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RESEARCH ARTICLE

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Visual feedback schedules influence visuomotor resistance to the Müller-Lyer figures

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Abstract We examined whether blocked or random visual feedback schedules influence visuomotor resistance to the Müller-Lyer (ML) illusion. Participants completed closed-loop (CL) and open-loop (OL) grasping movements to an object embedded within fins-in and fins-out ML configurations. In the blocked feedback schedule, CL and OL trials were completed in separate blocks of trials, whereas visual conditions were randomly interleaved in the random feedback schedule. The results of the blocked feedback schedule showed that OL, but not CL, trials were influenced in a direction consistent with the perceptual effects of the ML illusion. For the random feedback schedule, however, both CL and OL trials were influenced by the illusion. We have interpreted these results to reflect the fact that participants evoked distinct control strategies based on the predicted availability of visual feedback. Specifically, the refractory nature of CL trials in the blocked feedback schedule suggests that advance knowledge that visual feedback would be available during a response encouraged an online control strategy wherein metrical visual information supported grasping. When visual feedback was unavailable (i.e., blocked OL trials), or could not be predicted in advance of a response (i.e., random CL and OL trials), it is proposed that movements were structured offline via perception-based visual information that was "tricked" by the cognitive properties of the ML illusion.

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Visual feedback schedules influence visuomotor resistance to the Müller-Lyer figures

A topic of continued debate in the visuomotor control literature surrounds the degree to which pictorial illusions influence goal-directed actions. On one hand, a number of studies have reported that the trajectories of closed-loop (CL) and open-loop (OL) grasping movements are mostly, if not entirely, immune to pictorial illusions (e.g., Aglioti et al. 1995; Brenner and Smeets 1996; Danckert et al. 2002; Haffenden and Goodale 1998; Hu and Goodale 2000; Hu et al. 1999; Jackson and Shaw 2000; Westwood et al. 2000a, b): a finding frequently framed within the theoretical tenets of the perception/action model (PAM: Milner and Goodale 1995; see Goodale and Westwood 2004 for recent review) and the claim that visually derived actions are mediated by metrical (i.e., Euclidean) visuomotor networks residing in the dorsal visual pathway. On the other hand, some studies have reported that pictorial illusions influence either the early (e.g., Glover and Dixon 2002) or the entire time course (Franz 2003) of visually derived actions.[1] In the first instance, Glover and Dixon (2001a, b, c, 2002) reported that pictorial illusions (e.g., simultaneous tilt illusion, Titchener circles illusion) produced an early but not late influence on CL and OL grasping movements. According to Glover and Dixon, that dynamic illusion effect reflects the fact that independent visual representations support the early and late stages of action: a relative (i.e., non-Euclidean) "visual planning representation" supporting initial kinematic parameterization and a metrical "visual control representation" asserting gradual control over the unfolding response

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[1] We refer to visually derived actions as those responses wherein visual input is available to the performer at the time of response planning (i.e., closed-loop and open-loop responses).

(the planning/control model: PCM; see Glover 2004). In the second instance, Franz (2003) reported that the Titchener circles illusion influenced the entire time course of OL grasping movements. On the basis of those and other work, Franz et al. (2000, 2001) proposed that visually derived actions are wholly influenced by pictorial illusions because the visual system computes a single and relative representation of object size that is linearly transformed to support visually derived actions as well as perception-based activities (the common representation model: CRM; see Franz et al. 2000).

It is unlikely that each model outlined above is correct; however, it is possible that one or a number of parameters associated with the organization of a grasping response might explain the equivocal findings in the pictorial illusions literature. Recently, it has been proposed that the manner participants control their response (i.e., online vs. offline) influences the type of visual information (i.e., metrical vs. relative) used by the motor system—thus impacting visuomotor resistance to pictorial illusions (Heath and Rival 2005; Heath et al. 2004a; Westwood and Goodale 2003). In this framework, it is proposed the presence of continuous visual input from the grasping environment allows the performer to structure their response primarily online, i.e., use continuous visual input from the grasping environment to support movement planning and control processes. Moreover, an online control strategy is thought to engage unitary and metrical visual information for the planning and subsequent continuous control of a movement only after the response has been cued (so-called real-time movement control). Thus, it has been proposed that actions controlled primarily online unfold without pictorial illusions influencing the early or later stages of the response. When continuous visual contact with the grasping environment is not permitted, however, participants' responses may be structured without the benefit of response-produced visual feedback (i.e., the action is structured offline via central planning mechanisms). In this mode of control, the spatiotemporal characteristics of a response are structured primarily in advance of movement onset (i.e., offline) using unitary and relative visual information that renders the early and late stages of an action susceptible to pictorial illusions.

