

Erin K. Cressman · Ian M. Franks · James T. Enns
Romeo Chua

No automatic pilot for visually guided aiming based on colour

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Abstract It has been claimed that visually guided limb movements are automatically corrected in response to a change in target location but not when the same change in target is cued through a colour switch (Pisella et al. 2000). These findings were based solely on limb endpoint data. Here we examine the kinematic trajectory of the hand during the entire movement. Participants pointed rapidly to a target object that could change position either by changing spatial location, or by switching colour with a second object. Participants performed in two instructional conditions: a “go” condition to index intentional movements and a “stop” condition in which failures to stop pointing indexed automatic limb guidance. Kinematic analysis indicated efficient intentional pointing in both location and colour change conditions. However, only targets that changed spatial location elicited involuntary limb modifications and these occurred within 150 ms of the change. This conclusion held even after baseline differences in the efficiency of processing colour-defined targets were taken into account, thereby strengthening the claim of a strongly automatic pilot for visually guided limb movements.

Keywords Vision · Action · Dorsal-ventral systems · Automatic guidance

Introduction

Many researchers characterize the human ability to make rapid, on-line adjustments in pointing, reaching,

and grasping in response to unexpected changes in the task environment as evidence of an automatic pilot. By this they mean that limb movements are modified rapidly and in flight in response to changes in the location, orientation, or shape of a target object (e.g., Bard et al. 1999; Brenner and Smeets 2003; Desmurget and Prablanc 1997; Desmurget et al. 1999; Paulignan et al. 1991; Pisella et al. 2000; Prablanc et al. 1986). Moreover, the limb modifications occur well in advance of the point in time at which individuals become consciously aware of the changing task environment (Castiello and Jeannerod 1991; Castiello et al. 1991; Johnson et al. 2002) and under some conditions participants are also unaware of their own limb modifications in response to these changes (Chua and Enns 2005; Day and Lyon 2000; Fecteau et al. 2001; Goodale et al. 1986; Pélisson et al. 1986; Prablanc and Martin 1992; Prablanc et al. 1986).

The existence of an automatic pilot for visually guided action is consistent with the dual systems theory (Milner and Goodale 1995), which postulates the operation of two visual streams. The ventral, or cognitive, stream is said to project from visual cortex to inferior-temporal cortex and is responsible for our conscious perception and visual experience. The dorsal, or sensorimotor, stream projects from visual cortex to posterior parietal cortex and is believed responsible for on-line control of visually guided actions and operates outside of our conscious awareness (Goodale and Milner 1992, 2004; Goodale and Westwood 2004; Milner and Goodale 1995; see also Bridgeman 2000; Pisella and Rossetti 2000; Rossetti et al. 2000).

But how fully “automatic” is the pilot? Cognitive neuroscientists have previously distinguished between relatively “weak” versus “stronger” forms of automatic behaviour in the study of other information processing abilities. For example, the tendency for a suddenly appearing target in the visual field to attract the eyes and to initiate an ocular orienting response is only weakly automatic, since there are many conditions under which this spontaneous tendency can be overridden, as one does, for example, when continuing a gaze-locked

E. K. Cressman · I. M. Franks · R. Chua (✉)
School of Human Kinetics, University of British Columbia,
210-6081 University Boulevard, V6T 1Z1 Vancouver,
BC, Canada
E-mail: Romeo.Chua@ubc.ca
Tel.: +1-604-8221624
Fax: 1-604-8226842

J. T. Enns
Department of Psychology,
University of British Columbia, V6T 1Z4 Vancouver, BC, Canada

conversation with one person despite a new individual entering one's field of view (Egeth and Yantis 1997; Posner 1980). In contrast, on-line modifications to visually guided actions have been claimed to be strongly automatic because they resist all conscious volitional control (Day and Lyon 2000).

