COGNITIVE NEUROSCIENCE

Stimulus-locked responses on human arm muscles reveal a rapid neural pathway linking visual input to arm motor output

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Abstract

Previous studies have demonstrated that humans are sometimes capable of initiating arm movements towards visual stimuli at extremely short latencies, implying the presence of a short-latency neural pathway linking visual input to limb motor output. However, little is known about the neural mechanisms that underlie such hastened arm responses. One clue may come from recent demonstrations that the appearance of a visual target can elicit a rapid response in neck muscles that is time-locked to target appearance and functionally relevant for orienting gaze (head and eye) towards the target. Because oculomotor structures thought to contribute to 'visual responses' on neck muscles also target some arm muscles via a tecto-reticulo-spinal pathway, we hypothesized that a similar visual response would be present in arm muscles. Our results were consistent with this hypothesis as we observed the presence of rapid arm muscle activity (< 100 ms latency) that was time-locked to target appearance and not movement onset. We further found that the visual response in arm muscles: (i) was present only when an immediate reach towards the target was required; (ii) had a magnitude that was predictive of reaction time; (iii) was tuned to target location in a manner appropriate for moving the arm towards the target; and (iv) was more prevalent in shoulder muscles than elbow muscles. These results provide evidence for a rapid neural pathway linking visual input to arm motor output and suggest the presence of a common neural mechanism for hastening eye, head and arm movements.

Introduction

Under most experimental settings the time required to initiate a visually-guided reach is long, variable and sensitive to a host of experimental factors such as stimulus salience and the number of possible responses (Welford, 1980). Interestingly, several manipulations can substantially reduce response times. For example, when subjects are already reaching towards a target, they are capable of very fast corrections to sudden target displacements (Goodale *et al.*, 1986; Pelisson *et al.*, 1986; Day & Lyon, 2000; Pisella *et al.*, 2000; Franklin & Wolpert, 2008). Even when a movement has not yet been initiated, inserting a temporal gap between the disappearance of a central marker and the appearance of the visual target can substantially hasten arm response times (Fischer & Rogal, 1986; Bekkering *et al.*, 1996; Gribble *et al.*, 2002).

Although such rapid responses imply the presence of a short-latency neural pathway linking visual input to arm motor output, little is known about the underlying neural circuitry. One clue may come from recent experiments studying gaze shifts that demonstrate the presence of hastened eye movements and neck muscle responses that are time-locked to visual target presentation (Corneil *et al.*, 2004, 2008). Such responses are thought to form part of the visual-grasp reflex that orients the gaze axis (eyes and head) to novel visual stimuli (Hess *et al.*, 1946) and probably reflect rapid processing of visual information in oculomotor structures (Grantyn & Berthoz, 1985; Schmolesky *et al.*, 1998; Munoz *et al.*, 2000; Corneil *et al.*, 2002), including the superior colliculus (Dorris *et al.*, 1997). Because oculomotor structures also target arm muscles via polysynaptic tecto-reticulo-spinal projections (Illert *et al.*, 1978; Werner, 1993; Stuphorn *et al.*, 1999), we hypothesized that the sudden appearance of a visual target would also elicit stimulus-locked responses on arm muscles. Such a result would implicate a common neural mechanism for hastening eye, neck and arm responses towards a visual stimulus.

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We used a straightforward experimental approach whereby subjects maintained their hand at a central marker and made fast reaches towards suddenly appearing peripheral targets. Importantly, the central marker disappeared at 200 ms prior to the presentation of the target, which is known to potentiate the eye (Fischer & Boch, 1983) and head (Corneil *et al.*, 2007) components of the visual-grasp reflex and yield faster response times for arm movements (Gribble *et al.*, 2002). Consistent with our hypothesis, these conditions yielded rapid arm muscle responses (< 100 ms) that were time-locked to target appearance and not movement onset. Further experiments revealed that the presence of such 'visual responses' was critically linked to the immediacy of movement, response magnitude was predictive of reaction time, the response was tuned to the target's spatial location, and it was more prevalent on shoulder than elbow muscles. Taken together, our results provide new insight into the neural pathways linking visual input and motor output and emphasize the close ties between oculomotor and limb motor processing when responding to the sudden appearance of a behaviorally-relevant visual stimulus.

Materials and methods

Subjects

A total of 14 healthy participants (3 male, 11 female, aged 20–26 years, self-declared right-handers) took part in the experiments. Subjects provided written consent, were paid for their participation and were free to withdraw from the study at any time. The protocol was approved by the Health Sciences Research Ethics Board at Queen's University and conformed to the Helsinki Declaration.

Equipment

Arm kinematics were recorded using KINARM (BKIN Technologies, Kingston, ON, Canada), a robotic exoskeleton that records shoulder and elbow joint kinematics in the horizontal plane (Scott, 1999; Pruszynski *et al.*, 2008). Hand position and visual targets were projected above the arm in the plane of the task. Direct vision of the arm was occluded using a shield below the projection screen and a cloth bib. To account for variable delays in the projector between sending the command to draw a target and its subsequent physical appearance on the screen, visual target appearance was detected using a photodiode. All data were subsequently aligned to the photodiode signal.

