Ready steady slow: action preparation slows the subjective passage of time

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Professional ball game players report the feeling of the ball 'slowing-down' before hitting it. Because effective motor preparation is critical in achieving such expert motor performance, these anecdotal comments imply that the subjective passage of time may be influenced by preparation for action. Previous reports of temporal illusions associated with action generally emphasize compensation for suppressed sensory signals that accompany motor commands. Here, we show that the time is perceived slowed-down during preparation of a ballistic reaching movement before action, involving enhancement of sensory processing. Preparing for a reaching movement increased perceived duration of a visual stimulus. This effect was tightly linked to action preparation, because the amount of temporal dilation increased with the information about the upcoming movement. Furthermore, we showed a reduction of perceived frequency for flickering stimuli and an enhanced detection of rapidly presented letters during action preparation, suggesting increased temporal resolution of visual perception during action preparation. We propose that the temporal dilation during action preparation reflects the function of the brain to maximize the capacity of sensory information-acquisition prior to execution of a ballistic movement. This strategy might facilitate changing or inhibiting the planned action in response to last-minute changes in the external environment.

Keywords: motor preparation; time perception; vision; motor; reaching

1. INTRODUCTION

It is said that 'experts have all the time in the world' [1; pp. 34–73]. Indeed, tennis and baseball players [2] report the feeling of the ball 'slowing-down', and comment that they 'see' the ball more clearly before striking it. Because effective action preparation precedes such expert motor performance, these anecdotal comments imply that preparation for action may influence the perception of time. Distortion of time around the moment of action execution has been reported before. However, previous studies have focused only on time distortion either during or after motor execution [3–5] and never examined perception of time during the period of action preparation. Also, it has been reported that the ease to intercept a ball is associated with the perception of slowing-down of the ball speed [6]. But it is yet unclear what kind of motor process is involved, and whether these perceptual effects are a product of actual change in sensory processing.

Rapid ballistic movements, such as swinging a bat, cannot easily be modified during the initial phase of movement [7], though they may be adjusted 'on-the-fly' [8,9], particularly when the movement is non-speeded [10]. To maintain movement flexibility in the case of rapid movements, the optimal strategy for the brain may be to increase the capacity of sensory information-processing before execution of motor commands, to enhance detection of any environmental changes requiring changes in action plans. Our hypothesis is that the brain adjusts the flow rate of incoming information during motor preparation, and that process leads to perception of slowing down of time. Neuronal activity in the visuomotor areas is already observed during the motor preparatory period, and it has been shown that the visual areas in the occipital and parietal regions are reciprocally connected with the motor related areas [11]. Hence, it is plausible to think that, not only motor processing, but also sensory processing is adaptively tuned during the motor preparatory period.

In the present study, we examined whether time is distorted during preparation for an action, and further tested whether the phenomenon is associated with the increased capacity of information processing associated with neuronal processing of action preparation.

2. GENERAL EXPERIMENTAL PROCEDURES

(a) *Participants*

A total of 56 participants (experiment 1: 12, experiment 2: 9, experiment 3: 12, experiment 4: 12 and experiment 5: 11) participated. Participant's age ranged from 18 to 35 years. All had normal or corrected-to-normal vision, right-handed and were naive regarding the experimental purpose. All subjects gave informed written consent, and the study was approved by the UCL ethics committee.

(b) *General apparatus*

In all experiments, visual stimuli were presented on a gamma-corrected CRT monitor (HM703UT, Iiyama, Tokyo, Japan, 800 × 600 resolution, refresh rate of 85 Hz) at 79 cm viewing distance. A touch-screen panel

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(TD-171UF-3, Minato Electronics Inc., Yokohama, Japan) detected timing and location of touches. Participants initially placed the right index finger on a response key 35 cm in front of the screen. Participants fixated a cross in the centre of the screen throughout.

3. METHOD OF EXPERIMENT 1

(a) *Procedure*

We first tested whether the duration of a visual stimulus is perceived as longer during action preparation using temporal duration judgements. A filled white disc (diameter 2.6°) was presented on the centre of the screen 60, 80, 90, 95, 100, 105, 115, 135 frames (i.e. 700–1600 ms), and then replaced by a hollow disc (figure 1a).