In support of strong automaticity for visually guided pointing, Pisella et al. (2000) asked participants to point rapidly to targets that would occasionally (20% of trials) jump to another location immediately upon the start of the movement. Participants performed under one of two instructional sets: "location-go" (LG) and "location-stop" (LS). The LG instructions were to respond to the target jump by pointing to the new location, whereas LS instructions were to interrupt the movement if a target jump was detected. The main finding was that participants modified their pointing and touched down at the new target location on a significant number of trials, regardless of instructions. "LG" participants successfully corrected their actions approximately 30% of the time (a measure of a combination of intentional and automatic control) and "LS" participants incorrectly completed their movements to the new target location 9% of the time (a measure of automatic control).

In a second experiment, the target display consisted of a red and a green object. Participants were instructed to point towards the green object, and on perturbed trials, the green object would exchange positions with the red object. In contrast to the automatic corrections observed to perturbations in location (experiment 1), there were no automatic corrections in response to the colour switch.

At first glance, Pisella et al.'s (2000) results appear to support a strongly automatic system, mediated exclusively by the dorsal stream, which is incapable of processing colour. However, upon closer examination two important questions remain. First, the claim of strong automaticity is predicated on the finding that a small percentage of movements (9%) were adjusted toward the new target location when participants were instructed to stop in response to a detected change in location, whereas similar adjustments were not observed in colour switches. But what if the speed and accuracy of detecting these two kinds of signals is not equivalent? For example, if colour change detection is less efficient than location change detection, then participants may have simply required more time to initiate any type of movement correction (automatic or intentional) in response to a colour change. This issue could be addressed by a full comparison of the Colour-go (CG) and stop conditions, such as was provided for the LG and stop conditions. The CG data would provide important baseline information regarding the speed and accuracy of detecting colour changes. Unfortunately, this was not given in Pisella et al. (2000).

A second, and equally important, issue is that Pisella et al.'s conclusions were based solely on the final outcome of the pointing (e.g., movement time and end-point), precluding an examination of modifications

made during the movement. As shown by Day and Lyon (2000), to correctly examine on-line movement control, a detailed spatial and temporal analyses of trajectory deviations is necessary. Given the central issue of automaticity during on-line control in the study by Pisella et al. (2000), an analysis of unfolding movement trajectories is justified. Such an analysis would offer several advantages. First, it would reveal when changes to the movements first occur with respect to the onset of the visual events, and so colour and location change detection could be compared directly. Second, analysis of movement trajectories could provide a more sensitive index of "automaticity," one that does not depend on the completion of pointing movements. Specifically, a kinematic analysis of the "stop" conditions would allow examination of whether participants initiated any trajectory adjustments immediately prior to successfully interrupting their movements. Indeed, if the automatic pilot is mediated by the fast dorsal stream, it is likely that such modifications would occur prior to interruption of the movement by the slower, conscious, ventral stream. In contrast, if the colour-change target does not even engage the dorsal stream, then no similar modifications prior to movement interruption should ever occur for colour changes under the "stop-instructions."

To address these issues, we conducted a conceptual replication of Pisella et al. (2000) while simultaneously recording movement kinematics that occur between the initiation and end of each pointing action. We used a repeated-measures design in which all participants performed under four conditions: LG, LS, CG, and colour-stop (CS). We also limited our examination to movements of approximately 175–225 ms in duration, in order to maximize the likelihood of observing the automatic corrections reported by Pisella et al.

This design first of all permitted an assessment of whether there were automatic corrections in pointing (action modifications toward the changed target) that were masked by using the strict criterion of failing to interrupt pointing in the "stop" conditions. A strongly automatic pilot would predict that many more action modifications would be revealed by this more sensitive measure. Second, our design allowed an assessment of whether the high rate of successful "stops" in pointing to colour targets reflected the relatively inefficient processing of colour changes, or whether colour changes really don't produce kinematic corrections in the same way that location changes do.

Methods

Participants

Eleven right-handed university students (three female, eight male, mean age = 23.1 ± 3.2 years) with normal or corrected-to normal visual acuity participated in this study. Participants were remunerated \$25 for their involvement. All participants gave informed consent,

and the study was conducted in accordance with the ethical guidelines set by the University of British Columbia. Data from two participants were excluded for failure to follow basic task instructions.