Muscle activity

Muscle activity [i.e. electromyography (EMG)] was recorded using fine-wire electrodes (Chalgren Enterprises, Gilroy, CA, USA) inserted into muscles of the upper limb including flexors and extensors of the shoulder and elbow (Fig. 1A). In the immediate and delayed reaching task, we recorded from the brachioradialis (elbow flexor), triceps lateral (elbow extensor), pectoralis major (shoulder flexor) and deltoid posterior (shoulder extensor). For the spatial tuning task, we recorded from the pectoralis major and deltoid posterior. It is important to note that we used fine-wire electrodes because pilot studies using surface electrodes were almost universally unsuccessful at yielding a visual response (four positive results from 108 total muscle samples; brachioradialis, 0∕27; triceps lateral, 1∕27; posterior deltoid, 3∕27; pectoralis major, 0∕27).

Electrodes were inserted into the muscle belly oriented along the muscle fibres and spaced ∼1 cm apart. Analog muscle activity signals were amplified (gain, 10^3 or 10^4) and band-pass filtered (20–450 Hz) by a commercially available system (Bagnoli, Delsys, Boston). Prior to analysis, muscle activity was digitized (1000 Hz), filtered (two-pass Butterworth, second order, 20–450 Hz) and then full-wave rectified. Further details can be found in our previous publications (Pruszynski *et al.*, 2008, 2009).

As initial studies indicated that our principal signal of interest (the visual response) was quite small, we tended to use amplifi-
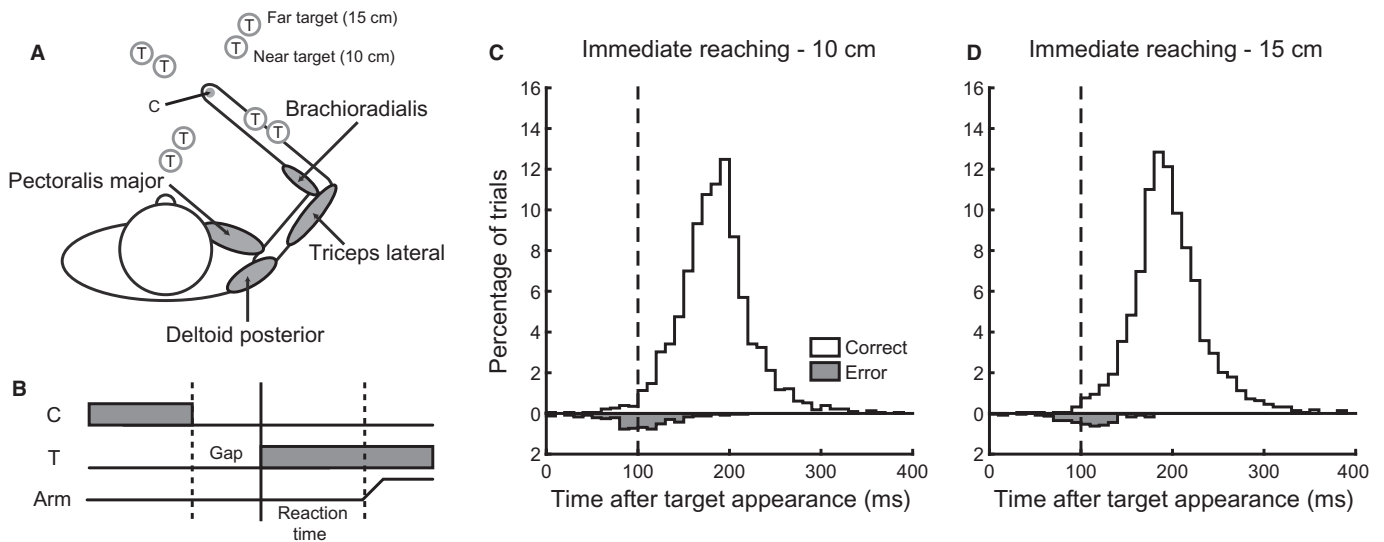

FIG. 1. Experimental paradigm and voluntary reaction time. (A and B) Subjects sat in the experimental apparatus with their hand at a central marker (labeled C) and reached to one of the presented peripheral targets (T) upon its appearance. The central marker always disappeared at 200 ms prior to peripheral target presentation (gap period). (C) Histogram of manual reaction times (10 ms bins) for the immediate reaching task (near target, 10 cm distance) across all subjects. The open histograms, drawn above zero, represent the number of trials in the correct direction, whereas the shaded histograms, drawn below zero, represent the number of trials in the incorrect direction. Dashed vertical line indicates the statistically determined minimum voluntary reaction time. (D) Same format as C except for the far target (15 cm distance).

cation settings that approached the functional range of the amplifier during voluntary movements to the targets (± 5 V post-amplification). These settings optimized our sensitivity but occasionally saturated that amplifier, compromising muscle recordings in those trials where saturation occurred. Therefore, any trials that included muscle activity exceeding ± 4.5 V post-amplification were deemed to be saturated and were rejected from further analysis (13% of trials).

Experimental tasks

Immediate reaching

Each trial began with the appearance of a central marker in front of the subject. Subjects ($n = 8$) moved their right hand to the central marker and were required to maintain this position for a period of 1–2 s (randomized). To encourage fast reaction times, the screen was then blanked (including the hand feedback indicator) for a 200 ms gap period, after which a new target (1 cm radius) appeared in the periphery (Fig. 1B). The insertion of the gap period between fixation target disappearance and peripheral target appearance is known to decrease reaction times for arm movements (Fischer & Rogal, 1986; Gribble *et al.*, 2002). Subjects were required to move their hand to the peripheral target within 500 ms after its appearance and were provided with feedback indicating success or failure at the end of each trial.

