

Rapid motor responses quickly integrate visuospatial task constraints

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Abstract We have recently shown that subjects can appropriately modulate their rapid motor responses (traditionally termed reflexes) to move their hand to a spatial target when the target is displayed ~ 2 s before a mechanical perturbation (Pruszynski et al. in *J Neurophysiol* 100:224–238, 2008). The goal of this study was to investigate how quickly visual information can be used to modulate rapid motor responses to an impending mechanical perturbation. Following a 2 s to 10 ms target preview delay (PD), a perturbation either displaced the subject's hand into or out of the previewed target. We also included a condition, where the target appeared after perturbation onset (target PD = +90 ms). In all cases, subjects were instructed to react as quickly as possible to the perturbation by reaching into the displayed target. Our results indicate that subjects began to incorporate visual information into their rapid motor responses with PDs as small as 70 ms. Interestingly, subjects reacted faster when the target was presented ~ 150 ms before the perturbation than when they had 2 s to prepare a response. Using receiver operative characteristic (ROC) analysis, we examined modulation of muscle activity as a function of preview delay in three predefined epochs. No modulation

was found in the short-latency epoch (R1; 20–45 ms). In contrast, both the long-latency (45–105 ms) and voluntary (120–180 ms) epochs were modulated at essentially the same time, 140 ms from visual presentation of the target to the beginning of each respective epoch.

Keywords Reflex · Visual integration · Long-latency response · EMG · Task-dependent · Upper limb

Introduction

The ability to use visual information to guide motor action is important for everyday life, and in many situations a correct response requires quickly processing visual information. Imagine a waitress navigating through a crowded restaurant while holding a tray of drinks. There is a table with patrons to her left and an empty area to her right. In the event of an unexpected bump on the arm, there is no guarantee that the waitress will be able to successfully avoid spilling the drinks on her customers. The outcome largely depends on how much time the waitress has to inspect the environment before the perturbation. This raises an interesting question about how much time is required to incorporate visual information into an appropriate corrective response to a mechanical perturbation.

The stereotypical sequence of muscle activity following a mechanical perturbation includes three distinct segments: the short-latency (20–45 ms post-perturbation), long-latency (45–105 ms), and voluntary response (120–180 ms) (Pruszynski et al. 2008). It is well established that the short-latency response is not easily modified by subject intent (Wolf and Segal 1996) and that such modification is a hallmark of voluntary control (Shadmehr and Wise 2005). Of particular interest is the long-latency response, which

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occurs prior to standard metrics of voluntary reaction time, yet can be modified by subject intent (Colebatch et al. 1979; Crago et al. 1976; Day et al. 1983; Hammond 1956; Hagbarth 1967; Lee and Tatton 1982; Lewis et al. 2006; Pearce et al. 2003; Rothwell et al. 1980). Although these studies provide strong evidence that rapid motor responses can be modified by subject intent, their use of verbal instructions to specify task constraints makes it difficult to determine how quickly visual information can be incorporated into a perturbation response.

We recently introduced a novel paradigm to study the modulation of long-latency responses, which replaced verbal instructions with visually-presented spatial goals (Pruszynski et al. 2008). In brief, goal targets were placed on the screen such that their position relative to where the perturbation displaced the arm instructed the subject how to respond. Since the presentation of the spatial target and the application of the perturbation can be precisely controlled, we used this paradigm to investigate how much time subjects required to modulate their long-latency responses to an unexpected perturbation. Previous studies have suggested that voluntary motor actions and long-latency responses are intimately linked as part of the same control process (Kurtzer et al. 2008; Pruszynski et al. 2008; Scott 2004). Therefore, we hypothesized that long-latency responses should be modifiable at latencies similar to voluntary responses.

Methods

Subjects

A total of 10 subjects (men, aged 18–25 years, 9 right-handed) participated in the main experiment and two control experiments, all of which were performed in the same session. All subjects were neurologically unimpaired, had normal or corrected-to-normal vision, were paid for their participation, and gave informed consent according to a protocol approved by the Queen's University Research Ethics Board.

Apparatus and experimental paradigm

Subjects performed the experiments with a robotic exoskeleton (KINARM, BKIN Technologies, Kingston, Ontario, Canada) that permits flexion and extension movements of the elbow and shoulder in the horizontal plane, and can apply mechanical loads to those joints (Scott 1999). All kinematic data were collected at 1000 Hz. The targets and hand feedback (white dot indicating the tip of the index finger) were presented in the plane of the task by a virtual-reality system. Direct vision of the hand was

occluded and the white dot representing the fingertip was extinguished prior to perturbation onset so that all perturbation responses were guided by sensory feedback from the limb.

Main experiment: target-dependent modulation as a function of preview delay

This experiment was designed to examine how quickly subjects could use visual information to modify their rapid motor responses to a mechanical perturbation. The task's spatial layout was described in our previous work (Pruszynski et al. 2008). Briefly, subjects maintained their hand in a small central area and responded to the same mechanical perturbation by placing their hand into the displayed peripheral target. These targets were placed such that the same perturbation could displace their hand either into (IN condition) or away from (OUT condition) the presented target (Fig. 1a). All trials progressed in the following sequence (see matching numbers in Fig. 1b):

1. Subjects maintained their hand in a small central area (radius = 3 mm) while countering a background load that activated the elbow flexor muscles (+2 Nm).
2. The hand feedback dot was extinguished after subjects stabilized their hand in the central area for one second with a hand speed less than 0.005 m/s.
3. After a random delay (400–700 ms), one of the two large peripheral targets (radius = 20 cm) was presented.
4. After a further delay, a torque was applied to the elbow joint in an elbow extension direction (+2 Nm). Critically, this preview delay (PD) between target presentation and perturbation onset was manipulated. The preview delay conditions were –2000 ms, –500 ms, –190 ms, –170 ms, –150 ms, –130 ms, –110 ms, –90 ms, –70 ms, –50 ms, –30 ms, –10 ms, 90 ms and catch. Negative and positive times indicate target presentation preceded and followed perturbation onset, respectively. In catch trials, a target was presented but no perturbation occurred.
5. If the subject did not reach the target within 1 s of perturbation onset, the peripheral target turned red to indicate an unsuccessful trial.

