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Deliberation in the Motor System: Reflex Gains Track Evolving Evidence Leading to a Decision

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Both decision making and sensorimotor control require real-time processing of noisy information streams. Historically these processes were thought to operate sequentially: cognitive processing leads to a decision, and the outcome is passed to the motor system to be converted into action. Recently, it has been suggested that the decision process may provide a continuous flow of information to the motor system, allowing it to prepare in a graded fashion for the probable outcome. Such continuous flow is supported by electrophysiology in nonhuman primates. Here we provide direct evidence for the continuous flow of an evolving decision variable to the motor system in humans. Subjects viewed a dynamic random dot display and were asked to indicate their decision about direction by moving a handle to one of two targets. We probed the state of the motor system by perturbing the arm at random times during decision formation. Reflex gains were modulated by the strength and duration of motion, reflecting the accumulated evidence in support of the evolving decision. The magnitude and variance of these gains tracked a decision variable that explained the subject’s decision accuracy. The findings support a continuous process linking the evolving computations associated with decision making and sensorimotor control.

Introduction

The nervous systems of simple animals channel information from the senses more or less directly to the motor system. More elaborate behaviors necessitate freedom from the immediacy imposed by evanescent sensory input and the real-time demands of motor control. Such elaboration arises in the sorts of cognitive decision making that dominate our mental lives. As such, decision making may be viewed simultaneously as a model for cognition and as an extension of simple sensorimotor couplings.

A simple form of decision making arises in the setting of perception under ambiguity, when signals are masked by the presence of noise. For example, the discrimination between two directions of motion in a noisy random dot display invites an analogy to a jury deliberating over the evidence to reach a verdict. For such simple perceptual decisions, much is known about the neural mechanisms underlying evidence accumulation and the rendering of a choice. When a choice is ultimately communicated through an action, say to move the eyes, the evolving decision process has its neural correlate in the firing rates of neurons in areas of the brain that play a role in planning eye movements.
suggesting that the human brain does not wait for a decision to be completed before recruiting the motor system but instead passes partial information to prepare in a graded fashion for a probable action outcome.

**Materials and Methods**

Subjects. We analyzed data from four subjects (2 female, 2 male, age range: 24–36 years). A fifth subject was recruited but failed to show reliable EMG responses. All had normal or corrected-to-normal vision and reported no neurological disorders. All subjects were right-handed according to the Edinburgh handedness inventory (Oldfield, 1971). The Cambridge Psychology Research Ethics Committee approved the experimental procedures and all subjects gave informed consent.

Behavioral task. Subjects were required to decide on the direction of a random-dot motion stimulus in a two-alternative forced choice task and to indicate their choice by moving to one of two targets by making either an elbow flexion or extension movement. The cue to move was a rapid robot-controlled extension of the elbow joint (10 mm in 60 ms) that elicits a stretch reflex. Subjects then indicate their decision by moving to the target corresponding to the direction of perceived motion, at which point the correct target is displayed.

Figure 1. Experimental setup for the direction-discrimination task. A. Subjects hold the handle of a vBOT manipulandum while deciding on the direction of motion (elbow flexion or extension direction) of a dynamic random dot display. B. Temporal sequence of a single trial. Subjects move to a home position at which point the hand cursor vanishes and a fixation-cross appears. The motion stimulus appears 500–3000 ms later and remains on for 100–1500 ms. The cue for the subjects to respond is a rapid robot-controlled extension of the elbow joint (10 mm in 60 ms) that elicits a stretch reflex. Subjects then indicate their decision by moving to the target corresponding to the direction of perceived motion, at which point the correct target is displayed. C. The time course of key experimental parameters.
drawing from a distribution chosen to approximate a flat hazard function (ensuring subjects could not anticipate the duration; Luce, 1986): 100 ms plus a random time chosen from an exponential distribution with mean 300 ms and truncated at 1500 ms.