The task was performed in blocks of 40 trials consisting of 10 reaches to each of the four target directions in random order. Targets were placed around the central marker so that the upper-left and lower-right targets were roughly aligned along the axis of the forearm and the lower-left and upper-right targets were perpendicular to the forearm (Fig. 1A). The central marker was positioned at the tip of the subject's index finger when shoulder and elbow angles were 45° and 90°, respectively. Each subject performed eight blocks with near (10 cm distance from fixation marker) targets and eight blocks with far (15 cm) targets for a total of 640 trials.

Delayed reaching

A subset of subjects ($n = 6$) who participated in the immediate reaching task completed a second task (in the same session) that dissociated the appearance of the peripheral target from reach initiation. In this task, the peripheral target appeared following the central hold period, but the central marker remained for a delay period of 1–2 s. The disappearance of the central marker was the cue to initiate the reach (GO signal) to the target. As before in the immediate reaching task (see above), subjects were encouraged to reach to the peripheral target as quickly as possible following the GO signal. For a trial to be deemed successful, they were required to move their hand to the peripheral target within 500 ms after the GO signal. Feedback indicating success or failure was provided at the end of each trial. Leaving the central marker during the delay period was treated as a timing error. Subjects performed 8 blocks of 40 trials consisting of 10 reaches to each of the four target directions at the far distance.

Spatial tuning

Spatial tuning of muscle activity was assessed using a higher density array of possible target locations. A separate group of subjects ($n = 8$) performed the immediate reaching task using 16 peripheral targets (distance, 10 cm) that were uniformly distributed around the central marker, and thus separated by 22.5°. Subjects performed 20 reaches to each target for a total of 320 trials.

Data analysis

Manual reaction time

The manual reaction time was defined as the time from peripheral target appearance (immediate task) or central marker disappearance (delayed task) to the point of reach initiation, when tangential hand velocity exceeded 5% of its peak value. Movements were considered to be in the correct direction if the direction of hand movement at 100 ms after manual reaction time was within ± 45° of the peripheral target. Trials with incorrect initial hand direction were excluded from further analysis.

Subjects occasionally made anticipatory reaching movements that occurred too quickly to be guided by target appearance. To calculate the minimum response time, the manual reaction times for all trials in the immediate reaching task (correct and incorrect initial directions, all subjects) were calculated and binned in 10 ms increments (range, 0–400 ms after target appearance). A one-tailed binomial test (Siegel & Castellan, 1988) was applied to each bin to determine when the response directions were above chance levels (1 : 4). The minimum reaction time was chosen as the time when five consecutive bins showed significant ($P < 0.01$) increases from chance. Any movement made before this time was rejected from further analysis. Note that determining voluntary reaction time for each individual was not possible because of the relatively low number of anticipatory reaches generated by each subject.

Visual response

The occurrence and timing of a visual response on arm muscles was determined by a procedure previously described in detail (Corneil *et al.*, 2004) that is similar to that used in several other studies (Bradley *et al.*, 1987; Thompson *et al.*, 1996; Pruszynski *et al.*, 2008). For every muscle sample, we compared the EMG activity for each target and the target in the opposite direction. Muscle activity for the pair of targets was sorted according to manual reaction time and then split into two equally-sized groups representing the fastest and slowest half of manual reaction times. For each half (slowest/fastest), we used receiver-operating characteristic (ROC) analysis (Green & Swets, 1966) to calculate the ability of an ideal observer to discriminate between the target directions based on the muscle activity. This procedure was performed for every sample (1 ms) between 40 and 300 ms after peripheral target appearance. Thus, multiple trials were used to generate a time-series of ROC values that represents the probability of determining the target being reached towards based on the EMG activity. The same procedure was performed independently on the slowest and fastest halves of trials.

The discrimination time, the time at which a reliable choice of targets could be made, was chosen as the time when the ROC value was $> 2/3$ or $< 1/3$ for at least five out of the next 10 ms. In ROC analysis, a value of 0.5 indicates that an ideal observer could not discriminate between the EMG activity, and an ROC value of 0 or 1 indicates perfect discrimination. Note that we chose threshold levels of $1/3$ and $2/3$, rather than $1/4$ and $3/4$ as are often used, because we were primarily interested in estimating the onset of discrimination; that said, our results were not qualitatively changed by modestly changing the threshold or timing parameters.

To determine if the EMG activity was linked to peripheral target appearance or the onset of hand motion, we compared the discrimination time for the average manual reaction time in the slow and fast groups by fitting a line to the data. Note that there is only a single data point for each group because these values were generated via the ROC procedure described above, which itself incorporates multiple trials. If the slope of the line is 1 (angle, 45°), then the discrimination time

co-varies perfectly with manual reaction time, and so the onset of EMG is time-locked with the onset of movement. If the slope of the line is infinity (angle, 90°), then the discrimination time remains the same regardless of manual reaction time, and the onset of EMG is time-locked to the appearance of the peripheral target (Thompson *et al.*, 1996). That is, a slope of infinity indicates that both slow and fast reaction time groups have the same EMG onset, suggesting that this activity is closely coupled to the presentation of the target and not the initiation of movement. We classified the results as visually related if the line of fit was > 2.41 (angle, 67.5°, halfway between 45° and 90°).

Correlation of visual response magnitude with manual reaction time

In order to explore the relationship between the visual burst and subsequent voluntary movement, we correlated the amplitude of the visual response with manual reaction time on a trial-by-trial basis. For this analysis, we defined a visual response window from 75 to 100 ms after peripheral target presentation.