In support of the hypothesis just described, Heath and colleagues (Heath and Rival 2005, Heath et al. 2004a; 2005; also see Westwood et al. 2000b) showed evidence that the type of control strategy evoked by participants influences visuomotor resistance to the ML illusion. In two studies (Heath and Rival 2005; Heath et al. 2004a), it was found that advance scaling of grip aperture to the perceived size of an object embedded within a ML illusion influenced CL and OL grasping movements for upwards of 80% of grasping time. It was proposed that scaling grip aperture in advance of the response disrupted the normally online operation of the visuomotor system and encouraged a mode of grasping control wherein the specification of premovement grip aperture as well as the spatiotemporal characteristics of the unfolding response were structured offline via relative visual information. In another study (Heath et al. 2005), grasping movements initiated with a neutral grasping posture (i.e., the typical thumb and forefinger pinched lightly together) were differentially influenced by the ML illusion depending on the availability of visual feedback during the response. Specifically, a consecutive series of CL grasping movements were refractory to the ML figures (i.e., from 20 to 80% of grasping time), whereas OL grasping movements performed in a separate block of trials were influenced by the illusion during the same time period (cf. Westwood et al. 2001b; but see Westwood and Goodale 2003). It was proposed that advance knowledge concerning the availability of visual feedback encouraged the adoption of different control strategies: an online strategy refractory to pictorial illusions (i.e., the CL trials) and, an offline strategy (i.e., OL trials) reliably influenced by the ML figures.

In the present investigation, we sought to test the hypothesis that structuring a grasping response online or offline influences visuomotor resistance to the ML illusion. To accomplish that objective, participants completed CL and OL grasping movements to an object embedded within ML figures in two visual feedback schedules: a blocked feedback schedule wherein visual conditions were performed in separate blocks of trials and a random feedback schedule where visual conditions were randomly interleaved on a trial-by-trial basis. The present manipulation is motivated by a number of studies demonstrating that blocked and random feedback schedules evoke distinct control strategies (e.g., Khan et al. 2002; Jakobson and Goodale 1991). Specifically, advance knowledge that visual feedback will be available during a trial (i.e., CL trials in blocked feedback schedule) is posited to encourage a primarily online and feedback-based mode of reaching/grasping control. In evidence to that position, a priori knowledge that visual feedback will be available during a response results in reaching/grasping movements with faster reaction times (e.g., Khan et al. 2002), reduced endpoint error (e.g., Elliott et al. 1999b; Heath et al. 2004b, Westwood et al. 2001a, 2003; Woodworth 1899), greater online limb corrections (e.g., Chua and Elliott 1993; Khan and Franks 2000; Keele 1968; Heath 2005), and smaller maximal grip aperture values (Berthier et al. 1996; Heath et al. 2004a; Westwood et al. 2000a) relative to OL trials performed under the same (i.e., blocked) feedback schedule. These kinematic discrepancies are frequently held as evidence that CL actions are controlled more online than their OL counterparts (see Elliott et al. 2001 for extensive review). Interestingly, however, when CL and OL trials are randomly interleaved on a trial-by-trial basis (i.e., random feedback schedule), the previously reported differences in reaction time (Zelaznik et al. 1983; Elliott and Allard 1985), number of online movement corrections (Khan et al. 2002; Jakobson and Goodale 1991), and maximal grip aperture (Jakobson and Goodale 1991) are nullified. More specifically, trials performed in a random feedback schedule (CL and OL) behave like the OL trials performed in the blocked feedback schedule. In particular, participants evoke a primarily offline mode of control wherein the spatiotemporal characteristics of the action are planned based on the visual information available to central planning mechanisms.

