Dependence of Reactive Responses in Human Bimanual Finger Movements on Sensory Feedback and Auditory Cues

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Ohki, Yukari and Kanae Watanabe. Dependence of reactive responses in human bimanual finger movements on sensory feedback and auditory cues. J Neurophysiol 91: 1260–1270, 2004. First published November 5, 2003; 10.1152/jn.00168.2003. We examined the effects of repetitive experience of feedback events and cue signals on adaptation of bimanual reactive response, both of which can be used to predict load forces on handheld objects. Normal human subjects used bimanual index fingers to hold two plates mounted on separate torque motors. Sensory-driven reactive forces from the fingers were measured during concurrent loading of both plates or isolated loading of the left plate. After repeated experiences of single load conditions, right and left fingers increased normal forces in a coordinated manner during concurrent loading, while the left finger responded almost exclusively during isolated loading of the left plate. However, after switching load conditions from concurrent to isolated load, or vice versa, several trials were needed to adapt to the new condition, as was clearly observed in the dynamic phase of responses from the right finger. Adaptation depends on the number of feedback experiences, and specifically on prediction error, showing intermediate predictions between the two conditions. Thus, influences of the previous experiences show similar properties to those observed in self-generated movement, which were reported previously. In addition, auditory cues informing subjects of coming load conditions also partially adapted responses to these conditions. The neuronal center for reactive responses is therefore influenced by both previous experience and cue signals, inducing the appropriate responses for the predicted sensory inputs.

INTRODUCTION

Sensorimotor control of the hand during object manipulation is characterized by feedback-driven, predictive control policies based on internal models that reflect both the behaviors of our motor system and the relevant properties of external objects (Johansson 1996; Johansson and Cole 1994; Wing 1996; Wolpert and Flanagan 2001). When we lift a handheld object, for example, internal models predict the consequences of self-generated actions, in addition to friction between the object and individual fingertips, and modify grip forces accordingly (Burstedt et al. 1999; Edin et al. 1992; Johansson and Westling 1984). This predictive control is essential, given the inevitable neuromechanical delays limiting the utility of closed-loop feedback control (Hogan et al. 1987; Johansson and Cole 1994).

However, sensory-driven feedback control is also essential during manipulation, to correct error during movements. An extreme example occurs when we manipulate “active” objects that may threaten grasp stability because of load changes with unpredictable timing. In such cases, normal subjects produce sensory-driven reactive grip responses to restrain the grasped object (Johansson et al. 1992a,b; Macefield 1996). However, even in these cases, human subjects try to predict the behavior of the object to compensate for delayed feedback effects. The simplest expression of such predictions is increased background grip force when a rapid load increase is expected at some time in the near future (Cole and Johansson 1993; Johansson and Westling 1988; Johansson et al. 1992a,c; Weinstein et al. 2000). In addition, the reactive grip responses themselves are rescaled using early cues about the rate of load-force changes (Cole and Abbs 1988; Johansson et al. 1992a; Weinstein et al. 2000) and friction (Birznieks et al. 1998; Cole and Johansson 1993). Furthermore, reactive grip response can be induced by sensory cues from different digits on either the same or the contralateral hand (Ohki and Johansson 1999), and gain from interdigital response is scaled by subject predictions about simultaneity of load forces to handheld objects (Ohki et al. 2002). The neuronal center for reactive grip response, which processes the sensory inputs to induce reactive movements, should therefore be influenced by feedforward predictive control to allow effective feedback control. The internal model generating motor commands may therefore also affect the center.

In self-generated bimanual movements, the forward internal model is proposed to be adapted by changing the weighting given to possible motor control modules based on sensory errors (Witney et al. 2000; Wolpert and Flanagan 2001). Subjects can thus make intermediate predictions between possible internal models, and adaptation sometimes takes more than three feedback events, i.e., appropriate feedback inputs to both hands in association with three manipulations of an object. If selection of an internal model also influences sensory-driven reactive movements, then adaptation of the reactive movement should show similar properties to those observed in self-generated movements. However, adaptation of reactive movement currently seems to be more transient, being completed within the first trial after changing the properties of an object, although effects of global predictions have also been reported (Birznieks et al. 1998; Weinstein et al. 2000).

The present study was designed to examine in detail the effect of previous experiences on current reactive movements, using the bimanual task developed by Ohki et al. (2002). In this task, subject predictions about load conditions to handheld
objects can be controlled. We compare our results with those obtained for self-generated bimanual movements by Witney et al. (2000) and examine the hypothesis that the forward internal model could affect the neuronal center for sensory-driven reactive movements.