Subjects were required to decide the direction of dot motion (flexion or extension direction) and move to the appropriate target. The cue to initiate movement was the onset of a position-controlled perturbation, at which point the visual display of the motion was extinguished. The perturbation was always in the elbow extension direction and was designed to move the hand 10 mm in 60 ms at constant speed (PD-controller: \( K = 1.2 \text{kN m}^{-1}, B = 0.8 \text{kN s}^{-1} \)). This perturbation was chosen to elicit a stretch reflex (R). After the perturbation the hand was again free to move under the usual background force and subjects moved to either the flexion or extension target to indicate their choice. Subjects were required to reach the target within 300 ms and were then informed about the correct target. For the 0% coherence trials the “correct” target was randomly chosen. After a familiarization session each subject performed 3600 trials. On each trial the position of the hand was recorded at 1 kHz.

We also conducted control experiments on our subjects in which we measured the fastest voluntary responses to haptic input without the stretch reflex loop being involved. To do this, the amplitude of the perturbation was reduced to 1 mm (easily detectable, but avoiding the stretch reflex) and subjects were exposed only to trials with maximum information: long viewing durations (\( \geq 0.8 \text{s} \)) and high coherence (51.2%). Subjects were instructed to move as fast as possible to the correct target when they felt the perturbation (and the dots were extinguished). The control experiment was conducted in a separate session and consisted of 60 trials of each motion direction presented in a random order.

**Electromyography.** Muscle activity was recorded from six muscles. Two mono-articular elbow flexors (musculi brachioradialis and m. biceps longum), two mono-articular elbow extensors (m. triceps laterale and m. triceps longum) and two biarticular muscles (m. biceps brevis and m. triceps longum). The brachioradialis muscle was excluded from analyses because it suffered from crosstalk of its surrounding muscles that were involved in gripping the handle of the manipulandum. Electromyograms (EMGs) were recorded with a Delsys Bagnoli system (DE-2.1 Single Differential Electrode). Electrode positions were chosen to maximize the signal for the individual muscles and to minimize crosstalk. Before electrode placement, the skin was cleansed with alcohol and an abrasive gel was applied to improve conductance. The EMG signals were analog bandpass-filtered between 20 and 450 Hz and sampled at 2 kHz.

**Behavioral performance analysis.** We analyzed the probability of a correct choice as a function of viewing duration (\( t \)) and motion strength (\( C \), proportion of coherently moving dots). We fit this behavioral data using a drift–diffusion model to explain each subject’s proportion of correct choices as a function of both motion coherence and viewing duration. The proportion of correct responses depends on the decision variable, \( DV \), which is modeled by the stochastic differential equation:

\[
dDV = kCdt + dW, \tag{1}
\]

where \( k \) relates the drift rate to the motion strength and \( W \) denotes standard Brownian motion (with unit variance over one second). Given a coherence and viewing duration, Equation 1 leads to a Gaussian distribution of the \( DV \) with mean \( kCt \) and variance \( t \). The probability of an extension or flexion choice is given as the integral of this distribution over the positive and negative values of the \( DV \), respectively. We fit this one-parameter diffusion model (parameter \( k \)) to each subject’s data so as to maximize the likelihood of each subject’s choices. Bootstrapping (1000 samples) was used to obtain confidence intervals on the parameter estimates. Preliminary analysis suggested that the data fit was not improved substantially by the inclusion of an absorbing bound (Kiani et al., 2008).

**Calculation of the decision variable on a single trial.** For each trial, we calculated the expected distribution of \( DV \) given that subject’s coherence-dependent drift rate. We can further refine the distribution of the \( DV \) by truncating (and renormalizing) to only positive or negative values depending on the decision the subject makes on that trial. The expectation of this truncated Gaussian distribution, denoted \( DV_{\text{Choice}} \), is our estimate of the \( DV \) that gave rise to the choice on that trial. However, the perturbation probes the state of the \( DV \) some \( \tau \) ms earlier, due to processing delays between visual input and any changes in EMG (Resulaj et al., 2009). We derived an estimate of this delay, \( \tau \), for each subject (see Eq. 2 in Electromyographic signal analysis, below). Our interest is in the \( DV \) at \( t - \tau \), which is based on the stream of information that could affect the reflex. Note that this is not simply the truncated part of the \( DV \) distribution at \( t - \tau \), as it is possible to have a negative \( DV \) at \( t - \tau \) and a positive \( DV \) at \( t \) (and vice versa). To estimate the \( DV \) at \( t - \tau \), we propagate the truncated distribution of \( DV \) at \( t \) back in time to \( t - \tau \) using the Kolmogorov backward equations (Kolmogoroff, 1931). We use the expectation of this back-propagated distribution, \( DV_{\text{prop}} \), in the analyses in Figure 5 (see Results).