In terms of potential research outcomes, if visuomotor resistance to the ML figures is in part determined by how participants structure their response, then the visual feedback schedules used in this investigation should differentially influence the degree to which actions are "tricked" by the illusion. Specifically, if participants know in advance that visual feedback will be available during an upcoming trial, it is hypothesized that responses will be structured primarily online and hence mediated by metrical visual information that is refractory to the illusory-array. When visual feedback is unavailable during a response (i.e., OL trials in the blocked feedback schedule) or cannot be predicted (i.e., CL and OL trials in the random feedback schedule), it is proposed that participants formulate their action primarily offline via central planning mechanisms. Since this offline mode of control is mediated by relative visual information, it is hypothesized that motor output will be influenced in a direction consistent with the perceptual effects of the ML figures.

Methods

Participants

Fourteen right-handed students from Indiana University volunteered to participate in this study. All had normal or corrected to normal vision and were naïve as to the exact purpose of the experiment. This research was performed in accordance with guidelines established by the Declaration of Helsinki (1964).

Apparatus and procedure

Participants stood for the duration of the experiment and completed grasping movements to a 5 or 7-cm target object embedded within appropriately sized fins-in and fins-out ML configurations (30° fin angles). For each trial, a single ML target array was presented. The long axis of the ML figure was situated perpendicular to the midline of participants and presented on a blackened table surface at a distance of 35-cm from a home position (i.e., a telegraph key located 5-cm from the front edge of the table top). Grasping the target object involved 35-cm of midline limb displacement anterior to the home position. Vision of the grasping environment was manipulated via liquid-crystal shutter goggles (PLATO Translucent Technologies, Toronto, ON, Canada), and an interval-timing device.

Participants rested the medial surface of their right hand on the home position with forefinger and thumb pinched lightly together (i.e., a neutral posture). Grasping movements were completed in two visual conditions and two visual feedback schedules (see below). Each trial began with a 2,000-ms preview phase in which the shutter goggles were set in their transparent state, thus providing vision of the target array and grasping environment. In the CL visual condition, following the preview phase, an auditory tone signaled participants to begin their grasping movement and the goggles remained transparent for the duration of the trial. As a result, continuous visual input was available for online modification, or modifications, to the grasping trajectory. In the OL condition, the auditory tone signaled participants to initiate their grasping movement following preview and the goggles reverted to their opaque state coincident with participant's release of pressure from the home position. In this condition, up-to-date visual information from the grasping environment was not available to the motor system during the response.

All participants completed CL and OL trials in two visual feedback schedules (blocked, random). In the blocked feedback schedule, visual conditions were performed in separate trial blocks. For example, consecutive CL trials ($n=48$) were performed before the same number of consecutive OL trials ($n=48$) was conducted. The presentation of visual condition in this feedback schedule was counterbalanced across participants. In the random feedback schedule, the two visual conditions were randomly interleaved. The presentation of feedback schedule (blocked versus random) was counterbalanced across participants. Twelve trials were made to each of the stimulus arrays (fins-in, fins-out) and target object (5 – 7-cm) in both feedback schedules (blocked, random) and both visual conditions (CL, OL), for a total of 192 trials. Stimulus arrays (fins-in, fins-out) and target object (5 – 7-cm) were presented pseudorandomly.

Three-dimensional kinematic data were collected via an Optotrak 3020 (NDI, Waterloo, ON, Canada) sampling at 200 Hz for 2 s following onset of the auditory initiation cue. Infrared-emitting diodes (IREDs) were placed on the lateral edge of the index finger, the medial edge of the thumb, and the styloid process of the wrist. IRED position data were filtered offline by using a second-order dual-pass Butterworth filter employing a low-pass cut-off frequency of 15 Hz. Subsequently, instantaneous velocities were calculated by differentiating the displacement data using a three-point central finite difference algorithm. Movement onset was defined as the first sample frame after which resultant wrist velocity attained and maintained a value of 50 mm/s for ten consecutive frames (50 ms). Movement offset was defined via a two-step procedure. First, resultant wrist velocity was required to fall below a criterion of 50 mm/s. Second, the first sample frame from within the velocity criterion in which no further mediolateral thumb displacement was detected was marked for movement offset. This procedure was used to ensure that participants had physically touched the target.