Each block of trials consisted of a random ordering of each preview delay for the OUT and IN conditions and six catch trials, for a total of 32 trials. Unsuccessful trials were repeated at the end of each block. Upon completion of a block, the subject's average performance time (the time the subject took to get into the peripheral target after perturbation onset, excluding catch trials) was displayed. The subjects were encouraged to reach for the peripheral target as quickly as possible by minimizing the displayed time

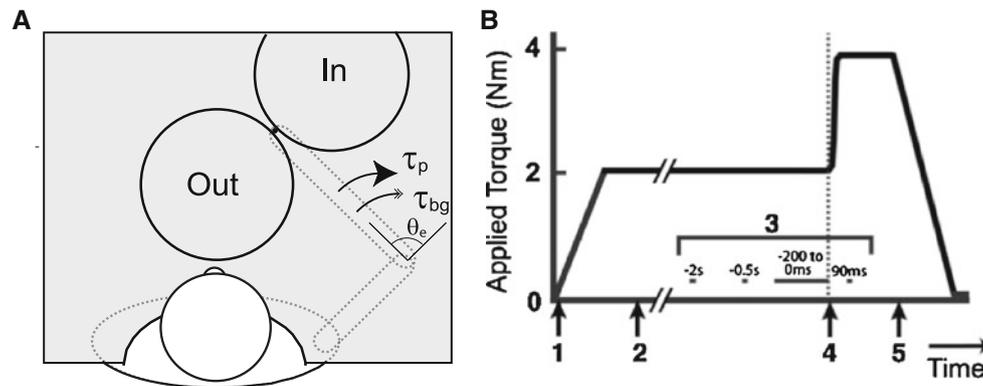


Fig. 1 Task apparatus and experimental paradigm. **a** Subjects were presented with one of two large peripheral targets (radius = 20 cm) located on the left or right side of their hand's starting position (central target, radius = 0.5 cm). The targets were chosen such that extension perturbations of the elbow either pushed the hand into (IN) or out of (OUT) the target. **b** Timeline for an exemplar trial. Labels on the *horizontal axis* denote. **1** Subjects shown the central target while the background load was introduced. **2** Hand feedback extinguished after the subject's hand was stabilized in the central target. **3** One of the peripheral targets was presented. **4** A rapid step perturbation was

applied in the elbow extension direction. **5** After 1000 ms the background load was removed for a 2 s inter-trial rest period. The vertical axis represents the applied torque with positive values indicating applied elbow extension. Note that the direction and the magnitude of the perturbation was the same for both the IN and the OUT condition (elbow extension, 2 Nm). Note peripheral target presentation (**3**) either took place at 2000 ms, 500 ms, 200–0 ms prior (negative preview delay) to perturbation onset (**4**) or at 90 ms after (positive preview delay) perturbation onset (**4**)

between blocks and to complete as many blocks as possible (range, 10–22 blocks; mean = 19 blocks). A mandatory rest was given to the subject after every three blocks. Preceding the main experiment subjects practiced until they were familiar with the task (<60 trials).

Control experiments: determining somatosensory and visually-cued voluntary onset

The purpose of the control experiments was to determine simple somatosensory (control experiment 1) and visual (control experiment 2) voluntary reaction times. In both control experiments, subjects had full knowledge about the position of the target prior to the task. In the somatosensory experiment, the OUT target was first displayed. A random time after the subject's hand stabilized in the central area (1000–3000 ms), a small perturbation was applied to extend the shoulder joint (+0.5 Nm) that was well above the subject's perceptual threshold but not large enough to elicit phasic EMG activity within 100 ms (Hammond 1956; Jaeger et al. 1982; Pruszynski et al. 2008). As in the main experiment, the subject was instructed to reach the OUT target as soon as they felt the perturbation. In the visual-cued experiment, the OUT target was presented a random time period following hand stabilization (1000–3000 ms), and the subject was instructed to reach to the target as soon as it appeared. For both experiments, each block consisted of 8 trials including 2 catch trials in which no perturbation or target presentation occurred. Each subject completed 6 blocks for a total of 48 successful trials, the first of which was treated as practice and not analyzed.

Muscle activity

Muscle activity (electromyography, EMG) was recorded via surface electrodes from 2 elbow flexor muscles: brachioradialis (monoarticular elbow flexor) and biceps long (biarticular flexor). Prior to electrode placement, the skin was cleaned and abraded with rubbing alcohol, and the electrode contacts were covered with conductive gel. Electrodes (DE-2.1, Delsys, Boston, MA) were placed on the belly of the muscle oriented along the muscle fibers. The reference electrode (Dermatode, American Imex, Irvine, CA) was attached to the knee. EMG signals were amplified at gains of 10^3 or 10^4 and band-pass filtered (20–450 Hz) by a commercially available system (Bagnoli, Delsys), then digitally sampled at 1000 Hz. Further details are provided in our previous studies (Kurtzer et al. 2008; Pruszynski et al. 2008; Pruszynski et al. 2009);

Data analysis

Behavior and kinematics Joint and hand position were low-pass filtered (20 Hz, two-pass, sixth-order Butterworth) and aligned on perturbation onset (Pruszynski et al. 2008). Due to the inherent delay and variability of the projection system, the precise target presentation times were determined using a photodiode. Subsequently, the measured preview delay times were binned into thirteen preview delay conditions (bin width; 20 ms): 90 ms, –10 ms, –30 ms, –50 ms, –70 ms, –90 ms, –110 ms, –130 ms, –150 ms, –170 ms, –190 ms, –500 ms, and –2000 ms. Note that the bins are centered. For example,

the -110 ms PD condition consisted of trials in which the target was presented between 120 ms and 100 ms before perturbation onset.

