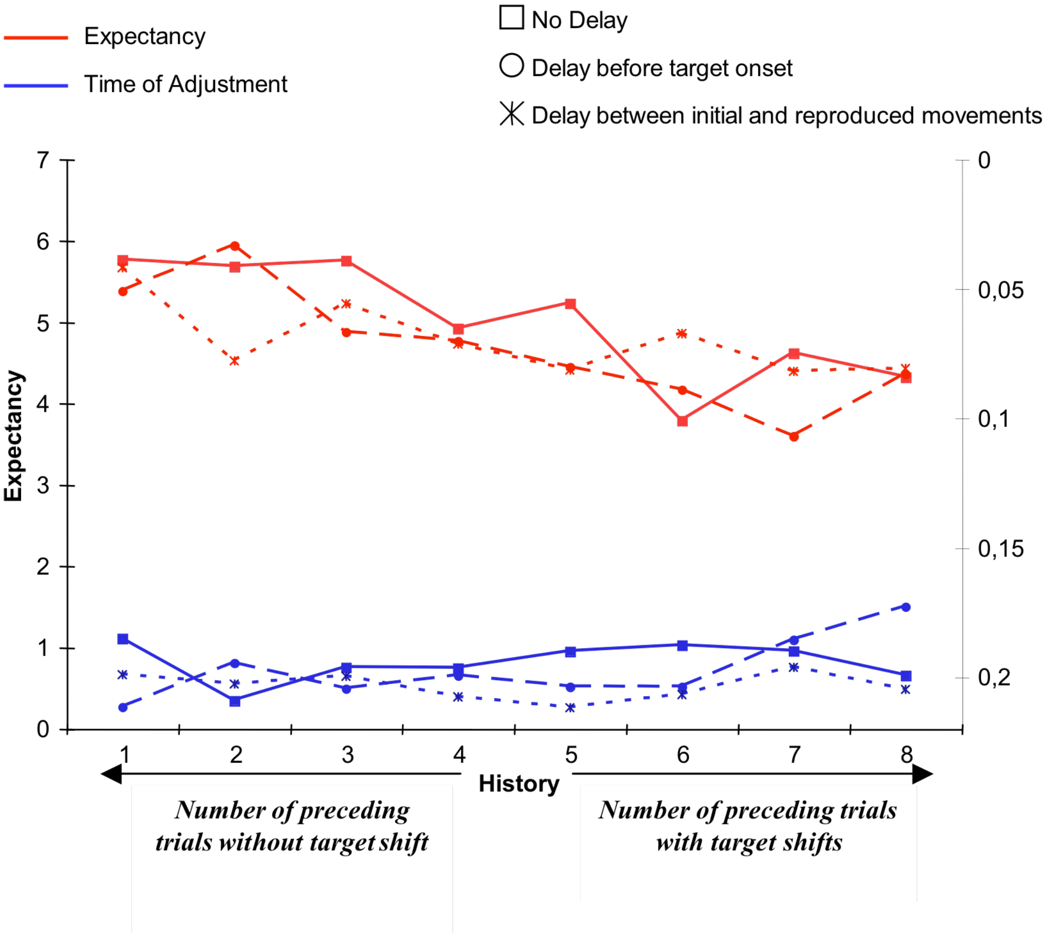

Expectancy
Time of Adjustment
☐ No Delay
○ Delay before target onset
✳ Delay between initial and reproduced movements
Expectancy
7
6
5
4
3
2
1
0
Time of adjustment (s.)
0
0,05
0,1
0,15
0,2
1
2
3
4
5
6
7
8
History
Number of preceding trials without target shift
Number of preceding trials with target shifts