Spatial tuning of the visual response

For each muscle sample, we calculated the preferred direction (PD) for the visual response (75–100 ms after target presentation) and move-ment-related activity (10 ms before and after movement onset) using the plate method (Gribble & Scott, 2002), an analytical approach for determining the tuning properties of a dataset without assumptions about the underlying tuning function. Confidence intervals for the population of PDs were calculated using standard methods from directional statistics (Mardia & Jupp, 2000). We were primarily interested in the similarity of PDs across epochs, which was assessed via a paired t-test (visual response PD – movement-related PD $\neq$ 0, $P < 0.05$). We further determined whether the population of PDs was unimodally distributed by using a Rayleigh test.

Results

Subject performance and features of the visual response

In the immediate reaching task, subjects made reaches from a central marker to one of eight (four directions, two distances) suddenly-appearing peripheral targets distributed uniformly around the hand. They had little difficulty reaching the targets within the imposed speed and accuracy constraints and almost always reached towards the correct target (near target, 94%; far target, 96%). Subjects occasionally initiated movements very quickly, which probably reflected a guess of target direction rather than a response triggered by the appearance of the visual stimulus (Fig. 1C and D). We empirically determined the minimum response time to the visual stimulus by finding the value of manual reaction time when the probability of reaching the correct target was significantly above chance levels of 25%. Based on this analysis, movement onsets occurring < 100 ms following target presentation were deemed anticipatory and excluded from further analysis (near targets, 4% of all trials; far targets, 2%). The 100 ms cut-off therefore set the minimal latency for a visual response to traverse the neural circuit from the retina to arm muscles and contribute to the initiation of a visually-guided reaching movement.

For all collected muscle samples, we found robust muscle activation that preceded movement onset that included excitation of agonist muscles, which move the arm towards the target, and inhibition of antagonist muscles, which oppose movement towards the target. Not surprisingly, the onset of this muscle activity reliably preceded the initiation of movement (Fig. 2).
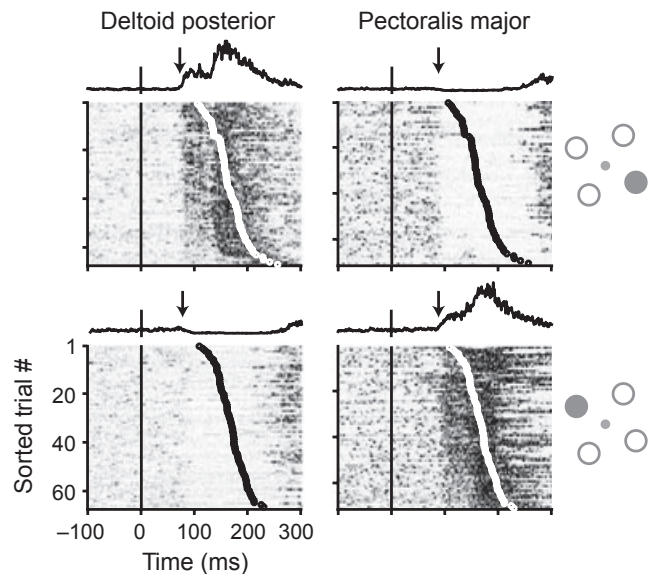

FIG. 2. Exemplar muscle activity in the immediate reaching task. Individual muscle recordings obtained from two simultaneously recorded muscles, the deltoid posterior and pectoralis major. Panels depict activity for the given target location and muscle sample. Data are aligned on visual target presentation (solid vertical line) and sorted according to manual reaction time (white or black dots within the rasters). Each panel presents rasters of rectified EMG activity from individual trials (darker colors indicate greater EMG activity) and the trace above the rasters is the mean EMG. The arrows indicate visual response onset.

Critically, we found the occasional presence of extremely rapid muscle activity that was time-locked to the appearance of the visual target regardless of when the movement was initiated. Such time-locked muscle activity, which we refer to as the visual response, appeared as a vertical band of activation at a fixed latency following target appearance (arrows in Fig. 2). The visual response sometimes appeared distinct from movement-related activity, especially for trials with long manual reaction times (see 10 slowest reaction time trials at the bottom of Fig. 2), when the visual response was separated from movement-related muscle activity by a period of muscle silence. For trials with shorter manual reaction times (see 10 fastest reaction time trials at the top of Fig. 2), muscle activity following the visual response generally did not return to baseline prior to the onset of movement-related activity. As with movement-related activity, the visual response demonstrated both excitation and inhibition as appropriate for the mechanical action of the muscle. For example, the visual response of the deltoid posterior (Fig. 2, left column) was clearly excited for the lower-right targets (requiring largely shoulder extension) and inhibited for the upper-left targets (requiring largely shoulder flexion) at approximately 75 ms following stimulus onset. The opposite pattern was apparent for the pectoralis major (Fig. 2, right column).