In the reaching preparation condition, participants released the response key immediately when the filled disc was replaced by the hollow disc, and reached to touch the screen with their right index finger at the central location where the hollow disc appeared. The reaction time (RT) was defined as the time elapsed between onset of appearance of the hollow disc and key release. Movement time (MT) was defined as the time between key release and touching the screen. To ensure that participants appropriately prepared for the reaching movement during the presentation of the white disc, RTs above 500 or below 100 ms were counted as errors. Likewise, MTs over 500 ms were counted as errors. Such error trials were presented again at random positions in the sequence of remaining trials. In a control condition, participants continually pressed the key after appearance of the hollow disc for 1000–1200 ms. Releasing the key on control trials was counted as an error. A '+' on the white disc cued the participants to prepare to reach, and '×' indicated the control condition without reaching. Assignment of '×' and '+' to the experimental conditions was counterbalanced across participants. Both conditions were presented in the same experimental session.

Following the instruction presented on the screen after each trial, participants judged whether the duration of the white disc was short or long compared with all other durations presented in the previous trials by pressing the response key placed in front of them. This is a version of 'method of single stimuli' [12], which requires participants to use their internal criterion for the judgement. The accuracy of the method is comparable (even more accurate [13]) to the method that always presents standard stimulus with the test stimulus for comparison, and is also used in temporal duration judgement tasks [14,15].

Before the task, participants underwent 64 reach training trials. They touched the centre of the screen in response to a visual stimulus as fast and accurately as possible. After that, they performed 48 initial trials to establish the criterion for categorizing durations as 'short' or 'long'. The main experiment consisted of six sessions; each session contained five trials per duration in both experimental and control conditions.

(b) *Analysis*

Logistic regression was used to relate the percentage of 'long' judgement responses to overall stimulus duration in each condition for each participant. The point of subjective equality (PSE) was calculated from each regression. PSEs between the two conditions were compared by paired
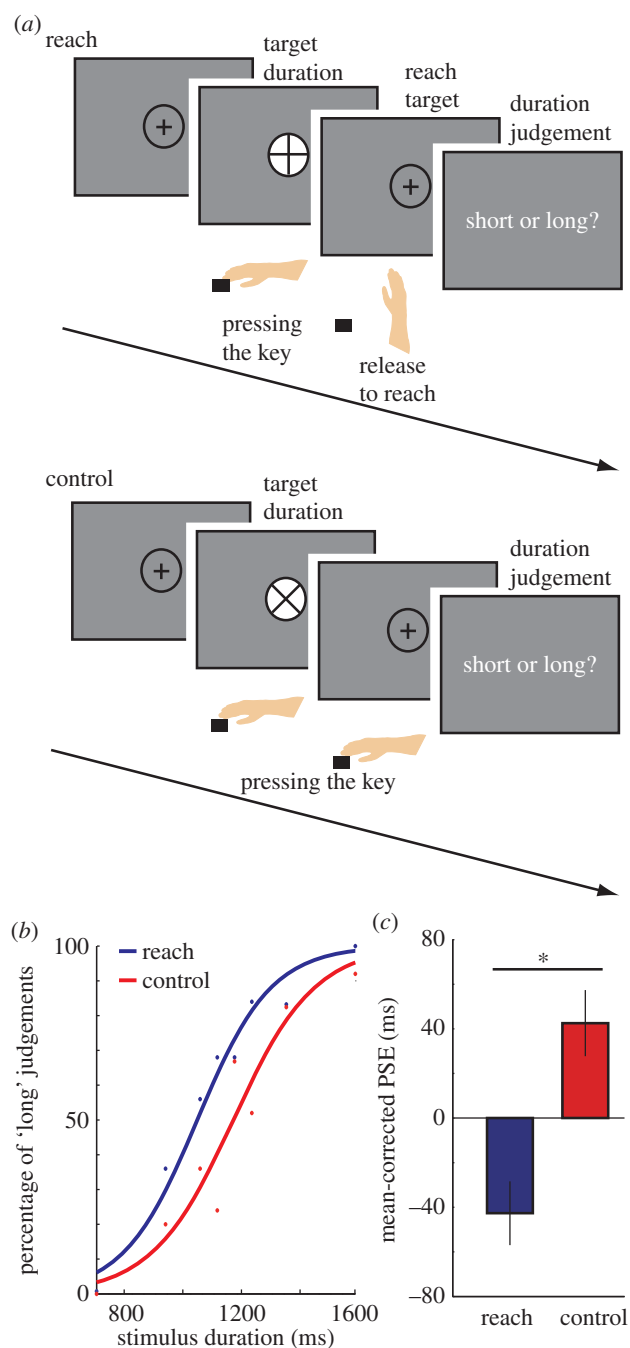

Figure 1. (a–c) Results of experiment 1. Error bars show standard error of means across participants (*$p < 0.05$). (a) Trial sequence of experiment 1. '+' on the white disc cued the participants to prepare for reach (reach), and '×' indicated the control condition without reaching (control). For half of the participants, these signs for conditional assignment were flipped. (b) Fitted psychometric function to the 'long' responses in each condition of a representative participant. (c) Point of subjective equality (PSE) for each condition averaged across participants. PSE-averaged across conditions were subtracted for each participant.

t-test (two-tailed). The same analysis was used for the data analysis of the following experiments 2–4.