The present study also examined the effect of cues, which help subjects to predict load conditions on objects without sensory feedback. We hypothesized that humans can use such predictions free from feedback events, for example, when we manipulate familiar objects, in which we can predict the properties of the objects from visual information before even touching them.

METHODS

The present study was conducted in accordance with the principles provided in the Declaration of Helsinki. With approval of the local ethical committee, experiments were performed on seven healthy right-handed human volunteers (3 females, 4 males) between 28 and 42 years old. Subjects were naïve to the research aims of the study and provided written informed consent. Subjects were seated in a chair with upper arms parallel to the trunk and forearms extended anteriorly in the horizontal plane. The forearms up to the palms were supported by a tabletop, and the hands were in intermediate pronation (palms down). Subjects used the tips of the left and right index fingers positioned side-by-side to restrain an instrumented apparatus (see APPARATUS; Fig. 1A; see also Fig. 1 in Ohki and Johansson 1999). Fingers were slightly flexed and the plane of the grasp plates approxi-
to 0.8 N, then ramped to 3 N at a rate of 4 N/s. The initial step load force served to trigger a distinct normal force response, and the following ramp phase of the load guaranteed a substantial response amplitude (Johansson et al. 1992a).

Test series

In any one test series, subjects experienced two types of trials, linked and unlink, each of which displayed different load conditions. In linked trials (L), the two grasp plates were loaded concurrently, whereas only the left plate was loaded in unlink trials (U). In one set of experiments, subjects participated in four different test series, comprising short-interval link-predictive, long-interval link-predictive, short-interval unlink-predictive, and long-interval unlink-predictive test series. Each series consisted of 200 load trials (25 batches of 8 trials). To prevent fatigue, short rest periods were given after every 40 trials.

LINK-PREDICTIVE SERIES. A beep (1000 Hz, 100 ms in duration) was given at the start of every batch (i.e., 8 trials). Each batch started with a succession of one to four linked trials, with the remaining trials in a batch unlink. Subjects were therefore able to safely predict the start of sequential linked trials by the beep (link-predictive). Conversely, subjects could not precisely predict the start of unlink trials. However, once the trial was changed to unlinked in the middle of a batch, subjects were able to predict the succession of unlinked trials until the next beep.

It should be noted here that 5 of the 25 batches started with an unlinked trial, with no linked trial delivered after the beep (see trials after the 3rd beep, Fig. 1C, top). This type of batch was introduced to clarify the effects of cue, and the 5 batches occurred in random positions within each series. However, even in such cases, the 8 unlinked trials after the beep were treated as U1–U8, as the beep clearly induced some adaptation of response to the linked trial. A total of 50 linked and 150 unlinked trials were included in the test series.

Although this series was designed to observe the progression of adaptation to unlinked trials, subjects also experienced sequential linked trials in the same series (L1–Lm). However, adaptation to linked trials was slightly different in nature from that observed in the other test series (see UNLINK-PREDICTIVE SERIES), as the starts of sequential trials were cued with beeps. We thus compared responses in linked trials between link-predictive and unlink-predictive series, to show the effects of cues on adaptation.

UNLINK-PREDICTIVE SERIES. Linked and unlinked trials were identical to those in the link-predictive series. Construction of this test series resembled the “three link condition” used by Witney et al. (2000). That is, 3 successive linked trials (L1–L3) occurred in each batch of 8 trials, starting with one of the 4 trials in the batch. The last linked trial was therefore followed by 2 to 5 unlinked trials in single batches. However, when the first trial in the next batch was unlinked, subjects perceived that the unlinked trials were continuing without notifying the start of the next batch (see start of 2nd batch, Fig. 1C, bottom). The test series was named unlink-predictive, as subjects were cued on the starts of sequential unlinked trials by beeps, although the starts of sequential linked trials occurred unexpectedly. Thus in this series, we could observe adaptation of reactive responses to linked trials with concurrent loading following unexpected changes in load condition from isolated load to the left plate. A total of 75 linked trials and 125 unlinked trials were included in the test series.

In the test series, subjects also experienced sequential unlinked trials (U1–Un), with starts cued by beeps. As with linked trials in the previous test series, effects of cue on adaptation to unlinked trials were analyzed by comparing responses between link- and unlink-predictive test series.

In both unlink- and link-predictive series, the number of trials was smallest for the eighth unlinked trial (U8, n = 5). Subjects let the apparatus slip in 0.005% of trials and, in such cases, the batch was repeated from the beginning, and the first trial after restart was excluded from analysis. Similarly, first trials after the short rest periods were excluded from analysis.