Dependent variables included: reaction time (RT: time from auditory initiation tone to movement onset) and grasping time (GT: time between movement onset and movement offset). In addition, GT was normalized and absolute grip aperture (GA: distance between thumb and index finger) was measured at 20, 40, 60, and 80% of GT. GA was measured at different time points to determine if the ML illusion differentially impacted grasping performance at different stages in the grasping trajectory. In addition to absolute GA data, we computed scaled illusion effects so that our work is comparable to all extant studies on this topic (e.g., Franz 2003; Glover and Dixon 2002). In line with Glover and Dixon (2002), scaled illusion effects were determined by the ratio of the mean illusion effect (i.e., mean GA for the fins-out figure minus mean GA for the fins-in figure) divided by the slope of GA to object-size function. Illusion effects were determined separately for participants at each time point, feedback schedule and visual condition. Slopes for each time-point, feedback schedule and visual condition were determined by averaging over participants.

Results

An alpha level of 0.05 was used to interpret all omnibus tests. Where appropriate, *F*-statistics were corrected for violations of the sphericity assumption using the appropriate Huynh-Feldt correction (corrected degrees of freedom are reported to one decimal place). Simple effects analyses were used to decompose significant main effects/interactions.

RT and GT data were subjected to 2 (feedback schedule: blocked, random) by 2 (vision: CL, OL) by 2 (target object: 5, 7-cm) by 2 (illusion: fins-in, fins-out) repeated measures ANOVA. The results for the RT analysis yielded effects for vision, $F(1, 13) = 10.63$, $P < .01$, and an interaction involving feedback schedule by vision, $F(1, 13) = 15.25$, $P < .01$. In the blocked feedback schedule, RTs for CL trials (207 ± 10 ms) were faster than OL trials (234 ± 15 ms) ($t(13) = 3.84$, $P < .01$), whereas RTs for CL (225 ± 14 ms) and OL (222 ± 13 ms) trials did not differ in the random feedback schedule ($t(13) = 1.32$, $p = 0.20$). The results for GT produced effects for vision, $F(1, 13) = 26.54$, $P < .001$, and target object, $F(1, 13) = 20.97$, $P < .01$. GTs for CL trials (711 ± 23 ms) were faster than OL trials (774 ± 29 ms), and GTs to the 7-cm object (738 ± 25 ms) were faster than the 5-cm object (748 ± 27 ms).

GA data were submitted to 4 (time: 20, 40, 60, 80% of GT) by 2 (feedback schedule: blocked, random) by 2 (vision: CL, OL) by 2 (target object: 5, 7-cm) by 2 (illusion: fins-in, fins-out) repeated measures ANOVA. This analysis yielded a four-way interaction, $F(3,39) = 3.28$, $P < .04$. For ease of interpretation, we elected to decompose this interaction, as well as outline all significant GA findings via separate 4 (time) by 2 (vision) by 2 (target object) by 2 (illusion) ANOVAs for feedback schedule.

Blocked feedback schedule

This analysis revealed effects for time, $F(1.7, 23.0) = 98.23$, $P < .001$, vision, $F(1,13) = 17.84$, $P < .001$), target object, $F(1, 13) = 76.86$, $P < .001$, illusion, $F(1, 13) = 5.71$, $P < .04$, and interactions involving time by vision, $F(2.0, 26.4) = 9.92$, $P < .01$, time by target object, $F(1.8, 23.8) = 46.86$, $P < .001$, and vision by illusion, $F(1, 13) = 6.98$, $P < .03$. In terms of the time by vision interaction, CL trials produced smaller GA values than OL trials at 20% ($t(13) = 2.74$, $P < .02$), 40% ($t(13) = 3.90$, $P < .01$) and 60% ($t(13) = 6.19$, $P < .001$) of GT; however, at 80% ($t(13) = 1.35$, $p = .19$) of GT, CL and OL trials did not differ (Fig. 1). Decomposition of the time by target object interaction showed that GA for the 5-cm target object was smaller than the 7-cm target object at 20% ($t(13) = 2.63$, $P < .03$), 40% ($t(13) = 7.20$, $P < .001$), 60% ($t(13) = 8.20$, $P < .001$) and 80% ($t(13) = 10.08$, $P < .001$) of GT. The vision by illusion interaction indicated that the fins-out ML figure elicited larger GA values than the fins-in ML figure during OL ($t(13) = 4.38$, $P < .001$), but not CL ($t(13) = 0.78$, $p = .45$) trials (Fig. 1).