4. RESULTS OF EXPERIMENT 1

Figure 1b shows the proportion of 'long' judgement at each stimulus duration of a representative participant. The PSE (the stimulus duration at which participants

judged as 'long' for 50% of the trials) was significantly shorter when participants prepared for action compared with the control condition (mean difference: 85 ms, $t_{11} = 2.93$, $p = 0.013$), showing that the participants perceived the visual stimulus to last longer when it was presented during motor preparation (figure 1c). These results support the claim that time slows down while preparing for action.

5. METHOD OF EXPERIMENT 2

The time dilation effect found in experiment 1 could be caused by a more general form of cognitive preparation. Given previous findings that attention lengthens perceived duration [16], enhanced arousal and vigilance during action preparation might expand perceived duration. This hypothesis would predict that time dilation would be observed even without preparation for reaching movement, as long as an attention-demanding task occurs at the end of an interval. To test this possibility, we repeated the same experiment, replacing the reaching task with a letter-detection task.

(a) Procedure

Procedures were broadly similar to experiment 1. However, one of two letters ('C' or 'G') was presented briefly (five frames; approx. 60 ms) after disappearance of the white disc (figure 2a). In the experimental condition, participants not only judged which letter was presented, but also judged the duration of the white disc. In the control condition, they ignored the letter and judged only the duration. The response key was pressed throughout. As in experiment 1, '+' or '×' on the white disc cued whether participants had to prepare for letter detection or not. Before the main task, participants underwent a practice session. Background luminance was set for each participant to ensure a consistent average-detection rate of 55 per cent. The main experiment consisted of seven sessions, including one practice session; each session contained four trials per duration in both experimental and control conditions.

6. RESULTS OF EXPERIMENT 2

There was no significant difference in the PSE between the letter-detection condition and the control condition; if anything, there was a slight tendency to report the duration to be shorter (longer PSE) when the letter detection had to be performed (mean difference: 72 ms, $t_8 = 1.61$, $p = 0.145$; figure 2b,c). These results indicate that time dilation is observed specifically for action preparation, and not in preparation for any cognitive task.

7. METHOD OF EXPERIMENT 3

If time dilation indeed depended on motor preparation, the amount of dilation should increase with the degree of motor preparation. It is known that the latency of motor response increases depending on the number of possible movement directions, and the motor preparatory neuronal activity in the motor areas is reduced when the degree of directional uncertainty is high [17–19]. On the basis of this established relationship, we manipulated the degree of motor preparation by manipulating the degree of uncertainty about the location of the reaching target.
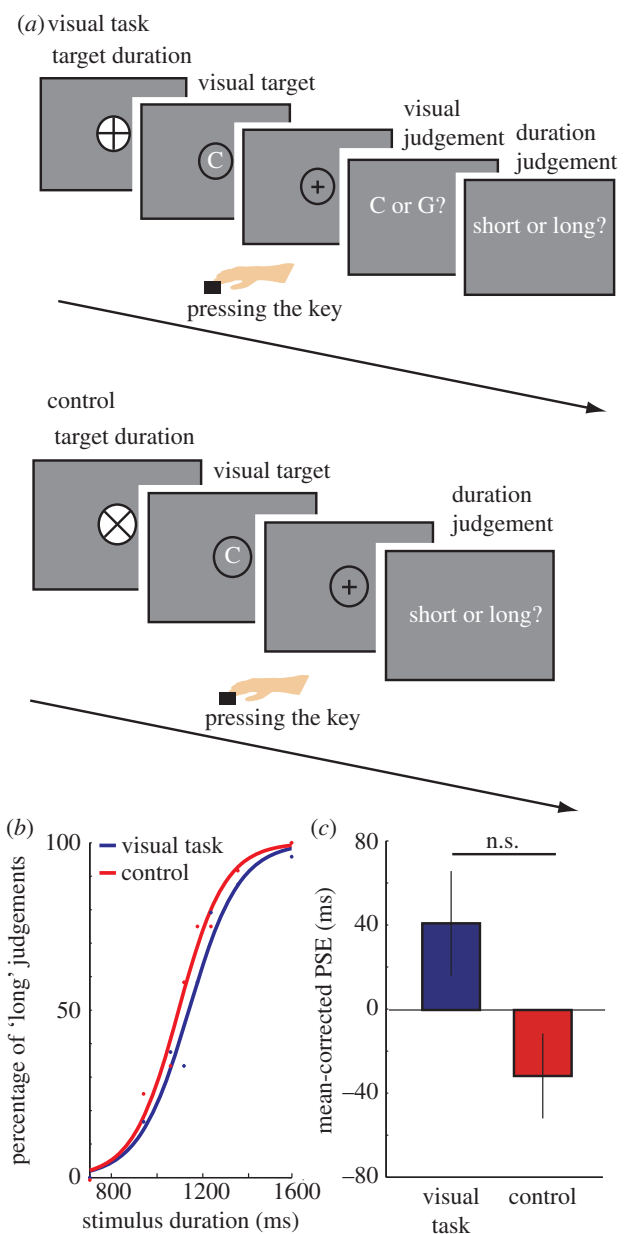