We quantified the presence of the visual response by calculating the discrimination time, the time when an ideal observer could reliably discriminate between muscle activity occurring for targets in opposite directions. Muscle activity time-locked to visual target appearance would result in discrimination times that were the same for the slowest and fastest movement onset trials (and thus appear as vertical lines on Fig. 3A and B). In contrast, discrimination times that co-varied with movement onset would not permit us to unambiguously determine the presence of stimulus-locked muscle activity (and would appear as lines with unity slope on Fig. 3A and B). We categorically defined those lines with slopes > 67.5° [halfway between 45° (unity) and 90° (vertical)] as stimulus-locked.
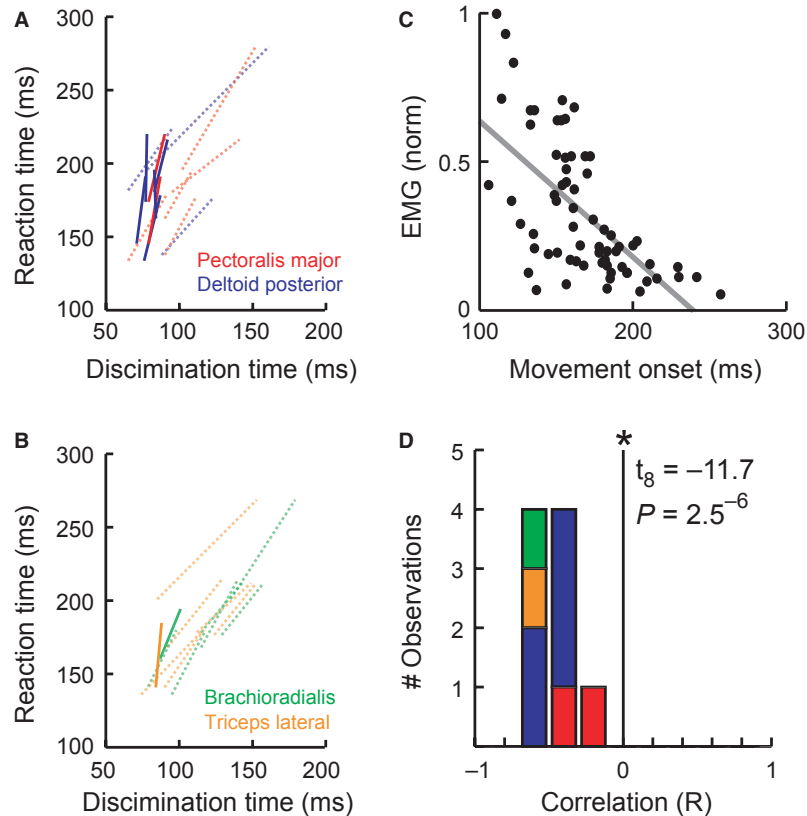
FIG. 3. Determination of visual burst and correlation with manual reaction time. We calculated the onset of EMG activity for each shoulder (A) and elbow (B) muscle sample. Each line connects the discrimination time of EMG activity for the slowest and fastest half of manual reaction times. Vertical lines indicate that the EMG onset time was independent of manual reaction time (and thus indicate the unambiguous presence of a visual response) and lines with unity slope indicate that the EMG onset was related to movement onset. Solid lines are those whose slope exceeded $67.5°$, which we used as a threshold determining the presence of the visual response (see Materials and methods). (C) For a muscle sample that demonstrated a visual response, we correlated movement onset time with EMG activity in the visual burst window (75–100 ms). Each point represents a single trial and the grey line is the result of a linear correlation. (D) The correlation coefficients of all muscle samples demonstrating a visual response. Each color represents one of the four collected muscles. Red = Pectoralis Major; Blue = Deltoid Posterior; Green = Brachioradialis; Orange = Triceps Lateral.

For the example muscle (deltoid posterior), we determined the presence of a visual response for the lower-right target at 74 ms post-target appearance and the upper-right target at 84 ms post-target appearance. Across the population of muscles (Fig. 3), we focused our analysis on the target position that resulted in the largest movement-related activity (deltoid posterior, lower-right; pectoralis major, upper-left; triceps lateral, upper-right; brachioradialis, lower-left). For the near target, we identified unambiguous visual responses in 7 of 16 (44%) shoulder muscle samples and 2 of 16 (13%) elbow muscle samples, indicating that the response was significantly more reliable at the shoulder than the elbow (2×2 contingency table, Pearson chi-square, df = 1, $P = 0.048$). Similar results were found for the far target [shoulder, 6 of 16 (38%); elbow, 1 of 16 (6%), $P = 0.033$]. Discrimination times were not significantly different (paired t-test, $P > 0.1$) for near (91 ± 18 ms, mean $\pm$ SD) and far (93 ± 22 ms) targets. Importantly, these discrimination times were < 100 ms and therefore capable of causally contributing to the shortest-latency movements to visual targets.

Visual response magnitude correlates with manual reaction time

The magnitude of the visual response was related to manual reaction times, suggesting a functional consequence for such activity. This can be seen in the example muscle samples (Fig. 2) where a smaller visual response accompanied trials with longer reaction times. We correlated visual-response magnitude (muscle activity 75–100 ms post-stimulus) and manual reaction time for the muscle samples that unambiguously demonstrated visually-related activity. Figure 3C illustrates such a correlation for a single exemplar muscle sample and Fig. 3D summarizes the correlations across the population of muscle samples. Each of the muscle samples demonstrated a significant negative correlation for both the near (average correlation coefficient, $r = -0.49 \pm 0.12$, mean $\pm$ SD) and far (-0.52 ± 0.11) targets, which yielded a significantly negative correlation across the population of muscles (t-test, $r \neq 0$; near: $t_8 = -11.8$, $P < 1 \times 10^{-3}$; far: $t_6 = -12.5$, $P < 1 \times 10^{-3}$) (Fig. 3D). Thus, the magnitude of the visual response appeared to have a causal effect on reaction time.