Random feedback schedule

This analysis produced effects for time, $F(2.1, 28.0) = 102.74$, $P < .001$, target object, $F(1, 13) = 60.16$, $P < .001$, illusion, $F(1, 13) = 7.58$, $P < .02$, and interactions involving time by vision, $F(2.4, 31.9) = 7.59$, $P < .01$, and time by target object, $F(1.8, 23.77) = 19.32$, $P < .001$. In terms of the effect of illusion, GA for the fins-out ML figure was reliably greater than the fins-in ML figure (Fig. 1). The time by vision interaction showed that GA for CL and OL trials was equivalent at 20% through 60% of GT, ts $(13) = 1.02$, 1.34, and 1.45, respectively, all ps $> .05$. At 80% of GT, OL trials yielded larger GA values than CL trials ($t(13) = 2.18$, $P < .05$) (see Fig. 1). In keeping with the results for the blocked feedback schedule, the time by target object interaction showed that GA for the 5-cm object was smaller than the 7-cm object at 20% ($t(13) = 3.53$, $P < .01$), 40% ($t(13) = 6.94$, $P < .001$), 60% ($t(13) = 6.91$, $P < .001$) and 80% ($t(13) = 8.26$, $P < .001$) of GT. Notably, the absence of a vision by illusion interaction indicated that the ML figures influenced both CL and OL trials.