Figure 2. (a–c) Results of experiment 2. Error bars show standard error of means across participants. n.s. denotes not significant. (a) Trial sequence of experiment 2. '+' on the white disc cued the participants to prepare for the letter-detection task (visual), and '×' indicated to ignore the detection task (control). In both conditions, participants kept pressing the standby key throughout. (b) Fitted psychometric function to the 'long' responses in each condition of a representative participant. (c) Mean-corrected PSE for each condition averaged across participants.

(a) Procedure

General procedure was broadly similar to experiment 1. However, after disappearance of the white preparation disc, another white target disc (diameter 2.6°) could appear either on the left-hand or right-hand side (±2.6°) of the fixation cross (target; figure 3a). Participants reached towards the target after its appearance, and then judged the duration of the preparation cue. In one condition, the preparation cue contained a line whose tilt direction predicted the position of the target (figure 3a). In the control condition, the preparation cue was not tilted, so did not predict target locations
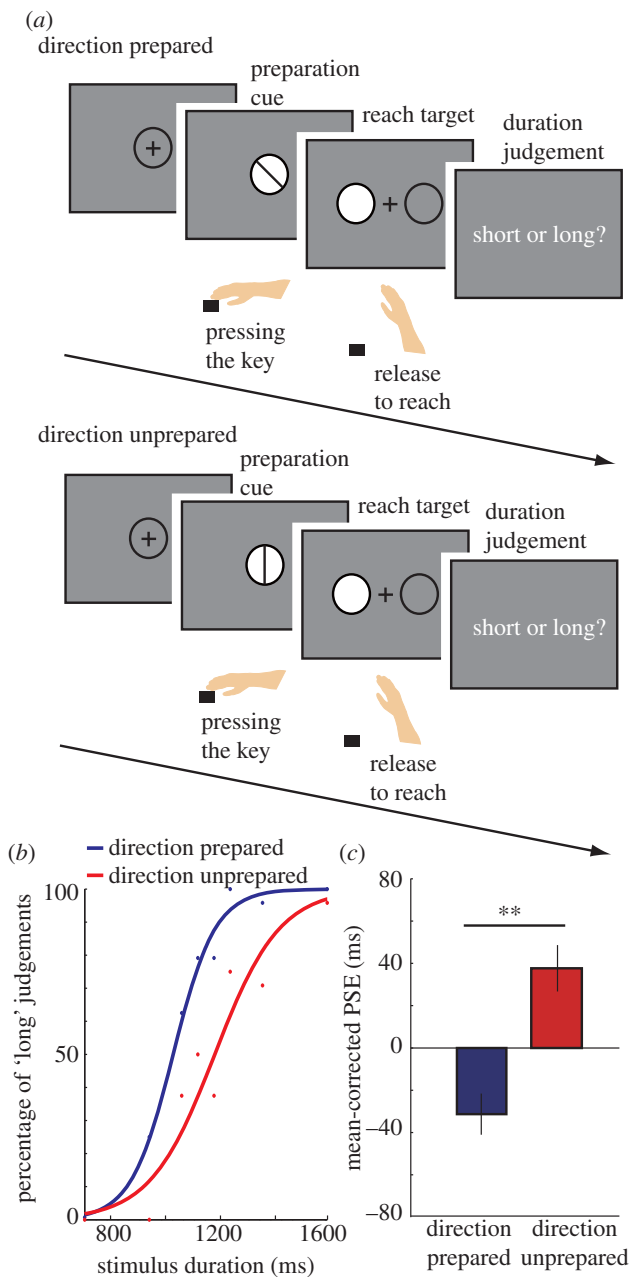
Figure 3. (*a*–*c*) Results of experiment 3. Error bars show standard error of means across participants (**p < 0.01). (*a*) Trial sequence of experiment 3. Participants knew the reach direction they had to subsequently perform from the tilted line on the preparation cue (direction prepared) in one condition. However, in the other condition, the line was vertical so the direction of reaching could not be prepared (direction unprepared). (*b*) Fitted psychometric function to the 'long' responses in each condition of a representative participant. (*c*) Mean-corrected PSE for each condition averaged across participants.

and the participants were uncertain about the target until its appearance (50% left and 50% right).