We also analyzed the kinematics of the movement after the perturbation in relation to the DV. For each trial, we calculated the distance the hand had moved toward the final choice target from its position at the end of the perturbation at three different points in time: 125, 155, and 255 ms after perturbation onset. For plotting purposes, we normalized these measures for each time point to have unit SD across all trials for that time point. We plot these normalized distances as a function of \( DV_{\text{prop}} \) in Figure 5 (see Results).

**Electromyographic signal analysis.** EMG signals were bandpass filtered (25–250 Hz, fifth order bidirectional Butterworth filter) and full-wave rectified. Reflex activity is known to scale with background muscle activity before perturbation onset (Pruszynski et al., 2009). Therefore we normalized each trial’s EMG by dividing the mean activity over a 100 ms window before perturbation onset. The mean activity in the time windows 20–45 ms (R1), 45–75 ms (R2) and 75–105 ms (R3) after perturbation onset was calculated for the individual muscles on individual trials. R1 and R2 contain no voluntary activity and even R3 has been shown to contain voluntary activity only on a very limited number of trials (Pruszynski et al., 2008).

Since EMG activity typically drifted over the course of the experiment (>4 h) we controlled for drift in the individual muscles. We calculated a 150-point chronological running mean and running SD for each muscle. For each trial, we subtracted the value of this running mean and divided by the running SD, both centered on that trial. The resulting values were the normalized muscular activities for the corresponding time windows.

We calculated the difference between the average normalized flexor muscle activity and the average normalized extensor muscle activity for each time window, thereby quantifying the magnitude of the reflex response and refer to this measure as the reflex gain (\( G \)). As stated earlier, all \( G \)s were normalized to background activity. However, to exclude changes in reflex responses due to coactivation (Akazawa et al., 1983; Carter et al., 1993; Lewis et al., 2010) based on accumulated evidence, we also analyzed muscle activity over the 100 ms window before perturbation onset. All procedures were the same as for the reflex gains, except for the first normalization step and that we summed the activity over all muscles. This preprocessing gives us four measures for each trial: G1, G2, G3 and Pre that reflect muscle activity in the R1, R2, R3 and pre-perturbation time window.

To test whether the reflex gains and preactivity depended on motion coherence (\( C \), positive for extension motion direction and negative for flexion motion direction) and viewing time (\( t \)), we fit a phenomenological model that allows the gains to be zero until a delay \( \tau \) and then to increase and plateau as a function of time, with the slope and plateau level dependent on the coherence. We modeled the gains using a cumulative scaled (half) Gaussian function rising after the delay \( \tau \), which represents the time delay between dot motion onset and changes in reflex gain:

\[
G(t, C) = \begin{cases} 0 & t \leq \tau \\ \frac{k}{\sigma \sqrt{2 \pi}} \int_{t-\tau}^{t} \exp(-t^2/2\sigma^2)dt & t > \tau \end{cases}, \tag{2}
\]

where \( \sigma = \sigma_0 + \sigma C \) and \( k = k_0 + k_1 C \) represent the time constant and amplitude of tuning, respectively, which can depend on the coherence level \( C \). We fit equation 2 to the flexion and extension choices from each
Subjects were required to decide between two possible directions of motion in a dynamic random-dot display and to indicate their choice by moving a handle to one of two targets (Fig. 1), requiring an elbow flexion or extension movement. We varied task difficulty by controlling both the strength (coherence) and duration of random dot motion. Subjects were instructed to indicate their direction decision as soon as the random dots were turned off, which occurred at an unpredictable time from motion onset. Simultaneous with motion offset, we applied a brief perturbation that extended the elbow, thereby eliciting a reflex response, which was quantified by EMG of forearm flexor and extensor muscles.