As described above, subjects had a full second to reach the target. Although subjects ultimately completed the task with a high success rate, we were interested in identifying whether a subject's initial motor response was behaviorally *appropriate* for the presented target. Preliminary analysis of the individual trials for short-preview delays demonstrated that some trials displayed a small inflection toward the wrong spatial location. Thus, we divided trials into two groups, *appropriate* and *inappropriate*, with the latter reflecting trials containing these small reversals, an approach similar to that presented by Crago and colleagues (1976). Since subjects behaved most consistently for the 200–400 ms post-perturbation time segment in the -190 ms preview delay condition (very few reversals according to visual inspection of the data), we used this as our baseline to deem whether trials were behaviorally appropriate or inappropriate. That is, if the elbow trajectories deviated from the 190 ms PD condition by more than 3 standard deviations for 5 consecutive time samples in the 200–400 ms post-perturbation time window, the trial was deemed to include an *inappropriate* response. It is important to emphasize that our approach operates at the behavioral level and cannot necessarily identify every type of inappropriate response. For example, subtle changes in muscle activity or systematic shifts in muscular co-contraction would likely be filtered out by the mechanical properties of the limb.

Muscle activity EMG signals were further band-pass filtered (25–250 Hz, two-pass, sixth-order Butterworth), full-wave rectified, and normalized to the mean background activity over the 50 ms preceding perturbation onset. Muscle activity was binned into standard epochs: response 1 (R1, 20–45 ms), classically referred to as spinal or short-latency motor response, response 2 (R2, 45–75 ms), response 3 (R3, 75–105 ms), and the voluntary response (VOL, 120–180 ms). R2 and R3 are collectively referred to as the long-latency motor responses. It is important to note that our principle analyses compared mean EMG within each predefined epoch and included data from both appropriate and inappropriate trials.

The receiver-operator characteristic (ROC) technique was used (Green and Swets 1966; Corneil et al. 2004) to determine the time point when each subject first showed changes in muscle activity as a function of target position. For each time step (1 ms), an ROC curve was generated to calculate the probability that an ideal observer could discriminate between the EMG responses for IN and OUT targets for each preview delay. Values of 0 and 1 represent perfect discrimination, whereas 0.5 represents chance.

Separation was defined as significant when the ROC remained above 0.75 for at least 5 consecutive time steps (Pruszynski et al. 2008). We were also interested in the point at which the ROC began to deviate from chance (Thompson et al. 1996), indicating when information about the spatial target began to emerge in the muscle activation pattern. This “ROC Knee” was calculated by performing a linear regression on the data ± 15 ms about the 0.75 discrimination point and finding the time that this line intersected pre-perturbation ROC levels (~ 0.5) (Pruszynski et al. 2008).

Results

Features of behavior

Figure 2 displays hand and joint kinematics from an exemplar subject for three selected preview delays (-2000 ms, -70 ms, $+90$ ms). The initial portions of the hand (Fig. 2a) and joint (Fig. 2b) trajectories were the same for both spatial targets (IN and OUT) because they were caused by the same mechanical perturbation.

When the visual target was presented 2000 ms before the perturbation (Fig. 2a, 2000 ms), hand trajectories quickly deviated toward the appropriate spatial target and hand positions were significantly different 350 ms after perturbation onset (99% confidence intervals did not overlap). Inspection of the mean elbow kinematics for the IN and OUT targets revealed that the subject began to deviate toward each respective target approximately 130 ms after perturbation onset (Fig. 2b, -2000 ms). Individual elbow traces for the IN target are shown in Fig. 2b. These trials were subdivided into *appropriate* and *inappropriate* trials according to the initial response made by the subject (Fig. 2b, thin lines, see “Methods”:) to determine whether the subjects early *behavioral* response was appropriate for the displayed target. Unsurprisingly, for the -2000 ms preview delay, the subject's initial response was always toward the *appropriate* (IN) target (Fig. 2b, -2000 ms, thin lines).

Strikingly, we found similar behavioral responses when the subject was given only 70 ms of target preview time (Fig. 2a, b -70 ms). The subject responded quickly to the perturbation by moving their hand toward the presented target (~ 140 – 150 ms post-perturbation, Fig. 2b, -70 ms), and achieved statistically different hand positions 350 ms following the perturbation (Fig. 2a, -70 ms); furthermore, very few responses were found to be initially *inappropriate* (4%). When the mechanical perturbation occurred prior to the presentation of the spatial target (i.e., a positive preview delay), subjects were inherently delayed in making an *appropriate* response because they could not predict which