While both of these conditions required participants to perform a reaching movement at the offset of the cue, the degree of motor preparation differed. When the target location was certain, the motor commands for an arm movement with a specific trajectory could be prepared in advance. By contrast, for uncertain target locations, action preparation could take a more generic form, thereby making a high degree of preparation unfeasible.

If temporal dilation was directly related to the degree of action preparation, the effect should be larger for certain target locations, than for uncertain target locations.

The experiment consisted of seven sessions, including one practice session; each session contained four trials (two for left, two for right target) per duration in both experimental and control conditions.

8. RESULTS OF EXPERIMENT 3

We found significantly shorter RTs when the target position was predicted by the cue than when it was not ($t_{11} = 6.62$, $p < 0.001$), confirming that advanced direction cues indeed facilitated motor preparation. Subjective lengthening of time depended on the degree of reaching preparation (figure 3*b,c*), because the perceived time was significantly longer (PSE shorter) when action could be fully prepared for upcoming movement direction, when compared with when the preparation was directionally unspecific (mean difference: 68 ms, $t_{11} = 3.34$, $p = 0.007$). The dilation of perceived duration was therefore directly linked to the specificity of action preparation; greater specificity produced greater temporal dilation. Importantly, reaching actions were required in both conditions in this experiment. Hence, the observed temporal bias cannot be explained simply by the execution of a reaching movement *per se*. Furthermore, the locations of the lateralized reaching targets in this experiment differed from the central location of the preparation cue used for duration judgements. Thus, the effect cannot be explained by a simple form of increased spatial attention towards the location of the preparation cue [20].

9. METHOD OF EXPERIMENT 4

We tested whether motor preparation directly acts on the speed of visual perception. This is important because the results of experiments 1–3 could be caused by action-related changes in judgements of duration [3], without any change in momentary perceptual experience itself [21]. We therefore measured the perceived temporal rate of visual events.

(a) *Procedure*

A flicker stimulus with different temporal frequencies was presented in the centre of the screen. The stimulus was a Gaussian luminance blob with a sigma of $1.3°$, and the luminance was modulated with a temporal frequency of 3, 5.5, 7, 7.5, 8, 8.5, 10 and 12 Hz. Michelson contrast was set to 1.0 [22], and the maximum luminescence value of the monitor was 95.0 cd m^{-2}. Four different durations (90, 95, 100 and 105 frames) were displayed for each stimulus frequency. Participants reached towards the screen after the appearance of the target in one condition, but not in the other (figure 4*a*). Participants were asked whether the presented frequency of the flicker was slow or fast. Participants performed seven sessions, including one practice session; each session contained four trials (one trial per duration) per frequency in both experimental and control conditions.