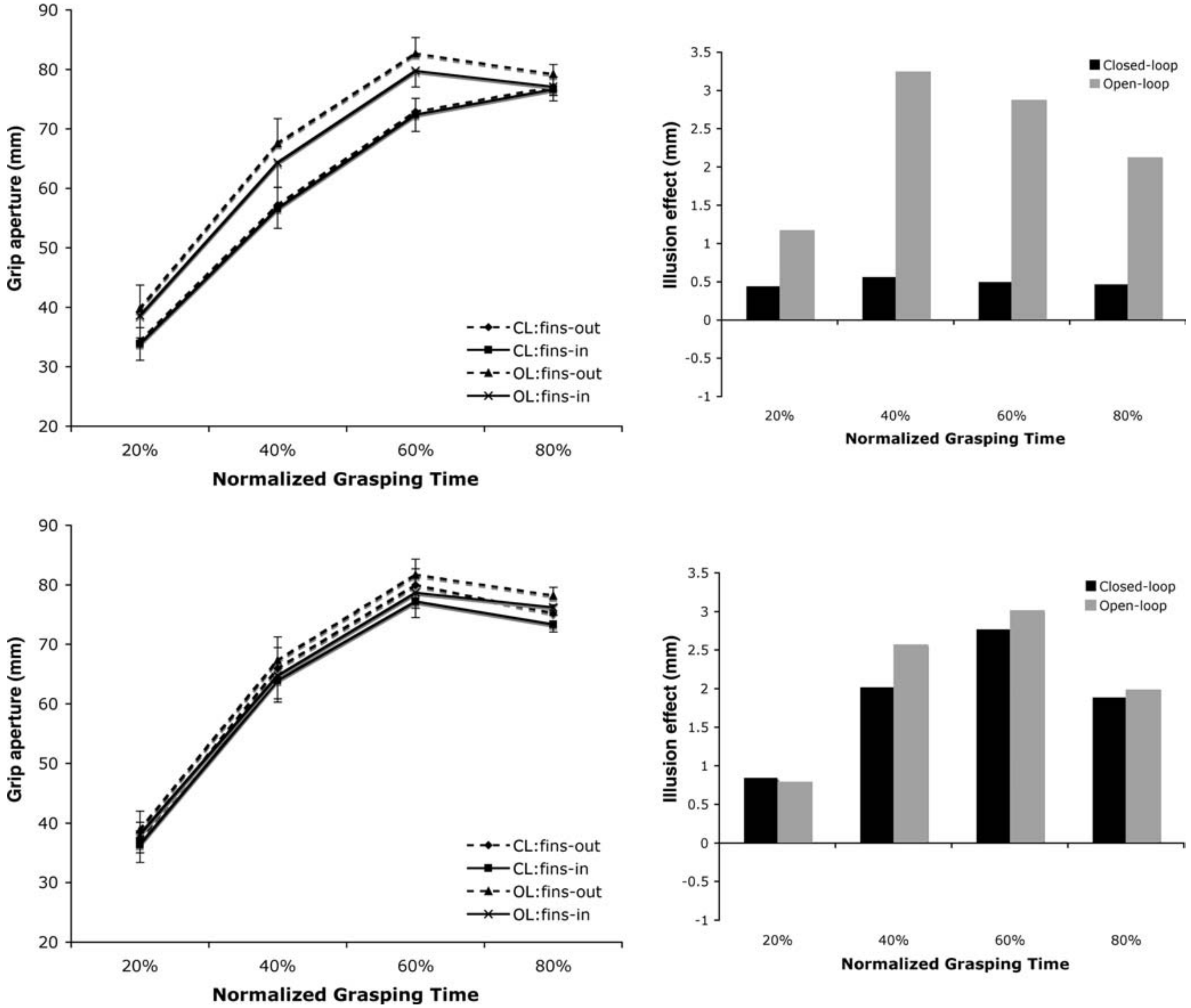

Fig. 1 The effect of the fins-in and fins-out ML configurations on grip aperture (mm) in blocked (*top panel*) and random (*bottom panel*) feedback conditions as a function of closed-loop and open-loop trials at 20, 40, 60, and 80% of grasping time. Error bars represent SEM. In addition, *insert bar graphs* represent mean difference scores between ML configurations (fins-out minus fin-in) at each time point (20, 40, 60, and 80% of GT) for each feedback schedule and visual condition

Scaled illusion effects

Scaled illusion effects were examined via 4 (Time: 20, 40, 60, 80% of GT) by 2 (Feedback schedule: blocked, random) by 2 (vision: CL, OL) fully repeated-measures ANOVA. This analysis did not reveal significant main effects or interactions (all ps > .13)[2](Fig. 2).

Discussion

CL and OL Trials in the Blocked Feedback Schedule

CL trials in the blocked feedback schedule yielded smaller GA values than OL trials, and GA values for the former were entirely refractory to the ML figures (i.e., from 20 to 80% of GT), whereas GA values for the latter were wholly influenced (i.e., from 20 to 80% of GT) in a direction consistent with the perceptual effects of the stimulus array. In line with that finding, in our analysis of scaled illusion effects we found no evidence that the ML figures elicited a time-varying effect on motor output. These findings match recent work showing that CL and OL actions performed in separate blocks of trials are

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[2] It was proposed by one of the Reviewers that lack of statistical power may have precluded a reliable effect of time using the scaled illusion effect metric. Indeed, the F statistic associated with the effect of time was < 1. As stated by Keppel and Wickens (2004), an F statistic < 1 does not permit meaningful determination of a replication sample size.

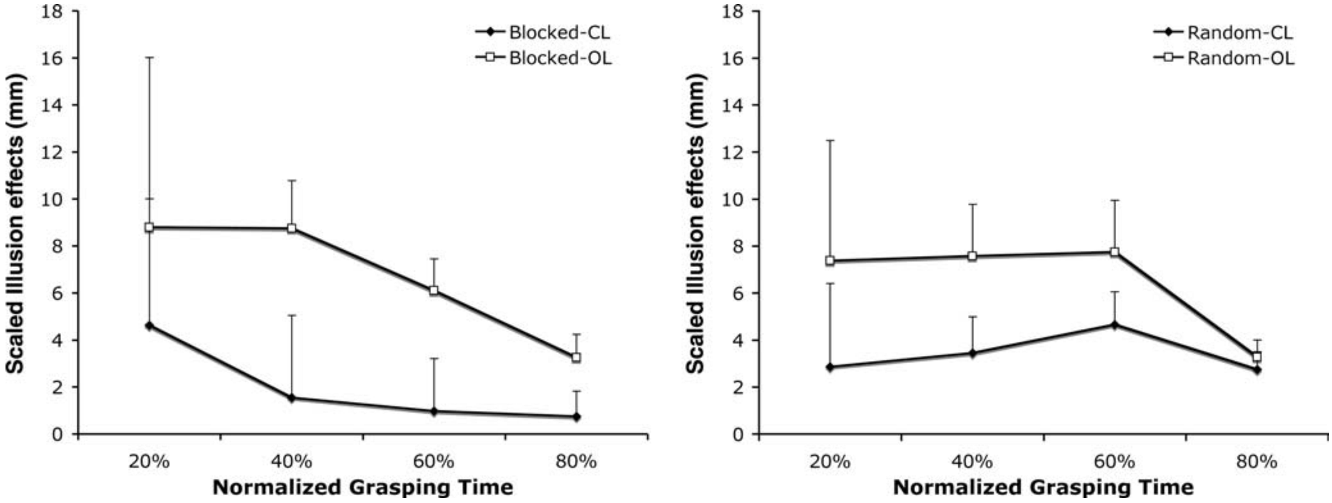

Fig. 2 Scaled illusion effects (mm) for blocked (*left panel*) and random (*right panel*) feedback schedules as a function of grasping time and visual condition. *Error bars* represent SEM

differentially influenced by the ML figures (Heath et al. 2005).