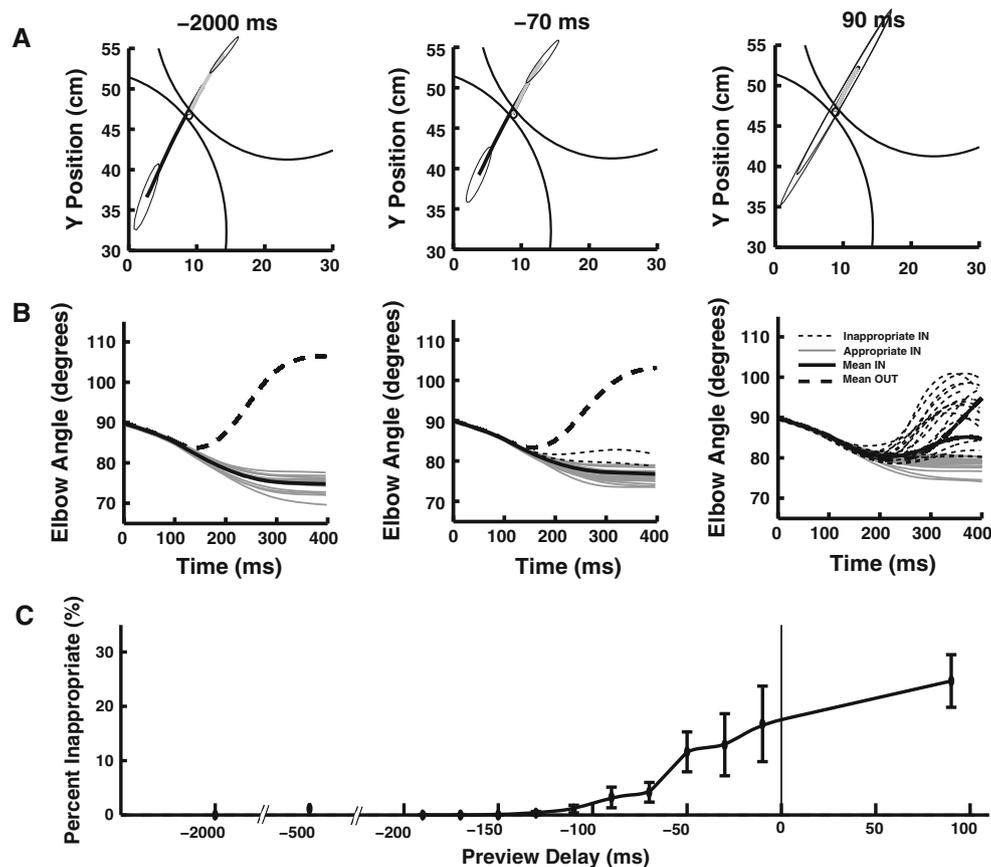


Fig. 2 Hand and joint kinematics for three selected preview delays. **a** Spatial hand position of an exemplar subject. Traces correspond to the mean response from the IN (gray) and OUT (black) target. End point ellipses represent the hand position of the subject 350 ms after perturbation onset (99% confidence interval). **b** Temporal kinematics for the elbow joint. The horizontal axis represents time after perturbation onset and the vertical axis represents the elbow angle that was initially 90 degrees at the time of perturbation onset. Thick black traces correspond to the mean elbow response for the IN (solid)

and OUT (dashed) conditions. Note that the IN and OUT targets required elbow flexion (indicated by a decrease in elbow angle, see Fig. 1a) and elbow extension, respectively. Thin lines represent individual traces for the IN condition. These trials were divided into *appropriate* (dark gray) and *inappropriate* (dashed black) responses (see “Methods”). **c** Average percentage of inappropriate responses across subjects plotted against preview delay (negative preview delay indicates that the target appears prior to perturbation onset). Error bars represent SEM

spatial target would eventually appear (Fig. 2a, b +90 ms). The subject generated a large percentage (25%) of *inappropriate* responses where their initial response was toward the OUT target even though the IN target eventually appeared (Fig. 2b, thin lines). As a result, hand trajectories remained undifferentiated even 350 ms after the perturbation and elbow kinematics did not begin to deviate until ~300 ms after perturbation onset.

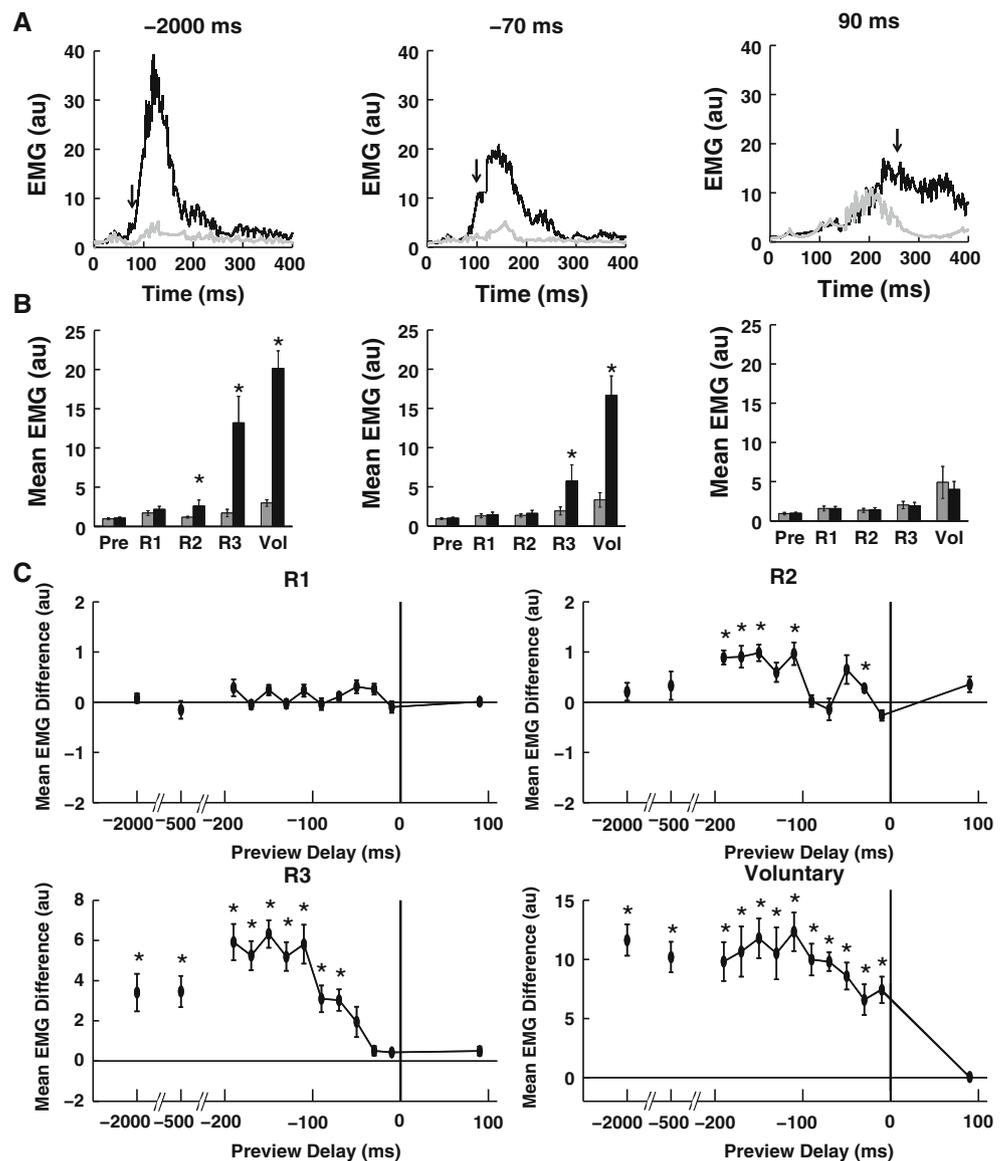
We examined subject performance for each preview delay by calculating the percentage of *inappropriate* trials as a function of preview delay (Fig. 2c). For preview delays between -2000 ms and 150 ms, subjects made essentially no *inappropriate* responses ($\ll 1\%$). For preview delays of 150 ms and -70 ms, *inappropriate* trials began to appear but remained quite rare ($< 10\%$). However, when the target preview time was decreased from 70 ms to 50 ms, we noted a sudden increase in the percentage of