10. RESULTS OF EXPERIMENT 4

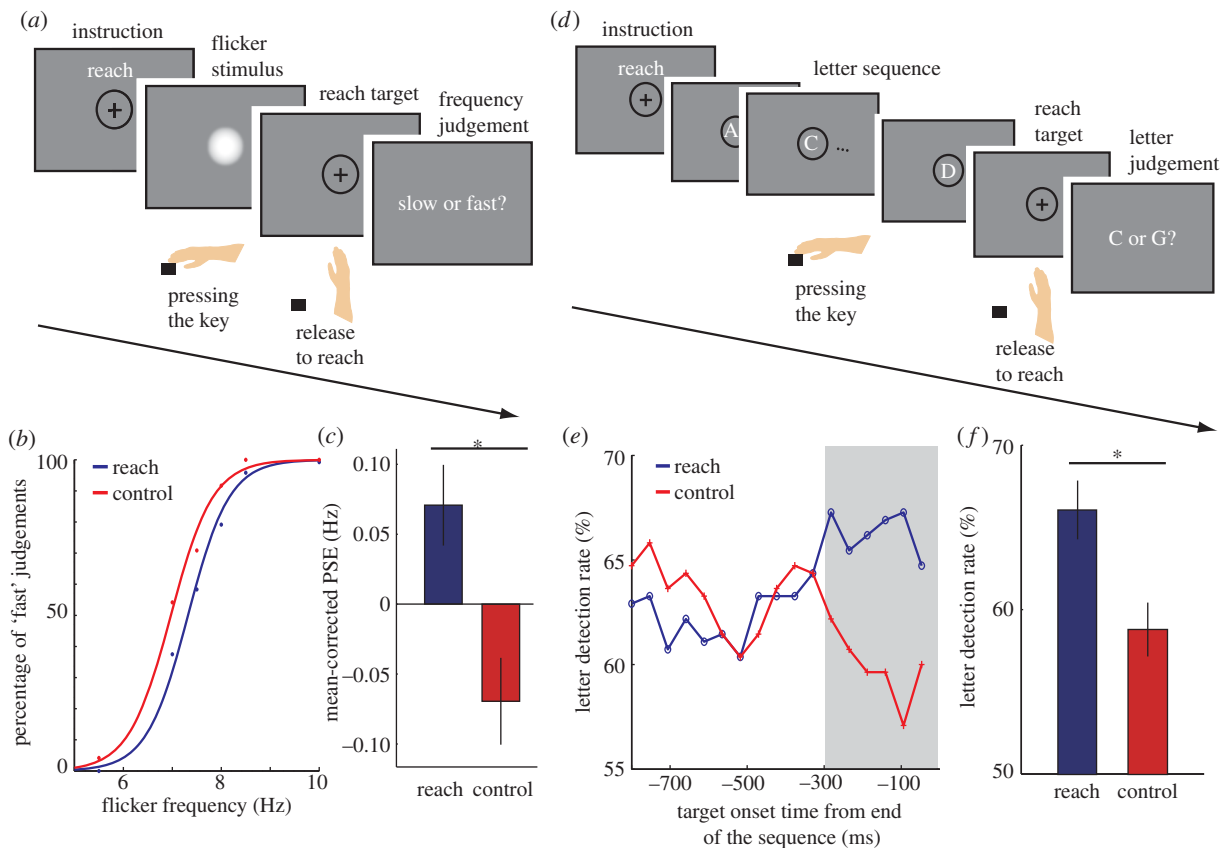The PSE for flicker frequency was significantly elevated during reaching preparation compared with the control

Figure 4. (*a–c*) Results of experiment 4 and (*d–f*) 5. Error bars show standard error of means across participants (**p < 0.05*). (*a*) Trial sequence of experiment 4. Participants saw a 'reach' or 'stay' instruction followed by a flicker stimulus. (*b*) Fitted psychometric function to the 'fast' responses in each condition of a representative participant. (*c*) Mean-corrected PSE for each condition averaged across participants. (*d*) Trial sequence of experiment 5. The instruction was 'stay' in the control condition. (*e*) Change in group-averaged letter-detection rate across time in both conditions. Data are smoothed in time for display purpose. (*f*) Letter-detection rate for each condition at the final 300 ms of the letter sequence (shaded area of (*e*)).

condition. Accordingly, higher frequencies appeared to be slower than they actually were, showing that visual events were subjectively slowed down by motor preparation (figure 4*b*,*c*; mean difference: 0.14 Hz, $t_{11} = 2.34$, $p = 0.039$). This suggests that motor preparation does not simply prolong the duration judgement, but operates directly on visual perception to alter the perceived rate of visual events. Therefore, the effect on perceived duration during the motor preparatory period is probably not a result of retrospective construction of duration by 'filling-in' after the action, because this would not be expected to change online perception of stimuli [21]. Further, our results again rule out explanations based solely on enhanced attention, because attention to the location of a flicker stimulus increases perceived flicker frequency [23], whereas we observed a decrease.

11. METHOD OF EXPERIMENT 5

The experiment above suggests that action preparation not only dilates perceived duration but also slows down the flow of visual experience. However, it remains uncertain whether action preparation simply alters visual time perception, or whether it also has functional consequences for efficiency of visual processing. If the slowing of visual experience during action preparation is owing to increased visual temporal processing, objective performance in processing rapid visual events should be enhanced. To examine whether visual processing is indeed enhanced by

being processed faster during action preparation, we combined the cued reaching task with a rapid serial visual presentation task. We predicted that action preparation would facilitate detection of target letters in the rapidly presented letter sequence. Moreover, because the degree of preparation increases as the time for action initiation approaches, letter-detection performance should increase towards the end of the preparation period.

(a) *Procedure*

A sequence of 24 items (upper case random alphabetical letters) were presented centrally in a disc, diameter of 2.6°. Each item was presented for three frames (approx. 35 ms) and was followed by one frame (approx. 12 ms) of a hollow disc. Every sequence included either the letter 'C' or 'G'. Participants detected which letter was presented. Target letters were presented at random timing within the sequence across trials. In one condition, participants reached towards the target that appeared after the letter sequence, and then judged which letter was presented (figure 4*d*). In the other condition, they kept pressing the response key during letter presentation, and then reported their judgement. Participants performed five sessions, each containing two trials per target position.