Data collection and analysis

Data were collected and analyzed using a laboratory computer system (SCIZOOM; Physiology Section, IMB, University of Umeå). Force signals were sampled at 400 Hz. Force rates were obtained as a function of time using symmetrical numerical time differentiation within a time window corresponding to ±5 data samples. That is, averages of 5 points before and 5 points after the point were obtained for each sampling point, and the slope between the two averages was calculated.

The following measurements from each finger were taken from every trial. Preload normal force was the normal force present at the onset of load increase. Grasp response onset latency was the time interval from onset of load force increase to onset of reactive normal force increase, as assessed from force rate signals. Although we identified one or more peaks in the normal force rate profile (Fig. 2) (cf. Johansson et al. 1992a; Ohki and Johansson 1999), first peak amplitude and first peak latency relative to onset of load force were measured. A normal force response was considered present when the maximum normal force rate exceeded 2.5 N/s. Responses of weaker strengths could not be reliably detected in single trial records. In such cases in which weaker responses occurred, none of the above response parameters were measured, but peak rates were set to zero in statistical analyses. To quantify synchronization of early responses by the two fingers, the correlation coefficient of dynamic responses was calculated in a single trial with normal force rates of left versus right fingers during 50–300 ms (i.e., 100 points, sampled at 2.5-ms intervals) after load onset (cf. Shadmehr and Mussa-Ivaldi 1994). Static normal force response was measured as the difference between preload normal force and normal force at 100 ms before the end of the hold phase.

In the results, amplitude of the first force rate peak and correlation coefficient of the dynamic responses are detailed, as prediction effects on reactive response were most marked in the early dynamic phase (Ohki et al. 2002). Preload normal force is known to be influenced by predictions (Cole and Johansson 1993; Johansson et al. 1992a,c; Johansson and Westling 1988; Weinstein et al. 2000) and is thus also mentioned.

Statistical methods

Numerical values of normal forces were input into statistical software (STATISTICA, Statsoft, Tulsa, OK). Unless otherwise stated, statistical reports were made using repeated measures ANOVA. One type of ANOVA was performed primarily to assess the influence of adaptation after unexpected changes in load condition. Factors comprised trial number (L1–L3 for linked trials or U1–U8 for unlinked trials) and interval length (2 levels: short or long interval). The other type of ANOVA was performed to analyze cue effects. Factors comprised cue (2 levels: with or without cue), trial number (see trial number above), and interval length (2 levels, see interval length above). In addition, planned comparisons were performed to analyze specific effects, as described in the results. Values of P < 0.05 were considered statistically significant and population estimates are given in the text in the form of subject mean ± SD (n = 7). For each subject, and for each experimental condition, values for all trials were averaged and subject SD (n = 7) was calculated for these “average trials.” Average trials were also used in ANOVA analyses. Prior to calculating subject mean, correlation coefficients were z-transformed to normalize distributions. In graphs, SE is indicated unilaterally (n = 7).
RESULTS

Response adaptation during sequential unlinked trials

For self-generated bimanual movements, Witney et al. (2000) used unlinked trials to assess development of the forward model, as any change in grip force seen in the nonloaded right hand reflects purely predictive components and thus is a consequence of internal modeling. Thus we first examined adaptive changes in reactive response during sequential unlinked trials.

The framed responses in Fig. 2 were performed by a representative subject during sequential unlinked trials; i.e., during link-predictive series with short (Fig. 2A) and long (Fig. 2B) intertrial intervals. Loading of the apparatus reliably triggered normal force responses at the loaded left index (Cole and Abbs 1988; Johansson et al. 1992a,c; Johansson and Westling 1988). Nonloaded right fingers occasionally displayed a transient force increase when left fingers were loaded in isolation (white arrows) (cf. Ohki and Johansson 1999). These responses at loaded and nonloaded fingers were observed in all subjects and in all test series. However, when normal subjects experience one type of load condition throughout most of the trials, normal force responses become adapted to that condition (Ohki et al. 2002). Adapted responses were also observed in the present task after experiencing sequential unlinked trials. Transient force increases at the nonloaded right finger decreased gradually from U1 to U8 (see U8 in Fig. 2, A and B).