Visual response is absent when movement is not imminent

To determine whether the immediacy of movement was required to elicit the visual response, a subset of subjects performed a modified reaching task that dissociated the appearance of the peripheral target and the initiation of movement (delayed reaching). Note that these subjects performed both reaching tasks (immediate and delayed) in the same experimental session. In brief, a peripheral target appeared but the central marker remained illuminated for a period of 1–2 s; the disappearance of the central marker was the cue to initiate the reach. Under these conditions, no muscle samples (0 of 24) yielded
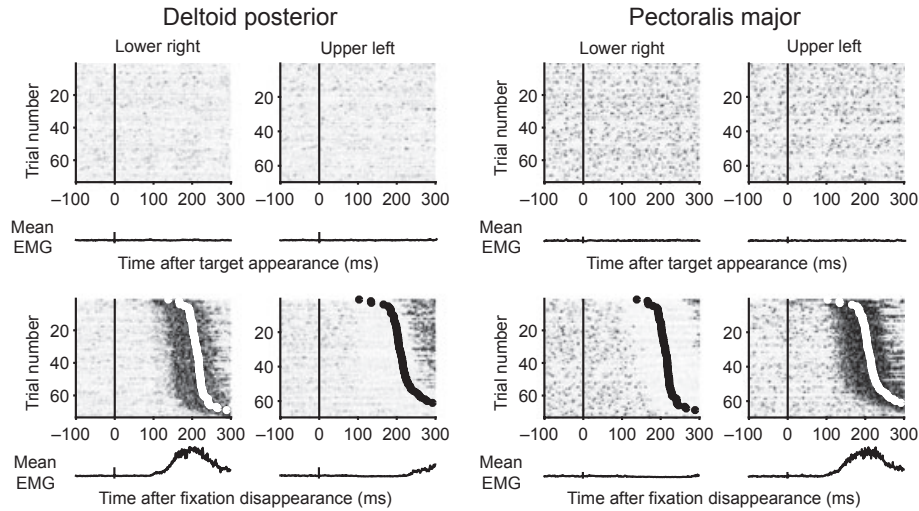
FIG. 4. Exemplar muscle activity in the delayed reaching task. Individual muscle recordings obtained from two simultaneously recorded muscles, the deltoid posterior and pectoralis major. Each panel presents rasters of rectified EMG activity from individual trials (darker colors indicate greater EMG activity) and the trace below the rasters is the mean EMG. Top row depicts activity for the given target location; data are aligned on peripheral target presentation (solid vertical line) and sorted by manual reaction time (white or black dots within the rasters on bottom row). Bottom row depicts the same data but they are aligned on central fixation disappearance, which is the GO signal in the delayed reaching task.

unambiguous visual responses (Fig. 4), suggesting that such a response is only present when directional visual target information is tightly coupled with movement. Note that we found no statistical difference in preparatory muscle activity between the delayed and immediate reaching tasks (paired *t*-test, $P > 0.1$). Therefore, the short-latency visual pathway was only effective at influencing muscle activity when subjects were ready to make a movement.

Spatial tuning of the visual response

Our results suggested that the visual response in the immediate reaching task was a coordinated response because it included both excitation of agonists and inhibition of antagonists that were appropriate for a given muscle's mechanical action rather than a global facilitation for all target locations (Fig. 2). To characterize the degree of spatial coordination of the visual response, subjects were asked to reach to 16 potential targets (distance, 10 cm; targets distributed equally every 22.5°) so that we could calculate spatial tuning functions relating muscle activity and spatial target direction. Because our initial results suggested that stimulus-locked responses were more prevalent in shoulder muscles, we focused recordings on the deltoid posterior and pectoralis major.

On average, activity within the visual response window (75–100 ms after target appearance) demonstrated PDs of 313 ± 34° (mean ± SD) and 197 ± 23° for the deltoid posterior and pectoralis major, respectively. PDs for movement-related activity were very similar: 325 ± 4° and 160 ± 2° for the deltoid posterior and pectoralis major, respectively. The population of PDs was significantly unimodal for both the visual response and movement-related muscle activity (Rayleigh test, $P < 0.05$). Visual responses had similar PDs to movement-related activity with an average difference of 11 ± 35° and 37 ± 23° for the deltoid posterior and pectoralis major, respectively. Differences in PD were significant for the pectoralis major (t-test, visual response PD – movement related PD $\neq$ 0, $t_5 = 3.9$, $P = 0.01$) but not the deltoid posterior ($t_6 = 1.1$, $P > 0.1$).
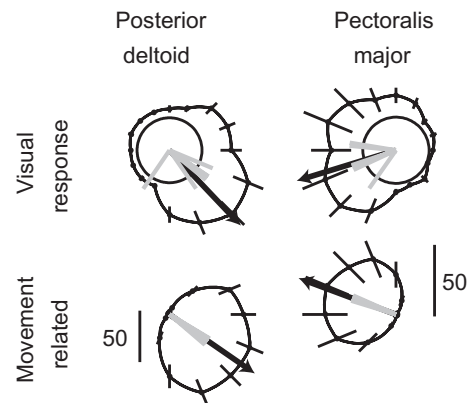

FIG. 5. Spatial tuning of stimulus-locked responses. Each panel presents the magnitude of muscle activity during the visual response epoch (75–100 ms post-target appearance) or movement-related (movement onset ± 10 ms) window for each of the 16 peripheral targets. Grey lines are the PDs of each individual sample and the black arrow is the mean across subjects. The displayed tuning function is formed by averaging the tuning function for each individual muscle after it had been normalized to the target direction for which it demonstrated the lowest level of activity. Thus, if all samples had lowest activity for the same target, the average tuning curve would have a value of '1' at that location. The choice of an alternative normalization scheme would not alter our conclusions as the statistical analyses are performed on individual PDs. The calibration circles in each plot represent baseline activity. Note that these are replaced by a calibration bar for movement-related activity that represents 50 × baseline.