We first analyzed the subjects’ behavioral accuracy and related this to a model of decision making. Across all trials, the random dot motion direction was 50% extension and 50% flexion, and the choices made by the subjects were 48% in the extension direction and 52% in the flexion direction. Decisions were more accurate on trials in which the subjects viewed stronger motion (Fig. 2A, B). Moreover, for each motion strength, the decision accuracy improved with longer viewing durations (Fig. 2C, D), consistent with previous findings (Kiani et al., 2008). These observations indicate that subjects’ decisions were based on an accumulation of noisy evidence supplied by the motion stimulus.
via the visual cortex. Indeed the choices are explained by the sign of the decision variable (DV) from the one-parameter drift-diffusion model (Eq. 1, see Materials and Methods, Behavioral performance analysis): All k-values, which relate the drift rate to the coherence level (Table 1) were significantly different from zero (p < 0.0001), rejecting the null hypothesis that there are no effects of coherence level. This one-parameter drift-diffusion model furnishes the smooth curves in Figure 2A and C for a typical subject; the curves in Figure 2B and D are averages of the fits for each of the subjects.

To assess the state of the motor system at the time of the perturbation, we recorded the EMG of elbow flexor and extensor muscles in response to the rapid extension of the elbow joint. These perturbations occurred at a random time from the onset of the random dot motion (truncated exponential distribution; 100 – 1500 ms, see Materials and Methods, Behavioral task), which coincided with the offset of the motion. Because of visual latencies, the perturbation is the first indication the subjects had that it was permissible to indicate their decision. In fact, visual information from the random dot motion is likely to be processed for another ~200 ms after the dots turned off (Huk and Shadlen, 2005; Resulaj et al., 2009). Thus, the perturbation allowed us to assess the state of the motor system while the decision process was still benefiting from additional information.

Figure 3 shows a typical subject’s averaged EMG signals elicited by the perturbation. For this example, we show data from correct trials for intermediate viewing durations in which the subject viewed weak or strong motion (left and right columns, respectively). The EMG signals show a classic short latency stretch reflex over the first 45 ms (Fig. 3, R1), which is evident mainly in the flexor muscles (Fig. 3, top row) and independent of motion direction. The EMG signals then begin to diverge in a manner that depends on the strength and direction of the random dot motion; flexor muscles (top row) show larger reflex responses when the motion supports a flexor response (blue trace), and extensor muscles (middle row) show larger responses when the motion supports an extensor response (red trace). The difference between flexor and extensor EMG signals (bottom row) suggest that the EMG signals accompanying the two directions of motion diverge earlier and more substantially for trials in which the dots moved more coherently (R2 and R3 time windows). On each trial, we used the integral of this difference to quantify the reflex gain (see Materials and Methods, Electromyographic signal analysis), in the three time-windows corresponding to short, intermediate, and long latency stretch reflexes (G1, G2, and G3, respectively).

We first show that G2 and G3 are modulated by both the strength and duration of the motion stimulus and that G1 is independent of accumulated evidence. To do this we grouped together trials sharing the same motion strength and motion direction and supporting the same choice (i.e., correct choices only for nonzero coherence). Neither the strength nor the direction of motion influenced G1 [Fig. 4, left column for single subject (A) and group average (B)]. This is not surprising, as G1 has been shown not to modulate with task constraints or contextual changes on the short time scales used in our experiment (see Pruszynski et al., 2008 for discussion). In contrast, both G2 and G3 were clearly affected by the strength and direction of motion as well as the viewing duration. Importantly, the effect of motion strength was reliable even when incorporating the dominant effects of direction (i.e., choice) and duration (G2: p < 0.018; G3: p < 0.002 for all subjects). We also checked for systematic changes in muscle activation just before the perturbation and found no indication for time or coherence dependence (p > 0.25 for all subjects). This excludes the possibility that the observed changes in G2 and G3 are caused by increased coactivation before perturbation.