Figure 3, A and B, shows response onset latencies in sequential unlinked trials (U1–U8) during the link-predictive series. Note that latencies in nonloaded right fingers are presented only for U1–U5, as some subjects showed no detectable response in U6–U8. Normal force response from left fingers loaded in isolation started at 72.5 ± 7.0 ms after load onset. Latency of nonloaded right fingers was 93.4 ± 10.0 ms, significantly longer than that of loaded left fingers [F(1,6) = 47.7, P < 0.01; main effect by finger, for factors: finger × trial number (U1–U5) × interval length] (Ohki and Johansson 1999). Changes in response onset latencies during sequential unlinked trials demonstrated no adaptive changes with changing interval length, which was 5.6 ms longer in long-interval series than in short-interval series (data pooled from two fingers; F(1,6) = 13.1, P < 0.05; main effect by interval length).

If adaptation requires several trials with appropriate sensory feedback, as seen with self-generated movements (Witney et al. 2000), responses to a sudden change in load condition would be followed by gradual adaptation of the response with successive trials. Figure 3, C and D, shows changes in preload normal force in unlinked trials during the link-predictive series. When load conditions suddenly changed from concurrent loading to isolated loading through the left plate, preload force at the right finger was relatively strong (U1). However, this preload force gradually weakened by 0.4 N, irrespective of interval length [F(7,42) = 7.8, P < 0.01; main effect by trial number], although force at the loaded left finger showed little adaptive change. However, the magnitude of these influences was rather modest compared with previous reports (Cole and Johansson 1993; Winstein et al. 2000). No significant effect by interval length was identified in preload forces for both fingers, although forces by the left finger were slightly stronger in short-interval series than long-interval series (broken lines in Fig. 3, C and D).

Contrasting with the relatively minor adaptive change for preload normal force, amplitude of response, particularly at the nonloaded right finger, displayed clear effects of adaptation during sequential unlinked trials. When load conditions suddenly changed from concurrent loading to isolated loading during the link-predictive series, response of the nonloaded right finger was relatively strong in the first trial (black solid line, representing changes in first force rate peak of the response, Fig. 3, E and F). During subsequent unlinked trials, response weakened by 9.0 Ns [F(7,42) = 38.8, P < 0.01; main effect by trial number] and was virtually absent by U8. Latency of the peak was 119.8 ± 2.1 ms in U1 and 109.4 ± 3.4 ms in U5. Close inspection revealed that the most prominent

Note that only the first 2 trials (e.g., U1–U2 for unlinked behavior) and the last trial (e.g., U8) were shown in the sequential experiences of one type of load condition. A: short-interval series. B: long-interval series. White arrows indicate responses of the nonloaded right finger in the unlinked trials.
reduction in peak amplitude (by 6.4 N/s) occurred after experiencing one unlinked trial, i.e., between U1 and U2. However, response in U2 was still stronger than that in U8 (P < 0.005, Tukey’s honestly significant difference test). The first force rate peak of the left finger loaded in isolation appeared at 121.3 ± 15.1 ms after load onset. Peak amplitude of the finger remained fairly constant during sequential unlinked trials (black broken lines, Fig. 3, E and F). The loaded left finger thus responded with minor response from the nonloaded right finger in the final stage of adaptation [F(7, 42) = 4.0, P < 0.01; interaction between finger and trial number, for factors: finger × trial number × interval length]. Neither finger displayed any significant difference in peak amplitude with changing interval length.

Adaptive change during unlinked trials was also observed in the correlation coefficient for dynamic responses of the two fingers (black lines, Fig. 3, G and H), which were high in U1 and declined in subsequent trials [F(7, 42) = 18.0, P < 0.01; main effect by trial number]. No correlation was observed between the correlation coefficient and interval length.

No adaptive change in the amplitude of response during hold phase was apparent during sequential unlinked trials. For example, amplitude of static response displayed no main effect by trial number during unlinked trials.

In contrast to the link-predictive series, subjects received advance notice of the starts of sequential unlinked trials in the unlink-predictive series (cf. Fig. 5). Thus by comparing responses during unlinked trials between link- and unlink-predictive series, we examined the effects of auditory cueing; i.e., subject predictions independent from feedback experiences. In U1, after switching from linked to unlinked trials, the first force rate peak of the nonloaded right finger tended to be weaker when subjects were able to predict the new load condition based on an auditory cue (gray solid lines from unlink-predictive series, Fig. 3, E and F) than when they were unable to make such a prediction (black solid lines from link-predictive series). Amplitude was influenced by the cue [F(1, 6) = 8.1, P < 0.05; main effect by cue], but the interaction of cue and trial number was also significant [F(7, 42) = 4.8, P < 0.01]. Indeed, subsequent trials displayed a smaller decline in amplitude with cue (gray solid lines) than without (black solid lines), and the effects of cueing were reversed between U1 and the remaining trials [planned comparison; F(1, 6) = 20.2, P < 0.01]. Note that after sequential unlinked trials preceded by the cue during the unlink-predictive series (gray solid lines), subjects were not notified when a linked trial would be imposed (cf. Fig. 1C). Change in amplitude thus suggested that subjects gradually shifted their predictions to a linked trial with concurrent loading during sequential unlinked trials in the unlink-predictive series, irrespective of feedback experiences. The same reversal of effect was also observed in the correlation coefficient between dynamic responses [planned comparison; F(1, 6) = 23.8, P < 0.01; Fig. 3, G and H].