Before the main task, participants performed three sessions of 24 trials letter-detection practice without

reaching. The background luminance was set to achieve average-detection rates of 62 per cent across participants.

(b) *Analysis*

Trials with letter targets in the first and last positions were excluded from the analysis, because the effect of visual masking was physically different (no previous or subsequent letter in the first and last position, respectively) compared with the letters presented in other positions of the sequence. The letter-detection rate at each time point was calculated in each condition. We predicted that letter detection should improve during the final phase of action preparation. This prediction was confirmed by divergence of grand average performance between reaching and control conditions over the final 300 ms of the letter sequence. A linear regression analysis to the change of detection rates over time was performed to confirm this, which tested the slope of the linear trend in each condition. For this analysis, time series of detection rates were averaged across participants and smoothed in time using a moving average method. Finally, we averaged the raw detection rate of the final 300 ms period for each participant and compared these between conditions by paired *t*-test. The same comparison was also carried out for the detection rate of the beginning of the sequence $(0 \sim 300 \text{ ms})$.

12. RESULTS OF EXPERIMENT 5

Figure 4*e* shows the averaged letter-detection rate as a function of time. As predicted, a clear and increasing divergence in performance between conditions was observed during the final preparation for a reaching movement. For the reaching condition, detection rates significantly increased towards the end of the sequence (slope = 0.35, $t_{16} = 4.52$, $p < 0.001$), whereas in the control condition, the detection rates significantly decreased (slope = −0.35, $t_{16} = 4.54$, $p < 0.001$). As a result, there was a significant difference of letter-detection performance between the two conditions at around 300 ms before the appearance of the reach target (figure 4*f*; mean difference: 7.2%, $t_{10} = 2.96$, $p = 0.014$). This difference was not observed for the initial phase of the sequence (mean difference: 3.6%, $t_{10} = 0.63$, $p = 0.541$). Because target detection in repeated serial visual presentation is necessarily an online process, rather than a reconstructive one, the results strongly support the notion that motor preparation strengthens the visual information-processing online. Thus, subjective experience of extended temporal duration is associated with increased speed of processing of visual information. In the control condition, participants were allowed to fully focus on the visual-detection task without performing an action. Thus, it is difficult to explain the enhanced detection performance by assuming that participants devoted more attention to the visual task during the reaching preparation compared with the control condition. Instead, action preparation allowed participants to perform the visual task better than they could do by voluntarily directing attention to the task.

13. DISCUSSION

We described a novel type of time distortion that occurs during the motor preparatory period before execution of a ballistic reaching movement. Visual stimuli presented during this period were perceived to be prolonged, relative to a control condition without reaching, and their flicker rate was perceived as slower. Moreover, the speed of visual information processing became faster, resulting in a higher detection rate of rapidly presented letters. These findings indicate that the visual processing during motor preparation is accelerated, with direct effects on perception of time.

Our findings might appear to be a variant of other temporal illusions related to action. In the chronostasis illusion, a visual or somatosensory event is perceived as prolonged immediately after voluntary action, such as a saccade or a reaching movement [3,24]. However, the present phenomenon differs from chronostasis in several important respects. Critically, our finding concerns the duration of an event prior to action execution, whereas chronostasis concerns the duration of an event following action execution. Moreover, chronostasis has been interpreted as a manifestation of retrospective compensation mechanisms in which the timing of a stimulus onset is backdated to the onset of action execution [3,24] to fill-in the period of sensory suppression caused by action execution [25,26]. If our findings were also owing to retrospectively linking onset of action execution to offset of the imperative stimulus, the amount of time dilation should increase with RTs. However, this was clearly not the case in experiment 3, as advance preparation lead to shorter RTs (figure 3) but also to longer subjective durations. Furthermore, stability of the saccadic target is crucial for the occurrence of the chronostasis effect; if the saccadic target shifts its location before or during the saccade, the post-saccadic time dilation is abolished [3]. Our effect does not require such spatio-temporal continuity. In all our experiments, the reaching target was presented only after the preparation period, and—in experiment 3—even appeared in a different location than the white disc relevant for duration judgement. Still the duration of the visual stimulus was dilated consistently in all experiments when an action could be fully prepared. Finally, time dilation during action preparation was accompanied by online modulation of visual processing speed (see experiments 4 and 5), which cannot easily be explained by retrospective mechanisms prolonging perceived duration. Taken together, time dilation during motor preparation appears to be a quite distinct cognitive mechanism compared with chronostasis.