Discussion

The key finding of the present study is that the appearance of a visual target elicited arm muscle activity that was time-locked to target appearance and not movement onset. We found that such a 'visual response' was present only when an immediate reach was required towards a suddenly appearing target (i.e. in the gap paradigm, Figs 2 and 4) and that its magnitude was predictive of manual reaction time (Fig. 3). Our results further demonstrate that, although the visual

response occurred at extremely short latencies (< 100 ms), it was not merely the release of a stereotyped pattern of muscle activation as would be commonly associated with a startle reflex (Brown *et al.*, 1991; Valls-Sole *et al.*, 1999). Rather, the visual response in a given muscle was directionally tuned to the target location (Fig. 5), with patterns of excitation and inhibition appropriate for the mechanical action required of that muscle to move the hand towards the target (Graham *et al.*, 2003; Kurtzer *et al.*, 2006). These results are consistent with recent observations that neck muscle activity is time-locked to target appearance (Corneil *et al.*, 2004) and extends past observations that arm muscle responses can occur at latencies approaching the minimal time required for performing a sensorimotor transformation (Biguer *et al.*, 1982; Gribble *et al.*, 2002). Taken together, the present work provides evidence for a rapid neural pathway that links visual input to arm motor output and implicates a common neural mechanism for hastening eye, head and arm movements.

Consistency of the visual response

It is important to emphasize that we found unambiguous visual responses in less than half of the collected muscle samples when using indwelling electrodes and that pilot studies using surface electrodes were almost universally unsuccessful. We suspect that the failure of surface electrodes provides an important clue as to why the visual response was seemingly so inconsistent. Previous studies have demonstrated that motor unit types are unequally distributed through-out a muscle such that slower motor units tend to be located deeper in the muscle (i.e. closer to the blood supply) than faster motor units (Singh *et al.*, 2002). Because the slower motor units are recruited first (Henneman, 1957), their activity probably dominates the visual response, but their location deep in the muscle makes it difficult to record their activity from surface recordings. In this scenario, inserting wires into the muscle probably yielded more positive results because the electrode was substantially closer to the source of the signal, but it was not perfect because there remained some variability in how deep the wires were embedded and how closely they were placed to the appropriate motor units.

Although we believe that the apparent inconsistency of the visual response (at least in shoulder muscles, see below) largely reflects the limitations of our electrode placement, we cannot rule out other reasonable explanations. For example, there may be substantial variability in the timing of the visual response such that, for some subjects or muscles, it is delayed and overlaps with movement-related activity, making it impossible to identify with our approach. It may also be that the visual response only occurs in conjunction with particular gaze behavior (see below) such as the generation of saccadic eye movements. Although subjects reported that they looked at the targets when they appeared, we cannot rigorously explore the link between gaze behavior and the visual response because we did not measure gaze position. Lastly, the visual response may simply be a vestigial process that is present in only a subset of the population.

Neural basis for the visual response

The short latency of the visual response reported here (< 100 ms) implies the presence of a short-latency neural pathway linking visual input to limb motor output. In principle, the visual response that we observed in arm muscles could reflect the earliest cortical processing of visual information via a pathway that typically contributes to voluntary arm movements. Although several previous experiments

suggest that few neurons in the primary motor cortex respond to visual stimuli fast enough to cause the visual response (Kwan *et al.*, 1981; Lamarre *et al.*, 1983; Wannier *et al.*, 1989), these studies did not utilize the gap paradigm that may yield earlier responses. As such, it would be fruitful to explore whether the gap paradigm substantially reduces visual response times in primary motor cortex.

Another potential contribution is from the ventral pre-motor cortex, which is known to respond quickly and robustly to visual stimuli (Rizzolatti *et al.*, 1981) and project to the corticospinal tract (Dum & Strick, 1991). In fact, recent work suggests that the ventral pre-motor cortex is the origin for descending projections that target both the oculomotor and skeletal-motor systems (Billig & Strick, 2009), making it an attractive neural center for the common control of eye, head and arm movements. The dorsal pre-motor cortex, which is involved in the planning and generation of arm movements (Wise, 1985; Kalaska *et al.*, 1997; Wise *et al.*, 1997), also contributes to the descending corticospinal tract (Dum & Strick, 1991). Recent studies have demonstrated that neurons in the dorsal pre-motor cortex respond to visual stimuli with onset latencies as early as 50 ms, and are directionally tuned to the location of the visual stimulus (Cisek & Kalaska, 2005). Furthermore, lesions in the posterior parietal cortex, which projects to the dorsal permotor cortex (Tanne *et al.*, 1995), can specifically impair a subject's ability to generate automatic corrections during reaching while leaving many other aspects of movement largely intact (Pisella *et al.*, 2000). This result suggests that the posterior parietal cortex and, more generally, the dorsal stream of visual processing (Goodale & Milner, 1992) plays a particularly important role in generating fast and automatic corrections during visually-guided reaching.

Areas that make up the dorsal stream, including the posterior parietal cortex and early extrastriate cortex, also project extensively to the superior colliculus (Fries, 1984; Asanuma *et al.*, 1985), a midbrain structure that is critically involved in visual orienting responses such as saccadic eye movements (Munoz *et al.*, 2000) and head rotation (Corneil *et al.*, 2002). In addition to projections that orient the eye and head, the superior colliculus has been shown to make polysynaptic connections to arm muscles via the tecto-reticulo-spinal pathway (Illert *et al.*, 1978; Grantyn & Grantyn, 1982). Recent work has demonstrated that such projections preferentially target proximal arm muscles (Stuphorn *et al.*, 1999), a result that is consistent with our observation that visual responses are more robust on shoulder than elbow muscles.