Although we have so far summarized adaptive changes during sequential unlinked trials, the first unlinked trials were preceded by variable numbers of linked trials (0–4; Fig. 1). Indeed, Witney et al. (2000) observed increased grip force modulation in the unlinked trial after three linked trials, rather than after only one. Effects of the preceding linked trials during sequential unlinked trials were therefore also examined. Figure 4 shows adaptive changes in first force rate peak of the non-
trials (0–4) × trial number (U1–U4) × interval length]. However, adaptation after no experience of linked trial (black dotted line) differed slightly from adaptation for other numbers of linked trials. Indeed, adaptation differed between short- and long-interval test series, and significant interaction was observed between the three factors [F(12,72) = 3.0, P < 0.01]. Differences between the two interval conditions were explained by the fact that the peak in U1 was stronger when subjects experienced no linked trial than when linked trials were experienced in the short-interval series. This indicates that subjects were able to prepare well for the coming linked trial by hearing beeps in the short-interval trial. Preload normal force also increased by 0.27 N in the short-interval series with beeps, whereas the corresponding value in the long-interval series was 0.13 N. However, under all other conditions, the peak was weaker when subjects did not experience a linked trial, irrespective of interval length [F(4,24) = 5.5, P < 0.01; main effect by experienced linked trials, data from U2–U4 included]. No significant difference was noted between number of experiences once subjects had experienced a linked trial [experienced linked trials (1–4) × trial number (U1–U4) × interval length]

Response adaptation during sequential linked trials

Although grip force modulation in linked trials does not represent a pure predictive component, Witney et al. (2000) observed adaptive change of grip force modulation during linked trials. Adaptive changes were therefore also examined during sequential linked trials (Fig. 5). In linked trials during the unlink-predictive series, normal force response of the left and right fingers started at 70.8 ± 5.5 and 77.6 ± 6.7 ms after the onset of concurrent loading, respectively (Fig. 6, A and B). Only latency of the right finger was shortened by 4.1 ms during sequential trials [F(2,12) = 27.5, P < 0.01; main effect by trial number]. Latency was also influenced by interval length for both left [F(1,6) = 25.5, P < 0.01; main effect by interval length, 3.8 ms difference] and right [F(1,6) = 23.3, P < 0.01;
FIG. 6. Adaptive changes during sequential linked trials after unexpected switch in load condition. Parameters are the same as in Fig. 3. Data were obtained from unlink-predictive series, except for those indicated by gray lines in E–H.

3.9 ms] fingers. Adaptive changes in preload normal force were again relatively minor. Significant effect was observed only in the left finger \( F(2,12) = 13.4, P < 0.01; \) main effect by trial number, 0.25 N decrease; Fig. 6, C and D]. Adaptive decreases in the left finger were similarly observed irrespective of interval length, although main effect by interval length was observed \( F(1,6) = 6.4, P < 0.05 \).

When load condition suddenly changed from isolated loading to the left plate to concurrent loading during the unlink-predictive series, normal force developed more slowly in the right finger than in the left (L1, Fig. 5). However, during experiences of sequential linked trials, normal force responses showed adaptation to the concurrent loading, and responses of the two fingers synchronized well (see responses in L3, Fig. 5). These adaptive changes were clearly observed in the amplitude of first force rate peak and correlation coefficient during sequential linked trials. First force rate peak of the right finger was relatively weak in the first trial after a sudden switch to the linked trial during the unlink-predictive series, developing significantly over sequential trials [black solid lines, Fig. 6, E and F; \( F(2,12) = 13.4, P < 0.01; \) main effect by trial number]. First force rate peak of the left finger remained constant during sequential trials (black broken lines, Fig. 6, E and F). Peak amplitudes of the two fingers thus differed significantly in L1 \( F(1,6) = 9.8, P < 0.05; \) main effect by finger, for factors: finger \( \times \) interval length], but this difference was eliminated in L3. Interval length exerted no influence. Latency of the peak did not show any adaptive change for either left or right finger (114.7 and 114.4 ms, respectively). The correlation coefficient of dynamic responses improved significantly during sequential linked trials in the unlink-predictive series \( F(2,12) = 20.6, P < 0.01; \) main effect by trial number; black lines, Fig. 6, G and H]. As for correlation coefficient, significant interaction was also observed between trial number and interval length. This was explained by the fact that values in L1 were lower for short-interval series than for long-interval series. Amplitude of static response displayed significant adaptive change at the right finger \( F(2,12) = 7.3, P < 0.01; \) main effect by trial number]. However, contrary to the results seen for first force rate peak, amplitude declined during sequential trials.