inappropriate trials (-70 ms: 4%; 50 ms: 12%). Note that even at the +90 ms preview delay, the percentage of *inappropriate* responses was below 50%, indicating that subjects were biased toward the IN target (see “Discussion”).

Muscle activity

For all preview delays, the mechanical perturbation we applied to the elbow joint elicited a consistent multi-peaked muscle response in all collected muscle samples. A typical EMG response for the OUT (black) and IN (gray) target for three selected preview delays is shown in Fig. 3a (2000 ms, 70 ms, +90 ms). The peak amplitude of the EMG response for the OUT target was larger when the subject had a longer period of time to preview the target (Fig. 3a, -2000 ms: ~40 au, -70 ms: ~22 au, +90 ms:

Fig. 3 Exemplar and population analysis of EMG. **a** Exemplar EMG response. Traces correspond to mean muscle activity of an exemplar muscle (brachioradialis) for the IN (gray) and OUT (black) conditions. Zero indicates perturbation onset. Arrows point to the threshold discrimination time. **b** Each bar represents the EMG responses (mean \pm SEM) of the exemplar muscle within the given epoch for the IN (gray) and OUT (black) targets. Symbol indicates significant EMG increase for the OUT targets as compared to the IN targets (paired t test, $*p < 0.01$). Data is from the same exemplar subject as in (a). **c** Averaged EMG difference (OUT–IN) across 10 subjects for every preview delay condition for the four different epochs. Symbols indicate significant increase from the zero baseline (t test, $*p < 0.05$, Bonferroni corrected)



17 au), and the separation point between the OUT and the IN responses occurred earlier for longer preview delays (Fig. 3a, -2000 ms: ~ 70 ms, -70 ms: ~ 100 ms, $+90$ ms: ~ 220 ms post-perturbation).

We were primarily interested in determining how target-dependent muscle activity (difference in muscle activity between IN and OUT conditions) changed as a function of preview delay. Figure 3b shows the mean EMG response in each of the predefined epochs of the same exemplar muscle. When the subject had 2 s to preview the target (Fig. 3b, -2000 ms), the differences between the IN and OUT signals were significant (t test, $p < 0.01$) in both divisions of the long-latency epoch (R2; 45–75 ms, R3; 75–105 ms) and also in the voluntary epoch (VOL; 120–180 ms). When the preview delay was decreased to 70 ms, significant modulation in the VOL epoch was still

present, but only the R3 division of the long-latency epoch showed target-dependent EMG modulation (Fig. 3b, -70 ms). As expected, a further decrease in sensitivity to target location was evident when the target was presented after the perturbation onset such that we found no significant difference between the IN and the OUT EMG signal for any of the epochs (Fig. 3b, $+90$ ms). Similar results were found in an analysis of individual muscle samples (Table 1).