The observations in Figure 4A and B are important because they demonstrate that the reflex gains are affected in a graded manner even when averaging over data only from correct choices. Using data for correct choices ensures that the averages portrayed in Figure 4B do not reflect mixtures of reflex gains from trials leading to different actions. The grouping in Figure 4A and B and the related statistics thus provide a conservative test for a graded,

![Figure 2](image-url) **Figure 2.** Performance on the random dot motion task. A, Proportion of correct responses, for one subject, plotted as a function of motion strength. Data are plotted separately for short, intermediate, and long viewing durations, as indicated. The curves depict a one-parameter diffusion model (Eq. 1) fit to the entire dataset. Error bars (SE of the proportions) are not visible as they all lie within the filled circles B, Group average for all subjects. Same conventions as A. Error bars are SEs across subject means and shaded areas show SEs across the individual subjects’ curves from the fits of the diffusion model. C, Proportion of correct responses, for one subject, plotted as a function of viewing duration for the 5 nonzero coherence levels. Points are shown at the center of the time bins (~75 trials per point). Error bars show SEs of the proportions, based on the binomial distribution. Colors represent different motion strengths, as indicated. The solid lines are fits of the drift-diffusion model D, Group average for all subjects. Same conventions as C. Error bars are SEs across subject means and shaded areas show SEs across the individual subjects’ curves from the fits of the diffusion model.

### Table 1. Parameter fit for the drift-diffusion model (k) to each subject’s choice data with the 95% CI of the bootstrapped parameters

<table>
<thead>
<tr>
<th>Subject</th>
<th>k</th>
<th>EMG delay (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6.52 (5.98 – 7.11)</td>
<td>157</td>
</tr>
<tr>
<td>2</td>
<td>11.52 (10.66 – 12.41)</td>
<td>168</td>
</tr>
<tr>
<td>3</td>
<td>3.96 (3.44 – 4.62)</td>
<td>158</td>
</tr>
<tr>
<td>4</td>
<td>8.75 (8.20 – 9.74)</td>
<td>166</td>
</tr>
</tbody>
</table>

EMG delay estimates the lag between visual input and changes in EMG that arise due to sensorimotor and processing delays.
The second for extensor muscles. The third row shows the time course of the difference between flexor and extensor muscles activity. This so that the SD (across trials) of the mean EMGs (in the R3 window within a trial) is unity. The first row shows activity for the flexor muscles, direction and red traces for evidence in the extension direction. For plotting purposes, the EMG traces for each muscle have been normalized (20 – 45 ms), R2 (45–75 ms), and R3 (75–105 ms). The direction of motion is indicated by color: blue traces for evidence in the flexion Vertical dashed lines indicate the onset of the positional perturbation. Gray areas indicate the time windows of the reflex response: R1 (20–45 ms), R2 (45–75 ms), and R3 (75–105 ms). The direction of motion is indicated by color: blue traces for evidence in the flexion direction and red traces for evidence in the extension direction. For plotting purposes, the EMG traces for each muscle have been normalized so that the SD (across trials) of the mean EMGs (in the R3 window within a trial) is unity. The first row shows activity for the flexor muscles, the second for extensor muscles. The third row shows the time course of the difference between flexor and extensor muscles activity. This measure diverges for flexion and extension evidence with a divergence that is faster for the higher coherence level.

Figure 3. Examples of EMG records used to infer reflex gains. Averaged EMGs are shown for trials ending in correct choices for two motion strengths (3.2 and 51.2% coherence, left and right columns, respectively) at intermediate viewing durations (270–350 ms). Vertical dashed lines indicate the onset of the positional perturbation. Gray areas indicate the time windows of the reflex response: R1 (20–45 ms), R2 (45–75 ms), and R3 (75–105 ms). The direction of motion is indicated by color: blue traces for evidence in the flexion direction and red traces for evidence in the extension direction. For plotting purposes, the EMG traces for each muscle have been normalized so that the SD (across trials) of the mean EMGs (in the R3 window within a trial) is unity. The first row shows activity for the flexor muscles, the second for extensor muscles. The third row shows the time course of the difference between flexor and extensor muscles activity. This measure diverges for flexion and extension evidence with a divergence that is faster for the higher coherence level.

motion-dependent change in the reflex. However, this grouping of trials obscures our central hypothesis that the reflex gains track the state of the DV. The evolving DV connects the stream of evidence from the visual system to either choice: it explains the proportion of correct and incorrect choices for the same motion stimulus (Fig. 2). To relate the evolving DV to the reflex gains measured, we must examine all trials associated with the same motion stimulus (Fig. 3). To relate the evolving DV to the reflex gains measured, we must examine all trials associated with the same motion stimulus (direction and strength). The averaged reflex gains, now grouped across all trials sharing the same motion stimulus (direction and strength), show a qualitative correspondence with the time course of the expected decision variable (Fig. 4C, inset). Our next attempt to quantify this relationship.