The effects of auditory cues were examined by comparing responses during sequential linked trials with (gray lines from link-predictive series, Fig. 6, E–H) and without (black lines from unlink-predictive series) cues. An interaction was identified between cue and trial number in first force rate peaks over sequential linked trials \( F(2,12) = 4.6, P < 0.05, \) data from L1–L3 analyzed; Fig. 6, E and F]. The effect of cue in L2–L3 was reversed from that in L1 during the short-interval test series [planned comparison; \( F(1,6) = 17.9, P < 0.01 \], and disappeared during the long-interval test series. In addition, the correlation coefficient between dynamic responses was affected differently by the cue in L1 and subsequent trials [interaction; \( F(2,12) = 4.2, P < 0.05 \).]

The effects of preceding unlinked trials on response were also analyzed during sequential linked trials in the unlink-predictive series. First force rate peak in the linked trial was significantly influenced by the number of experienced unlinked trials before the switch in load condition \( F(5,30) = 4.1, P < 0.01; \) main effect by experienced unlinked trials, for factors: experienced unlinked trials \( (3–8) \times \) interval length \( \times \) trial number]. This was largely attributable to the strong response after the eighth unlinked trial (U8), with no influence on first force rate peak observed if U8 was omitted from analysis [experienced unlinked trials \( (3–7) \)].

Adaptation to linked and unlinked trial depends on prediction error

Regarding adaptation with self-generated movement, the magnitude of anticipatory grip modulation changes depending on prediction error in the previous trial. We thus examined whether this was also the case for sensory-driven reactive movement.

Speed of adaptation was calculated in accordance with the model developed by Witney et al. (2001). In this model, subjects are assumed to alter future responses in proportion to prediction error on the current response. Thus the prediction for concurrent loading in the \( n \)th trial can be determined as \( p_n = p_{n-1} + (1 - p_{n-1})g_L \) when the load condition was concurrent in the previous trial, and \( p_n = p_{n-1} - p_{n-1}g_U \) when an unlinked trial with isolated load is experienced \( (g_L \) and \( g_U \), proportionality gains for linked and unlinked trials, respectively). Response amplitude in the \( n \)th trial can be assumed to be \( R_n = R_U + p_n(R_L - R_U) \) \( (R_U \) and \( R_L \) responses when \( p = 0 \) and \( p = 1 \), respectively), and thus proportionality gains can be determined by response amplitudes in sequential trials based on the following equations: \( R_n - R_{n-1} = g_LR_L - g_LR_{n-1} \) (linked trial) and \( R_n - R_{n-1} = g_LR_L - g_LR_{n-1} \) (unlinked trial).

Figure 7A shows a scatter plot of first force rate peaks for the right finger from single unlinked trials in the link-predictive series. In the graph, the abscissa and ordinate represent \( R_{n-1} \) and \( R_n - R_{n-1} \), respectively. As can be expected from the model described above, amplitude change from U1 to U2 displayed correlations with response amplitude in U1 for both
short- (black circle) and long-interval series (gray circle; $r \leq -0.80, P < 0.01$). Significant correlations were observed until $n = 4$ ($r \leq -0.52, P < 0.01$), and $g_U$ determined from the slope was about 0.8. Thus, although most adaptive change occurred between U1 and U2 (see above), adaptation was in effect for at least three consecutive trials.

Similar analysis was also performed for the linked trial during the unlink-predictive series (Fig. 7B). Although the responses of the right finger in the linked trial are not purely anticipatory and include a sensory-driven component, the negative correlation between $R_{n-1}$ and $R_n - R_{n-1}$ was observed until $n = 3$, irrespective of interval length [$r = (-0.38) - (-0.50), P < 0.01$]. Proportionality gain ($g_L$) as determined from the slope was about 0.4.