Figure 3c displays the mean EMG difference between the OUT and IN conditions across all subjects in every epoch, plotted against preview delay; the asterisk in the diagrams indicate that the difference between the OUT and the IN EMG response was significantly greater than zero (t -test, $p < 0.05$, Bonferroni corrected). In the short-latency epoch (R1), the EMG response for the IN and OUT target

Table 1 Subjects showing significant target-dependency by preview delay and epoch (total number of subjects = 10)

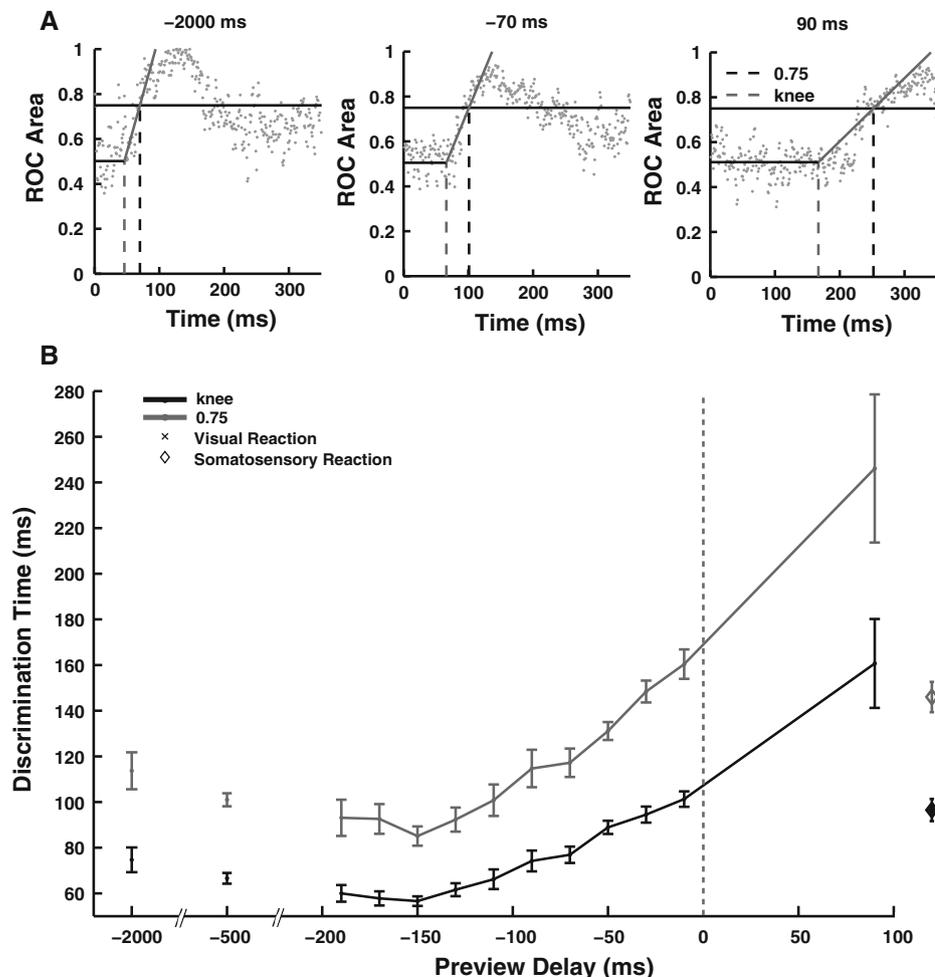
Preview delay (ms)	Number of subjects			
	R1	R2	R3	VOL
70	0	0	0	0
-10	0	0	0	5
-30	0	0	0	10
-50	0	0	1	10
-70	0	0	4	10
-90	0	0	7	9
-110	0	1	8	10
-130	0	1	10	9
-150	0	2	7	9
-170	0	2	8	8
-190	0	1	8	8
-500	0	0	8	10
-2000	0	1	5	10

was indistinguishable for all preview delays (Fig. 3c, R1). In the first division of the long-latency epoch (R2; 45–75 ms), significant muscle modulation appeared

for some of the preview delays (Fig. 3c). In the second division of the long-latency epoch (R3; 75–105 ms) and the voluntary epoch (VOL; 120–180 ms), target-dependent muscle activity modulation became more consistent. Target-dependent modulation was evident in all preview delays ending up to the -70 ms and -10 ms condition for the R3 and the VOL epoch, respectively. Overall, sensitivity to target location increased as the subject had more time to preview the target.

We used the ROC technique (2 Methods: Knee and Threshold, see “Methods”) to estimate when a subject showed target-dependent muscle activity, and termed this time point *discrimination time* (Pruszynski et al. 2008). For the exemplar muscle (Fig. 4a), when the time interval between target presentation and the perturbation was 2000 ms, the ROC response started to deviate from chance at about 50 ms (Knee analysis, see “Methods”) and crossed threshold around 80 ms after perturbation onset (Threshold analysis, see “Methods”). The discrimination time (both Knee and Threshold) for target-dependent modulation consistently increased as the subject had less time to preview the target before the perturbation onset

Fig. 4 ROC analysis of EMG data. **a** Temporal receiver-operator characteristic (ROC) analysis of EMG response between target locations for three selected preview delays. Vertical axes represent the ROC area, which indicates the probability that an ideal observer can identify the target position based on the EMG data. The horizontal line drawn at 0.75 represents an arbitrary significance threshold and the gray line is the regression used to determine the beginning of this trend (knee). **b** Mean discrimination time across subjects. Mean discrimination time obtained using Knee analysis (black) and threshold analysis (gray) of the ROC curve are plotted on the vertical axis and preview delays are plotted on the horizontal axis. Mean discrimination time for the control experiments are plotted on the right side of the graph (somatosensory task: diamond; visually cued task: x). Error bars represent SEM



(Fig. 4a -70 ms, $+90$ ms). Figure 4b shows the mean discrimination time (knee: gray, threshold: black) across subjects plotted against preview delays. A slight decrease in discrimination time was observed from the 2000 ms to the -170 ms preview delay conditions, followed by a consistent increase from the -150 ms preview delay.

Using the same technique, we also found the discrimination time for the two control experiments. For the somatosensory task, average discrimination times were 97 ms (knee) and 146 ms (threshold); and for the visual reaction task average discrimination times were 105 ms (knee) and 169 ms (threshold). The somatosensory task and the -2000 ms preview delay condition in the main experiment were directly comparable because subjects had full knowledge about the target location and had to react to a somatosensory stimulus. Consistent with our previous findings, we found the discrimination time in the -2000 ms condition (knee: 74 ms; threshold: 114 ms) was faster than in the somatosensory task.