Our goal is to estimate the mean DV at the time of perturbation on each trial and relate this to the reflex gains on the same trial. From the one-parameter fits to the behavioral data we obtain a relation between coherence and the mean drift rate of the diffusion process which determines the average temporal evolution of the decision variable for the different motion strengths. We assume that the subject uses the full evidence stream (i.e., the viewing duration t) to make a decision, and from this model we can estimate the distribution of the DV on each trial using all the motion evidence. From diffusion, the DV has a Gaussian distribution with mean described by the lines in the inset of (380). This excludes the possibility that the measured G3 is simply associated with the flexion/extension evidence and waiting time. The DV adds substantial explanatory power.

The second alternative is that G3 reflects a decision variable leading to the decision on that trial, without propagation back in time to the moment of the perturbation. This model is much better than the first alternative, but it has weaker explanatory power than our main hypothesis (smallest Δlog-likelihood across subjects = 30). This implies that the extra machinery required to estimate the DV at the time of the perturbation was warranted. From these analyses, we conclude that the evolving DV plays an essential role in explaining the reflex gains, and its state at the time of the perturbation is more informative than its state at the end of the trial.

The link between DV and reflex gain is further strengthened by examining the variance of G3 as a function of elapsed time during decision formation. According to the diffusion model, the variance of DV increases linearly as a function of time. Since G3 is monotonically related to the DV, we would expect to observe a monotonic rise in its variance as well. Figure 6 shows the variance of G3 as a function of stimulus duration on the 0% coherence trials. The variance increases approximately linearly for all four subjects, in accordance with the diffusion model.
The gradual changes seen in Figure 5A could arise in two different ways—through a continuous flow process or a mixture-of-states process. For a continuous flow process, the reflex gain would reflect the DV within the trial, varying smoothly between a low gain and the value attained at the time of the perturbations. Alternatively, in a mixture-of-states process, rather than track DV, the reflex gain would only take on one of two states, that is, either an uncommitted state with low gain or a committed state with high gain. Therefore, under this model, the gradual change in Figure 5A would result from averaging across trials in which subjects were either in an uncommitted low-gain state or a committed high-gain state.

To evaluate this possibility, we performed a mixture analysis (see Materials and Methods, Mixture analysis). We reconstructed reflex gain datasets for intermediate values of DV by mixing samples from low (uncommitted) and high (committed) values of DV. We mixed these in the correct proportion to match the mean reflex gain at the intermediate value of DV. Under a mixture-of-states process, this reconstructed dataset would have the same variance as the actual data, whereas for the continuous flow model this reconstructed dataset would have higher variance than the data (see Materials and Methods, Mixture analysis). We found that the variance was significantly higher ($p < 0.001$ for all subjects) in the reconstructed datasets, supporting the continuous flow model. This conclusion is further supported by examination of the distribution of G3 over sequential time-windows on the 0% coherence trials, which exhibit no evidence for bimodality ($p > 0.05$ across all subjects and all time-windos; Hartigan’s dip test).

A natural question is why the motor system would modulate the state of its reflex gains during decision formation before an action is required. One possible answer is preparation. Feedback gains, such as long latency reflexes, are key parameters in compu-
long viewing durations and high coherences. Figure 7 plots the difference in EMG between flexion and extension evidence for voluntary trials (blue) and for our standard perturbation trials (red) with the same durations and coherences. We determined the earliest EMG responses in the control trials and found a median response delay of 132 ms and <5% of trials showing a response earlier than 105 ms after perturbation onset. Less than 1% of trials showed EMG responses earlier than 90 ms after perturbation onset. We conclude that voluntary responses have no measurable contribution to our G2 (epoch ending at 75 ms) and minimal contribution to G3. Importantly, this analysis demonstrates that the quantities we analyze in our study reflect true involuntary reflexes.