The effect of motor preparation on the estimation of temporal durations (experiment 1 and 3) and on flickering rates (experiment 4) seemed to differ in strength. This may be due to the difference in the task; perception of duration and of frequency is not interchangeable, and is reported to dissociate with each other [27]. The critical point is that the perceived slowing of flicker rate and the dilation of interval duration show a consistent direction of the effects of action preparation on time perception. The additional finding of enhanced detection of rapidly presented stimuli suggests that a significant component of perceived time dilation may arise from changes in visual information-processing capacity during action preparation. Our results are consistent with a recent hypothesis assuming tight linkage between perceived duration of a stimulus and the amount of information provided by that stimulus [28].

One may argue that this effect is related to a general increase in arousal level related to action [29]. However, we believe that is not the case in our study. In experiment 2, we showed that just preparing to detect a letter without any action, which should also increase the arousal level, does not give effect on the duration of subjective time. Also in experiment 3, we showed that time dilates more when an action is specified during the preparation period than when it was not. It is likely that preparing for an uncertain target location increases arousal level more towards the target appearance than when the target location is specified in advance. But the effect was opposite to an explanation related to arousal. Therefore, we argue that even if our effect is related to an arousal level, it is strongly coupled with an efficient action preparation, and is difficult to tease it apart from an action preparation process itself. Since the time dilation, slowing down of perceived flicker frequency and the increase in letter-detection rate all occurs at the same action preparatory period, we believe that these effects are related to each other.

Our finding that motor preparation modulates time perception is also compatible with the existing literature suggesting a close relationship between the motor system and time perception. Motor preparation is mediated by neuronal firing in a hierarchically organized action generation network consisting of frontal [30] and parietal [31] areas. Non-human primate electrophysiological studies have shown that neurons in these areas code the velocity of forthcoming hand movements [32] and are also responsible for coding the passage of time [33] or for anticipation of the timing for action execution [34]. Neuroimaging studies in humans also confirm involvement of motor areas such as the dorsal premotor cortex and the supplementary motor area in duration judgements [35]. These findings suggest a tight link between motor activity and temporal processing. Our finding that motor preparation directly influences visual processing performance (experiment 5) suggests that the preparatory activity in motor areas is linked to modulations of sensory mechanisms that enhance speed of sensory processing.

The neurotransmitter dopamine has pervasive effects on the brain's sensorimotor and motivational systems. Dopamine depletion in Parkinson's disease produces difficulty in both action initiation [36], and interestingly, a contraction of perceived time [37]. Dopamine is also thought to contribute to an internal pace-making mechanism, because dopamine antagonists slow down the putative 'internal clock' and contract the perceived duration of time [38]. These results seem consistent with our current finding that preparation for action, which possibly reflects the result of drive from dopaminergic circuits in the basal ganglia to the frontal motor areas, prolongs the perceived duration of time. Moreover, the speed of the internal clock may directly relate to the sensory information-processing speed, because dopamine agonists improve the recognition of rapidly presented stimuli in healthy volunteers [39]. This also resembles our finding of higher detection rates for rapidly presented letters during action preparation. On the basis of these similarities, we suggest that the dopaminergic system involvement in action preparation may be a possible neuronal mechanism underlying our time distortion effects. However, further studies are needed to elucidate the underlying physiological mechanism [40].

When a planned movement is quick and ballistic, it is important for the brain to maximize any opportunities for stopping/changing the planned action before the actual motor execution. Boosting speed of sensory information acquisition just prior to motor execution clearly increases the capacity to adjust action plans according to the rapidly changing environment. It has been shown that the ability to withhold a pre-planned action when a stop signal occurs is enhanced when the action is more prepared compared with when action is less prepared [41]. This paradoxical result cannot be readily explained by models which base response speed on the balance of excitation and inhibition within the motor system alone. By contrast, the suggested link between motor preparation and sensory acquisition speed readily explains the paradox: speeding up of visual processing during full motor preparation would enhance sensory processing of the stop signal, and thus increase the probability of stopping. Recent evidence indicates that sensory information acquired during preparation is buffered so that it can be used to adjust motor commands even after movement initiation [10]. Increasing the speed of sensory processing would also maximize the opportunity to adjust a pre-planned action as it enters the execution pipeline, by increasing the information available in the buffer. As such, the slowing down of perception triggered by action preparation may represent a flexible, strategic modulation of sensory acquisition speed. As expert ball-game players assert, being maximally prepared may allow 'more time' to perfect the hit.

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