Discussion

The goal of this study was to identify how quickly subjects can use visual information to selectively respond to mechanical perturbations applied to the upper limb. Prior to the beginning of each trial, subjects had no knowledge of target location. The instruction on how to respond to the perturbation on a given trial was delivered by displaying one of two spatial targets to the subject. Therefore, presentation of the target is equivalent to instructing the subject how to respond to the perturbation. By manipulating the time between target presentation and perturbation onset, we found subjects began to incorporate the visual information into their subsequent response to the perturbation ~ 70 ms after target presentation. This finding complements recent preliminary suggestions that long-latency responses reflect the ongoing accumulation of evidence favoring the execution of a movement toward one target or the other (Wolpert et al. 2009).

Consistent with our previous work (Pruszynski et al. 2008), and also with many other studies (Crago et al. 1976; Hammond 1956; Marsden et al. 1972; Rothwell et al. 1980), we did not observe target-dependent muscle activity in the short-latency epoch (R1). This does not imply modulation of short-latency response is not possible. In fact, systematic changes in the R1 epoch have been shown in similar tasks but such changes generally require extensive training (Christakos et al. 1983) in a single task and direct reinforcement of R1 magnitude (Wolf and Segal 1996; Wolpaw et al. 1983; Wolpaw and O'Keefe 1984). In our present experiment, these conditions were not met as subjects were only given a few practice trials prior to the

experiment, the trial order was randomized and subjects did not receive feedback about their muscle activity. It is important to emphasize that the lack of modulation in the R1 epoch observed in this task is contrasted by dramatic changes for certain motor behaviors. For example, many studies have demonstrated substantial changes in the R1 response over the course of cyclical movements such as gait (Forssberg et al. 1975; Akazawa et al. 1982; Capaday and Stein 1986; Zehr et al. 2003), sinusoidal tracking (Dufresne et al. 1980; Johnson et al. 1993), and hand cycling (Zehr and Chua 2000).

In contrast to the short-latency response, we did observe modulation in the long-latency and voluntary responses. The minimal latency for modulating the R2, R3, and VOL epochs was -110 ms, -70 ms, and -10 ms, respectively, when measured relative to perturbation onset (Fig. 3c). Importantly, this means, the time from visual presentation to the beginning of each predefined epoch was ~ 140 ms, suggesting the time required to modulate long-latency and voluntary responses is approximately the same.

A coupling between voluntary and long-latency motor responses has been previously suggested using very different paradigms (Bonnet 1983; Mutha et al. 2008; Rothwell et al. 1980). For example, in the Bonnet (1983) study, subjects started the task by pointing at a central target. A warning signal (LED target) was then presented either on the right or left side of the central target. The location of the warning signal carried information about the subsequent movement the subject will have to make (i.e., point to the left or right). Subjects were instructed to maintain central position when they saw the warning signal. At 1 s after the warning signal, a response signal (LED light) was presented instructing the subject to move quickly to the target. During the 1 s preparatory period before the onset of the response signal, a perturbation could occur. Subjects were asked to return their hand to the central position when they felt the perturbation. Bonnet found that rapid motor responses were not influenced by the impending direction of movement when the perturbations were applied 800 ms before the response signal. When the perturbations were applied 400 ms before the signal, motor responses at 60 – 80 ms were modulated by the impending movement direction, whereas responses at 40 – 60 ms were only partially modulated. Responses at the 20 – 40 ms epoch were never modulated by the impending movement direction. This result shows that engagement of the voluntary motor system also influences long-latency responses to mechanical perturbations.

The work of Mutha and colleagues (2008) also investigated the influence of visual task information on the modulation of muscular responses to a mechanical perturbation. In that study, subjects made reaching movements to a target which could sometimes jump to a new location at

movement onset. On some trials, the target jump was accompanied by a mechanical perturbation to test whether the new target position was incorporated in the stretch response. Consistent with our findings, the authors demonstrated that a 100 ms delay between the target jump and the mechanical perturbation was sufficient to cause changes in the long-latency stretch response. It is important to emphasize, however, that the authors did not manipulate the timing between the perturbation and target jump to determine the minimal latency taken to elicit changes. Furthermore, their approach could not address this question at longer preview delays as their subjects were actively engaged in a movement and would begin a corrective response to the new target location within ~ 200 ms. These visual corrections would cause large changes in muscle and mask any changes associated with changing feedback responses. Our study did not have this limitation because, in our postural task, the cue to begin the movement was the perturbation not the appearance of the visual target.

We have suggested that the many similarities between long-latency and voluntary motor responses are likely due to primary motor cortex (M1) participating in both processes (Scott 2004). Neurophysiological support for this hypothesis is provided by the fact that many neurons in M1 that are active during voluntary motor tasks also respond quickly to mechanical perturbations applied to the limb (Herter et al. 2009; Thach 1978; Wolpaw 1980). In fact, such overlap between voluntary and rapid feedback responses appears much greater than the overlap in neural processing in M1 across two voluntary motor tasks, posture versus reaching (Kurtzer et al. 2005). Alternatively, the similarity in timing that we observed may reflect that similar signals arrive at different parts of the motor system at roughly the same time (Lourenco et al. 2006; Kimura et al. 2006; Shemmell et al. 2009). Further research is required to more directly test how neural processing in regions such as primary motor cortex participates in both voluntary and rapid perturbation responses.