**Discussion**

By probing the state of the motor system with a sudden perturbation to the arm, we have shown that reflex gains adjust dynamically to track the evolution of a decision as it is being formed. Even for trials ending in the same (correct) decision, the medium- and long-latency reflex gains (G2 and G3) are modulated in a graded manner depending on both the strength and the viewing duration of the random dot motion stimulus (Fig. 4). It had been shown previously that G2 and G3 can be modulated in preparation of movements that differ in magnitude and speed (Pruszynski et al., 2008). The novel extension pursued in our study is to link these gains to the process of decision formation.

To connect the reflex gains to the decision process we exploited a virtue of the random dot motion task: decision accuracy can be explained quantitatively by the accumulated evidence, termed the decision variable, in support of one or the other alternative. This single decision variable represents the integral of the noisy motion evidence and is thus affected by both motion coherence and viewing duration (Heekeren et al., 2004; Bogacz et al., 2006; Gold and Shadlen, 2007; Heekeren et al., 2008; Donner et al., 2009). In reaction time versions of the random dot motion task, the choice accuracy and reaction time are explained by a drift-diffusion model in which the DV reaches a positive or negative bound, which terminates the process and determines the choice outcome (Gold and Shadlen, 2002, 2007; Smith and Ratcliff, 2004). In our task, subjects were cued when to move and we therefore used a simplified (one-parameter) diffusion model that assumes accumulation of all evidence provided by the display. The decision is simply based on the sign of the DV at the end of the trial.

The drift-diffusion model explains the choice data for each of the subjects (Fig. 2) and allows us to infer the state of the decision variable—its probability distribution—at the time of the perturbation on each trial. The evolution of the expected value of the

Figure 5. Reflex gains and kinematics track the decision variable. The DV was derived from the drift-diffusion model fit to each subject’s choice function and estimated at the time of the perturbation (DV_{pert}). For these graphs, the DVs, reflex gains, and kinematics were combined for both directions of dot motion by changing the sign of the DV and reflex gains for trials with flexion motion. **A**, Reflex gains as a function of DV_{pert} for one typical subject (left) and the group average (right). Curves are running means of the single-trial estimates across ±0.2 units of DV. Shading indicates SEs across trials. **B**, Movement excursion toward the choice target as a function of DV_{pert} for one typical subject (left) and the group average (right). Movement excursion was calculated for three time points (125, 155, and 255 ms) after perturbation onset. As the excursions at these time points have very different magnitudes, for plotting purposes the movement excursions have been normalized so that the SD (across all trials) for each time point is unity. Curves are running means, as in **A**.

**Control experiment**

In the control experiment we examined voluntary responses to tactile input for trials with maximal information, that is, with

Tactational models of sensorimotor control (Todorov and Jordan, 2002; Scott, 2004; Todorov, 2004; Pruszynski et al., 2008). Setting them ahead of time might support greater efficiency of the ensuing movement. However, it is possible that, although we observe reflex modulation, it may be too small to induce an observable change in the kinematics. To test this, we calculated the distance moved toward the choice target at three time points after the perturbation onset (see Materials and Methods, Calculation of decision variable on a single trial). Figure 5B shows that the distance moved increases with the DV_{pert} even as early as 125 ms after perturbation onset. A similar relationship is evident between G3 and distance (data not shown). Therefore, higher DV_{pert} correlates with a more rapid approach to the choice target, suggesting that setting the reflex gains before movement is indeed beneficial for generating rapid movements.
In the current study we measured the reflex gains and show that there is supraspinal modulation of their gain during decision making, reflecting changes in excitability of the response pathways. The rationale for studying the reflex gains in relation to decision making is that such feedback gains are key control parameters within the framework of optimal feedback control (OFC). This framework unifies diverse motor functions, such as planning, on-line control, coordination, and the interaction of effort and noise (for reviews see Scott, 2004; Todorov, 2004; Diedrichsen et al., 2010). OFC proposes that the sensorimotor system acts to minimize a cost function that is usually a combination of accuracy and effort. To achieve this, the nervous system implements feedback controllers with adjustable time-varying gains. Normally, these feedback gains contribute to establishing the smooth movement trajectories that transport the hand from rest to target, for example. However, it has been shown that also before movement these feedback gains, i.e., intermediate and long latency responses, are modulated to optimize task performance (Kurtzer et al., 2008; Pruszynski et al., 2008). We extended this observation by showing that the same feedback gains are affected by an evolving cognitive process of decision making leading to movement selection. Importantly, reflex gains were not modulated by the outcome of a decision (e.g., a mixture of uncommitted and committed states) but instead track the accumulating evidence in a graded fashion.