Given its anatomical connections, the superior colliculus may be particularly well-suited to mediate the visual response. In fact, previous authors have suggested that the superior colliculus plays an important role in hand–eye coordination (Werner, 1993; Lunenburger *et al.*, 2001). It is well known that a substantial proportion of neurons in the superior colliculus are rapidly activated by visual stimuli and involved in the generation of saccadic eye movements (Sparks, 2002). Less appreciated is that many neurons in the superior colliculus are activated during the preparation and execution of arm movements. In fact, a notable fraction of neurons are exclusively related to reaching and demonstrate no visual or saccade-related activity (Werner *et al.*, 1997a,b). These reach-related neurons tend to be well correlated to arm movement and exhibit activation patters similar to (and preced-ing) proximal arm muscle activity. Of particular relevance is a population of reach-related neurons that discharge only when reaches are made toward a particular location relative to the current gaze axis (Stuphorn *et al.*, 2000). These gaze-dependent neurons are located in an area of the superior colliculus that receives short-latency visual input and is involved in generating saccadic eye movements. As pointed out by Stuphorn *et al.* (2000), such gaze-dependent neurons

are well-suited to signal mismatch between gaze and arm orientation. Since gaze shifts often occur prior to arm movements when making a targeted reaching movement, the visual response on arm muscles may reflect the generation of a saccade toward the target. If true, then the visual response should be abolished by requiring subjects to maintain fixation at the central target while reaching to peripheral targets.

Taken together, the visual response on arm muscles is strikingly similar to visual responses described for rapid saccadic eye movements (Fischer & Boch, 1983; Dorris *et al.*, 1997) and neck muscles (Corneil *et al.*, 2004). These responses occur very rapidly, are time-locked to the visual stimulus, and coordinate the musculature appropriately to move their respective effector towards a visual stimulus. Based on these similarities, it is tempting to speculate that the eye, neck and arm visual responses form different components of the same coordinated response, the visual-grasp reflex (Hess *et al.*, 1946), which acts to orient gaze and body towards particularly salient visual stimuli.

The visual response and automatic corrections during reaching

When reaching towards a visual target, subjects are sometimes able to generate very rapid corrections to sudden changes in target position (Goodale *et al.*, 1986; Pelisson *et al.*, 1986; Day & Lyon, 2000; Pisella *et al.*, 2000; Franklin & Wolpert, 2008) or movements of the visual field (Saijo *et al.*, 2005). Such corrections can sometimes occur prior to (Castiello & Jeannerod, 1991) or without (Goodale *et al.*, 1986; Pelisson *et al.*, 1986) conscious awareness of a target displacement. Furthermore, when subjects are asked to respond to a target jump by moving in the opposite direction they are often unable to suppress an initial correction towards the target (Day & Lyon, 2000; Pisella *et al.*, 2000; Franklin & Wolpert, 2008). These previous results suggest that such rapid corrections are part of an automatic guidance mechanism for visually-guided reaching.

The functional features of the visual response reported here, including its short-latency onset and directional tuning, suggest that it may be a viable mechanism for coordinating the rapid visuomotor transformation required to automatically guide reaching toward a visual target. However, methodological differences between our experiments and previous work preclude a simple link between the visual response on arm muscles and the automatic corrections reported during reaching. The biggest such difference is that we utilized a movement initiation paradigm in which the appearance of the peripheral target was the cue to initiate a rapid reach towards the target. Most previous studies have demonstrated automatic corrections during reaching when the goal target was suddenly moved after a movement had been initiated (Goodale *et al.*, 1986; Pelisson *et al.*, 1986; Van Sonderen *et al.*, 1988; Pisella *et al.*, 2000; Saijo *et al.*, 2005). In fact, one study that examined both scenarios suggested that automatic corrections are substantially more robust when a movement is already in progress (Day & Lyon, 2000). The more robust presence of automatic corrections when movement is already initiated suggests that either a different mechanism is at play prior to movement initiation or that the same mechanism becomes more potent after movement initiation. Either scenario may account for the fact that we did not identify unambiguous visual responses in all muscles sampled and the present results cannot resolve between these two rational scenarios.

The visual response that we recorded was primarily observed on shoulder muscles and not elbow muscles. If the same neural mechanism that generates the visual response also contributes to automatic corrections, then our results make a strong prediction about the nature of automatic corrections. Specifically, automatic corrections should be observed when they predominantly involve shoulder muscle activation and not when they primarily involve elbow muscle activation. In most previous studies reporting the presence of automatic corrections, targets were displaced to the left or right when the hand is located in front of the subject and thus required largely shoulder muscle responses (Kurtzer *et al.*, 2006). Far fewer experiments have used a methodology favoring corrections driven largely by elbow muscle activation. However, when Van Sonderen *et al.* (1988) introduced initial movements and target jumps in various directions of the planar workspace of the right arm, they reported faster responses when corrections were to the upper-left and lower-right than when corrections were to the lower-left and upper-right. Although the authors did not explore our suggestion, their result is broadly consistent with the notion that shoulder muscles can generate corrective responses at faster latencies than elbow muscles. Future experiments explicitly testing our prediction would help to establish whether the visual response and automatic corrections are generated by a common neural mechanism.

Abbreviations

EMG, electromyography; PD, preferred direction; ROC, receiver-operating characteristic.

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