Figure 6

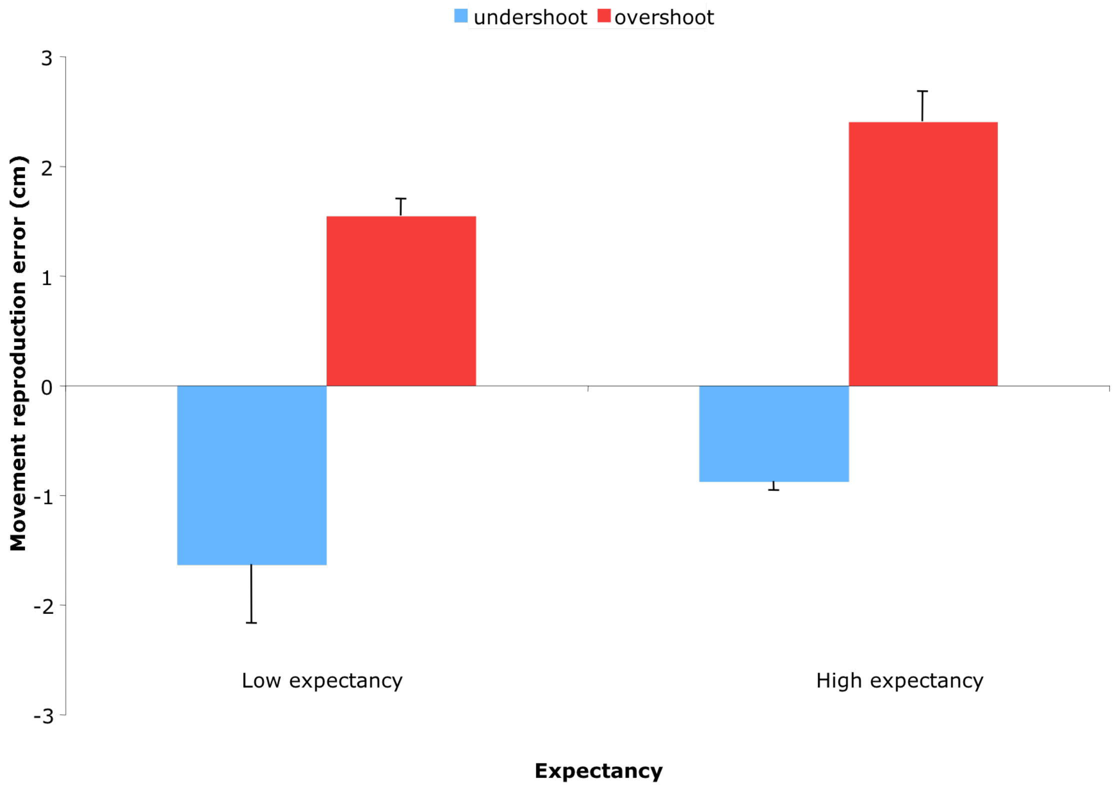

undershoot
overshoot
3
2
1
0
-1
-2
-3
Movement reproduction error (cm)
Low expectancy
High expectancy
Expectancy

Figure 7

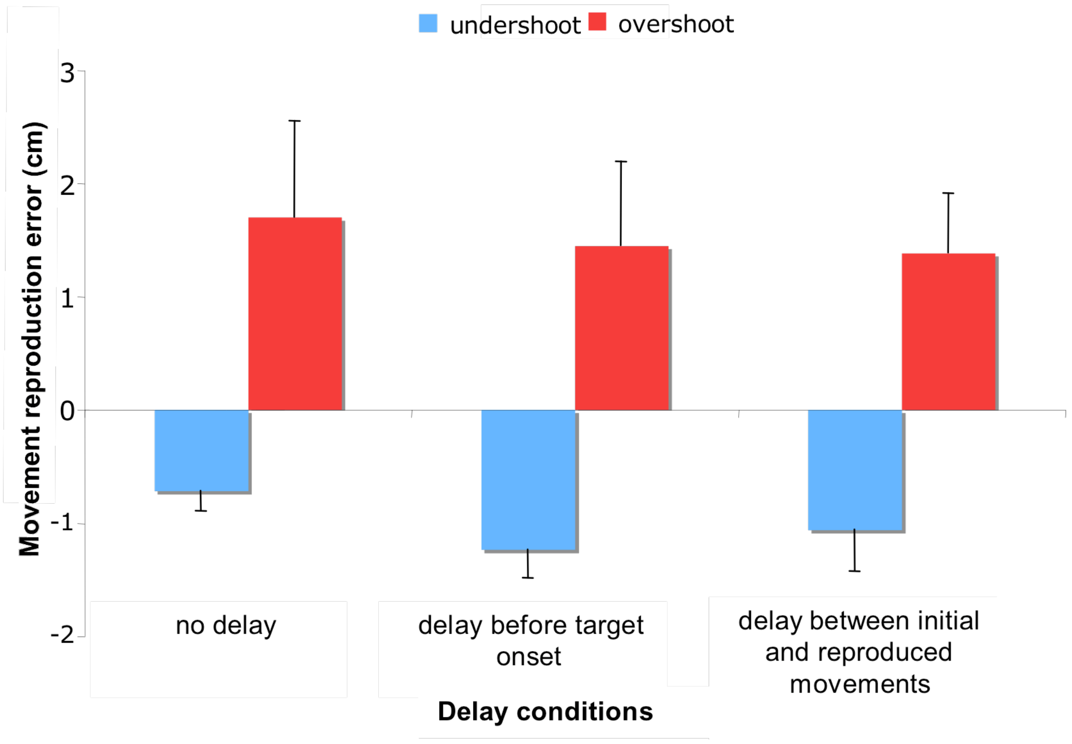

undershoot
overshoot
Movement reproduction error (cm)
3
2
1
0
-1
-2
no delay
delay before target onset
delay between initial and reproduced movements
Delay conditions

Figure 8

	E1 alone					E1 - E2				
Run length	**5**	**4**	**3**	**2**	**1**	**1**	**2**	**3**	**4**	**5**
Number of runs	**1**	**2**	**4**	**8**	**16**	**16**	**8**	**4**	**2**	**1**

Table 1

No shift before a shift					Shift before a shift			
Run length	**4**	**3**	**2**	**1**	**1**	**2**	**3**	**4**
Number of runs	**2**	**4**	**8**	**16**	**16**	**8**	**4**	**2**

Table 2

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