Hastened motor responses for short-visual preview delays

One notable finding in this study is that all the participants were biased toward the IN target for short-preview delays. Such a strategy is energetically efficient as the subject can succeed for the IN target with relatively low motor outputs, whereas responding to the OUT target requires a large motor response to overcome the applied perturbation and move the arm to the target. Indeed, the analogous verbal instructions for the OUT and IN target are “resist” and “do not intervene/yield”, respectively (Colebatch et al. 1979; Crago et al. 1976; Hammond 1956; Rothwell et al. 1980). The fact that subjects preferentially plan to “yield” is

consistent with reports that motor outputs are more likely to be triggered by a startling acoustic signal as the subject is given more time to prepare the movement (Carlsen and Mackinnon 2010; Mackinnon et al. 2006). The implication in both of these experimental contexts is that subjects plan to generate a default response (i.e., do little), and only change this plan to the more costly option if they have sufficient information and time to do so.

Perhaps, the most interesting observation in this study was that subjects appeared to respond faster, when the visual target was presented only a short time before perturbation onset (~ 150 ms) as compared to when they had more time to view the target (2 s). This hastening of the motor response may be due to the effect of multisensory integration. When two or more sensory modalities are presented at about the same time, manual response latencies can be much shorter than to either unisensory stimuli presented alone (Diederich and Colonius 2004; Forster et al. 2002; Giard and Peronnet 1999; Lamarre et al. 1983). In oculomotor tasks, this response hastening is caused by sensory integration primarily in the superior colliculus where single neurons respond to stimuli from two or more modalities, including visual, auditory, and/or somatosensory (Meredith and Stein 1983; Meredith and Stein 1986; Rowland et al. 2007; Meredith et al. 1987; Wallace et al. 1996; Bell et al. 2005; Wallace et al. 1998). For manual tasks, several frontal lobe areas have been shown to contain bimodal neurons that respond to visual and somatosensory stimuli (Rizzolatti et al. 1981a, b; Graziano et al. 1994).

The fastest response times generally occur when there is maximal temporal overlap of unisensory response profiles arriving at these multimodal neurons (Lamarre et al. 1983; Meredith et al. 1987). This inter-stimulus presentation delay that produces the largest performance enhancement can be predicted to approximately equal the difference in mean response times to unisensory stimuli alone (Hershenson 1962; Meredith et al. 1987; Diederich and Colonius 2004). Since the difference in unisensory response times can be calculated using our visual (105 ms) and somatosensory (97 ms) control experiments, simple multi-sensory integration would have predicted that subjects discriminate fastest when the target presentation preceded the perturbation by 10–20 ms. (difference in response time of the two unisensory control experiments: 8 ms, knee; 23 ms, threshold). However, the fastest discrimination occurred when the stimuli were offset by 150 ms, suggesting that the integration was not caused by simple synchronicity of sensory inputs.

There are fundamental differences between our experimental paradigm and that of previous studies, which could have caused the discrepancy in identifying the fastest response. In the present experiment, only the visual stimulus carried information about the goal, the somatosensory

stimulus served as the go signal. Most previous studies on multisensory integration rely on both stimuli carrying relevant goal information. On the other hand, hastened motor responses have been observed when non-target stimuli (auditory and somatosensory) were delivered before the presentation of a visual target in oculomotor tasks (Amlôt et al. 2003; Diederich et al. 2003; Frens et al. 1995; Nozawa et al. 1994). These studies are similar to the current study insofar as an orienting stimulus was delivered shortly before the subject had to respond, indicating to them that they would be required to respond shortly. Due to the large number of conditions, the visuospatial target in the current experiment was not a very reliable predictor of when subjects would have to respond, but it is possible that it sufficiently prepared subjects to cause hastened motor responses (Rothwell et al. 1980).

Ultimately, the fact that we observed a hastened response for the ~ 150 ms PD indicates that this timing put the motor system into a preparatory state better suited to execute the motor response. Many studies have demonstrated that activity of single neurons in primary motor cortex and dorsal premotor cortex show preparatory activity prior to movement onset (Tianji and Evarts 1976; Weinrich and Wise 1982; Weinrich et al. 1984; Godschalk et al. 1985), and that this activity is predictive of reaction time (Riehle and Requin 1993; Bastian et al. 2003). More recently, it has been suggested that neural variability across the population of neurons in dorsal premotor cortex provides a signature of motor preparation (Churchland et al. 2006). In this experiment, monkeys were presented with a visual target, which instructed them where to reach. After some delay, the target either stopped vibrating (visual jitter) or was slightly enlarged, which cued the monkey to execute a reach toward the target. The principle finding was that the variability of the neural population in premotor cortex decreased with preparation time and that the neural variability predicted the subsequent reaction time. Interestingly, the reduction in neural variability that they observed attained a relatively stable level within ~ 150 ms of target presentation and was subsequently followed by a slower increase in neural variability (see Fig. 6 in Churchland et al. 2006). The temporal progression of neural variability in their reaction time reaching task is similar to the progression of task-dependent modulation that we observe in the long-latency epoch, suggesting that the timescale of preparing the long-latency response is similar to preparing a voluntary movement. It is natural to speculate that cortical planning areas, such as premotor cortex, are initially engaged by the salient appearance of a spatial target, and quickly work to setup a the long-latency response but that attentional mechanisms wane as time passes yielding a slow drift back toward unpreparedness (Pashler 1999). In addition to neurophysiological studies,

future work could explore this possibility by testing whether the distribution of possible preview delays has an effect on preparing the long-latency response. For example, the nervous system may substantially delay preparing a response if the preview delays are always greater than one second. In that scenario, the one second preview delay condition may appear just as hastened as the 150 ms preview delay condition in the present experimental conditions because delaying preparation may also delay the subsequent drift.

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Conflict of interest S.H.S. is associated with BKIN Technologies, which commercializes the KINARM device used in this study.

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