**DISCUSSION**

The present study examined the effects of repetitive experiences of feedback events on the adaptation of bimanual reactive response. We hypothesized that, if the internal model, with which the brain generates motor commands, could modulate the neuronal center engaging in reactive responses, adaptation of the reactive response would be controlled in a manner resembling that observed for voluntary movement (Witney et al. 2000, 2001). We therefore utilized a bimanual task similar to that used by Ohki et al. (2002). During the task, subjects performed bimanual manipulation of two objects. The objects were loaded under computer control, allowing instant changes in load condition, that is, simultaneity of load forces to the objects, on a trial-to-trial basis. Changes in load condition were either preceded by an auditory cue or occurred unexpectedly without cue. Subjects were required to maintain the object in the original position and thus needed to produce a rapid increase in normal force when object load changed.

The task in the present study was comparable to the bimanual task that has been used to examine predictive mechanisms for self-generated movements (Witney et al. 2000), although our apparatus differed from the one used in that study in two major ways. First, our apparatus was not designed to exert force on one plate by movement of the other, as seen in systems used to examine self-generated movements (Blake et al. 1998; Witney et al. 2000). However, concurrent load to both plates provides a good reproduction of situations in daily life, in which a single object is held in both hands and pulled by a third party. Indeed, even in self-generated movement, the crucial part is not necessarily to replicate sensory feedback caused by the other hand, but to reproduce sensory feedback consistent with a context (Witney et al. 2001). Second, movements of our plates were rotational, so they were turning in different directions, and this certainly cannot be reconciled with the behavior of a single object. However, movement of the plates during test series was 2 mm at most, as can be seen in the previous study (Fig. 2 of Ohki and Johansson 1999). Given the 10-cm beams connecting plates to servomotors, the distance between the two plates did not change considerably. Indeed, our subjects reported that they could not feel any difference in directions of movements for the two plates. We therefore performed direct comparison of the predictive mechanisms influencing self-generated and sensory-driven reactive movements.

**Comparisons of predictive mechanisms for self-generated and reactive movements**

As reported previously (Ohki et al. 2002), we observed that not only preload normal force, but also normal force response became adapted to a load condition when subjects repeatedly experienced that condition during sequential trials. However, response immediately after unexpected change of load condition was clearly influenced by previous condition, and at least several trials were required for the subject to display complete adaptation to the new condition, as seen with self-generated movement (Witney et al. 2000). Such adaptive changes were predominantly observed in responses of the right finger when loading differed dramatically between the two conditions. Adaptive changes were clear in the early dynamic part of the response, both when the finger was not loaded and when concurrent loading was present.

Adaptation revealed a number of properties similar to those observed with self-generated movement. First, striking simi-
larieties in adaptation were observed during short- and long-interval series. Specifically, adaptation depends on feedback events (i.e., cutaneous inputs from the finger carrying information regarding stability of the finger–object interface), but not on time after an event (Witney et al. 2000 for self-generated movement). Second, feedback experiences influence future responses in a manner whereby prediction error determines modification of the response, as revealed after analysis of adaptive speed in self-generated movement (cf. Witney et al. 2001). In reactive responses, speed of adaptation to concurrent load ($g_L \approx 0.4$) differs from that to isolated load ($g_U \approx 0.8$), although the former value is somewhat smaller than the corresponding value for self-generated movement ($g_L = 0.51–0.55$). Differences in $g_U$ might be explained by the fact that $g_L$ was determined from reactive responses in linked trials, which represent a mixture of sensory-driven and predictive components. Finally, as seen in Fig. 7, subjects can display intermediate prediction between the two basic response patterns on a single trial basis. The only difference from the results seen with self-generated movement was that effects of the number of preceding feedback trials before unexpected change of load condition could not be detected. However, this could be due to the construction of the current test series, in which subjects gradually shifted predictions in preparation for a sudden switch in load condition. The results of the present study therefore fit the hypothesis that selection of an internal model can modulate the neuronal center processing sensory-driven reactive responses.

Previous studies have reported that automatic normal force responses, triggered by inputs from cutaneous receptors in the fingertips, are under predictive control and are scaled using early cues about rate of load force changes (Cole and Abbs 1988; Johansson et al. 1992a; Weinstein et al. 2000) and friction (Birznieks et al. 1998; Cole and Johansson 1993). However, such adaptation is known to occur quickly, with initial adjustment taking place soon after the subject touches an object, and thus before loading force and total adjustments are completed within one or two trials. Such quick adaptation is also known to take place for self-generated movements. Parameterization of grip force to load force during self-generated movements is proposed to be under predictive control depending on previous experience, which is described as anticipatory parameter control (Johansson and Cole 1994). For example, several studies have examined how subjects perform when the normal physical properties of an object, such as weight, frictional surfaces, and surface orientation, are changed with each trial (Birznieks et al. 1998; Edin et al. 1992; Gordon et al. 1993; Jenmalm and Johansson 1997; Johansson and Westling 1984). Such studies have demonstrated rapid updating to the new situation within one trial. Similarly, studies of unusual dynamic properties in objects have displayed quick learning of the new dynamics by subjects (Wing and Flanagan 1998). However, if such parameter control is insufficient to allow adaptation to the current context for self-generated movement, several trials are required to switch to the proper control pattern. Such slow adaptation was observed when bimanual coordinated and independent movements must be switched (Witney et al. 2000) or when the object displays unusual weight (Flanagan et al. 2001). The current study therefore shows that such slow adaptation could also take place for sensory-driven reactive responses.