From an evolutionary perspective, it is perhaps unsurprising that information about a stimulus might affect structures in the brain that control the motor system that will ultimately act upon that information. Yet, according to traditional accounts of decision making, the process of deciding should complete before the motor system is brought into play (Donders 1868/1969; Sternberg, 1969). Such an architecture, termed sequential flow, seems consistent with the common sense notion that decisions are about propositions or categories, independent of what, if anything, we will do as a consequence (Freedman and Assad, 2011). A central executive or other high level processor (Sigman and Dehaene, 2005) makes the decision and communicates the answer to the appropriate motor system if and when an action is required. On this view, the motor system is informed of the decision outcome, not partial evidence.

To the contrary, our findings suggest that there is continuous flow from the decision making process to set feedback gains in the motor system. This is consistent with neurophysiological studies...
in nonhuman primates that use microstimulation to elicit an eye movement during the decision making process (Kustov and Robinson, 1996; Gold and Shadlen, 2000, 2003; Horwitz et al., 2004; Connolly et al., 2009). Without the benefit of the present findings, the continuous flow exhibited by nonhuman primates on this task might be interpreted as evidence that such species lack a central executive. Instead, we provide evidence that the human brain also supplies the motor system with partial evidence to prepare circuitry for an eventual act.

Complementary evidence in support of continuous flow in humans comes from the analysis of movements of a computer mouse during a lexical decision task (Spivey et al., 2005) and from analyses of sequences of movements suggesting concurrent processing of visual information in a variety of tasks (Resulaj et al., 2009; Song and Nakayama, 2009; Purcell et al., 2010). These and other findings support the idea that motor preparation incorporates not just readiness to act but qualitative information leading to that action (Coles et al., 1985; Michelet et al., 2010). The present result shows that this information is not restricted to anticipation (Tanji and Evarts, 1976; Miller et al., 1992; Crommond and Kalaska, 2000) or certainty (Bastian et al., 2003), but incorporates a rich representation of a decision variable, that is, the accumulation of evidence leading to a choice.

Our findings do not imply that decisions are always tied to actions. Even in a task like ours, decisions do not feel like they are about an action but about a property of the visual stimulus, suggesting the presence of some higher order decision process. Nonetheless, the motor system receives a continuous flow of evidence as the decision evolves, presumably because there is some benefit for preparation. That said, we often make abstract decisions about propositions independent of what, if anything, we will do as a consequence. In such cases, the motor system is unlikely to receive partial information about the evolving decision (Gold and Shadlen, 2003). However, even here it seems likely that partial evidence will flow continuously, not to the effectors of action, but to the implementers of subsequent decisions (Cisek, 2007; Shadlen et al., 2008).

The dividends of continuous flow include readiness and computational savings when an action is required. But we suspect a deeper connection between the brain’s apparatus for evaluating evidence and the control of motor function. Both decision making and motor control require acting in real time on streams of noisy evidence. Thus, both rely on inference, termination rules, time constraints, and predicted costs—operations that are best understood with the tools of probability theory (Knill and Pouget, 2004; Körding and Wolpert, 2006; Tenenbaum et al., 2006; Anderson, 2011). While we have shown flow from the decision-making process to the motor system, we expect elements of the motor task, such as the range of possible actions or the value effort/costs associated with them, to influence the settings of the decision-making process, such as the tradeoff between decision speed and accuracy. Therefore, we suspect that the flow demonstrated in our experiment may be part of a larger bidirectional interplay between the brain processes that underlie decision making and motor control.

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