The results from the blocked feedback schedule do not conform to current models of visuomotor control. First, the fact that neither CL nor OL trials elicited a time-varying impact on motor output is not consistent with the PCM's assertion of a ''dynamic illusion effect'' (Glover 2004). Recall that the PCM predicts an early illusory-effect that is gradually resolved as visual and/or nonvisual (efference copy, proprioceptive and/or memory-based target information) feedback resources are processed online via a metrical ''visual control representation'' (Glover and Dixon 2001a, b, c; 2002). Second, the present findings are not matching with the CRM's claim that visually derived actions and perception-based activities are supported by a single and relative representation of object size (Franz 2003; Franz et al. 2000, 2001). Certainly if a common internal representation were used for grasping (and perception), then the CL and OL trials studied here would have been similarly influenced by the ML figures. Third, the fact that OL trials were influenced by the ML illusion counters the PAM's view that visual input from the grasping environment at the time of response planning is sufficient to implement metrical grasp parameters (see Aglioti et al. 1995; Danckert et al. 2002; Haffenden and Goodale 1998; Westwood et al. 2000a; Westwood and Goodale 2003).

Why then did the ML figures differentially influence the CL and OL grasping movements studied here? A possibility outlined in the Introduction is that the manner the CL and OL actions were structured (i.e., online vs. offline) might have influenced the type of visual information (i.e., metrical vs. relative) used by the motor system. Concerning the hypothesis that CL and OL actions were structured differently, we found that reaction times for OL trials were greater than CL trials and that the former elicited larger GA values for the majority of the grasping trajectory (i.e., for upwards of 60% of GT). Previous studies have linked the longer reaction times of OL trials to movements that are more preprogrammed (e.g., Carson et al. 1990). Moreover, OL trials are thought to elicit larger GA values due to the specification of a greater margin of error via offline planning mechanisms to accommodate for the absence of response-produced visual feedback (e.g., Berthier et al. 1996; Goodale et al. 1994; Wing et al. 1986). That offline control strategy and instantiation of an artificially large hand opening, however, is not necessary for CL trials. Presumably that is because the presence of highly accurate and up-to-date visual information voided any uncertainty about the size or location of the to-be-grasped object and allowed CL actions to be controlled primarily online.

Concerning the view that online and offline modes of grasping control were supported by different forms of visual information, we found that OL actions were wholly ''tricked'' by the ML figures (i.e., from 20 to 80% of GT), whereas CL trials were refractory to the illusion during the same time period. Those results suggest that the different modes of control attributed to the CL and OL trials were supported by unitary—but independent—visual information (Milner and Goodale 1995). More specifically, the results of the blocked feedback schedule suggest that metrical visual information served the early (i.e., at 20% of GT) and continuous online control of CL trials (e.g., Bédard and Proteau 2004; Elliott et al. 1999a; Georgopolous et al. 1983), whereas relative visual information mediated the offline control of OL trials (cf. Heath 2005; Heath et al. 2005).

CL and OL trials in the random feedback schedule

Of course, we included the random feedback schedule as a means to test the assertion that the visual information mediating actions structured primarily online or offline is distinct. We found that grasping movements performed in an unpredictable visual environment resulted in comparable GA values for CL and OL actions, and both visual conditions were influenced by the ML figures throughout the response. In terms of the scaled illusion effect, that metric did not show evidence that the ML figures elicited a time-varying impact on grasping responses.

Recall that the predicted availability of visual feedback has been shown to influence how actions are controlled (Elliott and Allard 1985; Jakobson and Goodale 1991; Khan et al. 2002; Zelaznik et al. 1983; but see Winges et al. 2003). CL actions performed in a random feedback schedule typically show increased reaction times and decreased reliance on response-produced visual feedback relative to blocked feedback schedule counterparts (Khan et al. 2002). Additionally, Jakobson and Goodale (1991) reported that a variable feedback schedule produced similar maximal GA values between CL and OL actions. In the present investigation, we found that reaction times for CL, but not OL, trials increased in the random as compared to the blocked feedback schedule. In addition, an unpredictable visual environment produced comparable GA values for CL and OL trials. In line with Khan and colleagues (2002) and Jakobson and Goodale(1991), we have taken this as evidence that CL and OL actions in the random feedback schedule were structured primarily offline. In other words, participants structured their grasp parameters such that they did not intend to use visual feedback, even during trials when it was available.