Possible neuronal substrates for adaptive changes

The cerebellum has been considered crucial for forward modeling of movements (Miall et al. 1993). In accordance with the hypothesis that the internal model also affects reactive movement, the cerebellum is known to affect the predictive adaptation of reactive responses. For example, cooling the cerebellum eliminates preparatory responses to resist displacement of handheld objects (Dugas and Smith 1992) and eliminates prediction-dependent modification of scaled wrist responses to pulse and step perturbations (Hore and Villis 1984). In addition, neurons in the cerebellar cortex display preparatory responses that change in parallel with preparatory increases in grip force preceding force-pulse perturbations (Dugas and Smith 1992). Although cerebellar patients are able to use sensorimotor memory about object load to adapt force output based on previous experience, they are significantly less efficient at such activity than healthy controls (Müller and Dichgans 1994).

The present results suggest that the neuronal center for sensory-driven reactive responses also displays predictive adaptation (Ohki et al. 2002; Weinstein et al. 2000) in association with selection of an internal model. Automatic motor responses of digits elicited by tactile input are likely to be mediated by a variety of centers that engage different areas in the CNS. These areas would include subcortical centers, such as the spinal cord, and cortical sites (Deuschl et al. 1995; Jenner and Stephens 1982; Johansson et al. 1994; MacNeil and Johansson 1994). The influence of subject predictions on response onset latency indicate that initiation of response is also the target of predictive adaptation, which takes place in the subcortical reflex center (cf. Johansson et al. 1994). However, strong adaptive changes are also observed in the early dynamic phase of the reactive response, which most probably involves cortical centers, including the primary motor cortex (Johansson et al. 1994). In accordance with our results, subject preparations are known to influence neural activity in both the primary somatosensory areas (Evarts and Tanji 1974, 1976) and the premotor cortex (di Pellegrino and Wise 1991; Godschalk et al. 1981; Riehle and Requin 1993). Interestingly, when relatively long preparatory periods are introduced, reaction times increase (cf. Teichner 1954) and set-related activities in the premotor cortex are decreased (Wise and Kurata 1989). These could explain the small differences between responses in short- and long-interval series; responses in the long-interval series displayed consistently longer latencies with weaker preload forces, although similar adaptive changes were observed for both interval lengths. Furthermore, auditory cues induced stronger preparation for linked trials in short-interval series than in long-interval series in the link-predictive series (U1, Fig. 4).

The evidence has increasingly suggested that motor skill learning can be mediated by experience-driven changes within the somatosensory (Braun et al. 2000, 2001; Moore et al. 1999) and motor (Gandolfo et al. 2000; Karni et al. 1995) cortices. Different neuronal groups in cortical centers may therefore be involved in bimanual coordinated movement and unimanual movement, causing different reactive responses when sensory input occurs. Indeed, a separate group of neurons in the primary motor cortex is known to be activated during bilateral movements (Aizawa et al. 1990).
Adaptation without feedback experiences

The present study also displayed top-down effects on the adaptation of finger response to a load condition. That is, the auditory cue or speculation by the subject about the potential for a sudden switch in load condition in the near future could modify response. However, these effects seem rather weak in comparison with those resulting from sensory feedback. That is, if the subject experienced a feedback signal contradictory to the cue in the link-predictive series, response in the next trial was adapted, depending on the immediate sensorimotor memory obtained from the previous trial (Fig. 4).

With self-generated movement, visual information is known to affect the anticipatory parameterization of fingertip forces. Particularly when subjects encounter misleading visual size cues about the weight of an object, they continue to influence predictive force control for a number of trials despite somatosensory information (Flanagan et al. 2001). The influence of visual cues thus appears stronger than that of auditory cues. One possible reason for this difference is that visual size cues are frequently used in daily life to gauge the weight of an object, whereas auditory cues were temporarily used in the current experiment. Thus repeated experiences might strengthen the influence of visual cues on the internal model or visual cues might even be involved in the model.

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REFERENCES