Bearing in mind that CL trials were refractory to the ML figures in the blocked feedback schedule, the change in sensitivity of CL actions in an unpredictable visual environment is congruent with our hypothesis that an offline mode of grasp control is mediated via perception-based (i.e., relative) visual information that can be "tricked" by the ML figures. Notably, this finding suggests that intrinsic tasks constraints influence the type of visual information supporting motor output.

A key theoretical question that remains unresolved is when the motor system accesses relative visual information for the offline control of action. One possibility is that participants deliberately shape the parameters of the to-be-executed grasping movement while previewing the target object and hold that movement plan in memory until response cuing (Henry 1986). A second possibility is that participants formulate the constituent elements of a motor plan at the time of response cuing using real-time visual information (Klapp 1975; Westwood and Goodale 2003). Although the present study cannot disentangle between the alternate possibilities, a key piece of evidence favoring the second possibility relates to the response latencies associated with trials in the random feedback schedule. Recall that planning times for CL trials in the random feedback schedule increased to a level commensurate with OL trials. That increased planning time suggests that performers were engaging visual information after response cuing and not before in order to specify more fully the spatiotemporal characteristics of the to-be-executed grasping movement. Although Westwood and Goodale (2003) have proposed that real-time visual information permits the computation of absolute object metrics, it is entirely possible that the longer planning times associated with offline grasping control might disrupt the normally online preparatory set (Schluter et al. 1999), and thus favor any interactions that might exist between the visual systems mediating metrical (i.e., the dorsal visual pathway) and relative (i.e., the ventral visual pathway) visual information.

One last issue to be addressed is where in the central nervous system the effect of a pictorial illusion might arise. Dyde and Milner (2002) have pointed out that the effects of some illusions (e.g., simultaneous tilt illusion) are structural in nature and thus exist at very early cortical levels (i.e., V1 and V2). Importantly, as ventral and dorsal visual pathways share early visual input, their respective control of perceptions and actions is thought to be influenced by the so-called structural illusions (Milner and Dyde 2003; see also Coren et al. 1978). In contrast, when an illusion arises due to an obligatory contextual feature, or features, of the stimulus array (e.g., induced Roelofs effect, rod-in-frame illusion, Titchener circles), Dyde and Milner(2002) proposed the origin of the illusion exists deep within the ventral visual pathway. Such an origin is thought to give rise to perceptions, but not actions, that are tricked by these so-called strategy illusions (Coren et al. 1978). In terms of the ML figures, both structural (e.g., optical blur: see Chiang 1968; Coren et al. 1978; but see Skottun 2000) and strategic (see Greene and Nelson 1997; Mack et al. 1985; Redding et al. 1993) origins have been put forth. Although the precise origin(s) of the ML illusion is beyond the scope of the present research, it is worthy to mention that a structural basis for the illusion is not compatible with the present findings. Indeed, if the genesis of ML illusion were entirely structural, then one would have predicted that the different feedback schedules and visual conditions used here would not have differentially influenced the degree to which the ML figures influenced motor output (see above). As such, the present results suggest that the nature of the ML illusion is in part strategic and mediated by later occurring visual processing mechanisms (i.e., the ventral visual pathway).

Conclusion

It is proposed that when provided advance knowledge that visual feedback will be available throughout a response, participants evoke a primarily online mode of grasping control mediated by metrical visual information. When visual information is unavailable or cannot be predicted, however, it is proposed that participants adopt a primarily offline mode of grasping control supported by relative visual information. Although existing models forwarded to explain the effects of the ML figures on CL and OL actions do not entirely conform to the present results, the fact that online control resulted in grasping movements entirely refractory to the ML figures, whereas offline control resulted in actions wholly influenced by the ML figures is consistent with the PAM's notion that unitary visual information—whether metrical or relative—is independently accessed and used by the motor system to support actions (see Goodale and Westwood 2004).

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