Apparatus

Stimulus display

All stimuli were presented on a custom-built 18×24 in. display panel. The display consisted of an array of bi-coloured (red/green) light-emitting diodes (LED) below a transparent plexiglass sheet. A sheet of white tracing paper situated between the LED array and the plexiglass kept the LEDs hidden from view. Activation of a single LED either in red or green (i.e., the target) was viewed by the participant as a clearly visible point source of light, measuring 5 mm in diameter.

Participants viewed the display panel, oriented 20° from horizontal, from a distance of approximately 60 cm, with their head movements restricted by a chin-rest. The participants were positioned such that their midline was aligned with the vertical meridian of the panel and a starting position (demarcated by a 12 mm circular marker) located centrally at the bottom of the panel. Targets were presented in one of two positions, located 2.5 cm to left or right of the vertical meridian of the display, and approximately 27 cm forward from the starting position.

Motion analysis

Participants pointed with their right-hand using a stylus. An infrared-emitting diode was placed at the tip of the stylus and 3D position was monitored using an OPTOTRAK (Northern Digital, Waterloo, ON, Canada) motion analysis system (3D resolution 0.01 mm). The tip of the stylus was equipped with a microswitch that provided an analogue signal indicating whether or not the stylus was in contact with the surface of the display panel. The 3D position of the stylus and the status of the microswitch were sampled at 500 Hz.

Procedures and design

In an initial session, participants completed a block of control trials, in which a single green target appeared randomly in one of the two possible target locations. Participants completed 50 trials to each target, for a total of 100 control trials. Participants were told that they could begin their movement anytime following the appearance of the target and that it was not a reaction time task. Participants were required to complete the movement with a movement time goal of 200 ms. Movement time was measured from the instance of stylus lift-off to the moment of stylus contact with the

display panel. Movement time feedback was provided on every trial. In order to proceed with the experiment, participants were required to meet a criterion in which the last 20 trials of the control block had to have been performed with a mean movement time between 185 and 215 ms, and a mean ± 1 SD range that fell between 160 and 240 ms.

Upon successful completion of the control block, participants completed the four experimental conditions: LG, LS, CG, and CS. Go and Stop conditions were performed in separate sessions over 2 days and the order was counterbalanced across participants. The first session was performed immediately following the first control block. The second session was preceded by a block of approximately 20 practice trials similar to the first control block.

In the LG and LS conditions, a single green target appeared in one of the two target positions (100 trials per position). On 20% of the trials, the target moved to the second target position instantly upon movement initiation (Perturbed trials). On the remaining 80% of the trials, the target remained at its original location. In the LG (Go) condition, participants were instructed to move to the target and to correct their movements if necessary (see Fig. 1). In the LS (Stop) condition, participants were instructed to abort their movements immediately if the target changed location.

In the CG and CS conditions, a green and a red target appeared simultaneously at the two target positions. The green target appeared on the left side on 100 trials and on the opposite side on 100 trials, for a total of 200 trials. On 20% of the trials, the green and red targets interchanged position immediately upon movement initiation. Similar instructions regarding the Go and Stop procedures were provided as in the LG and LS conditions. The green target always served as the goal object for participants.

During each experimental condition, participants were reminded that this was not a reaction time task and instructed to maintain the 200 ms movement time goal. Movement time feedback was provided if the movement time for an unperturbed trial fell outside a 175–225 ms bandwidth. No movement time restrictions were placed on responses during perturbed trials.

Data reduction

The raw data from the OPTOTRAK were converted into 3D coordinates and digitally filtered using a second-order dual-pass Butterworth filter with a low-pass cut-off frequency of 10 Hz. Instantaneous velocity along the 3D displacement curve was determined by calculating the resultant change in displacement at each time point. The start and end of the movement was determined by the status of the stylus microswitch (from stylus lift-off to stylus contact). Overall endpoint accuracy was calculated in the form of radial error, representing the linear distance between the target

coordinates and the coordinates of the stylus at the end of the movement.

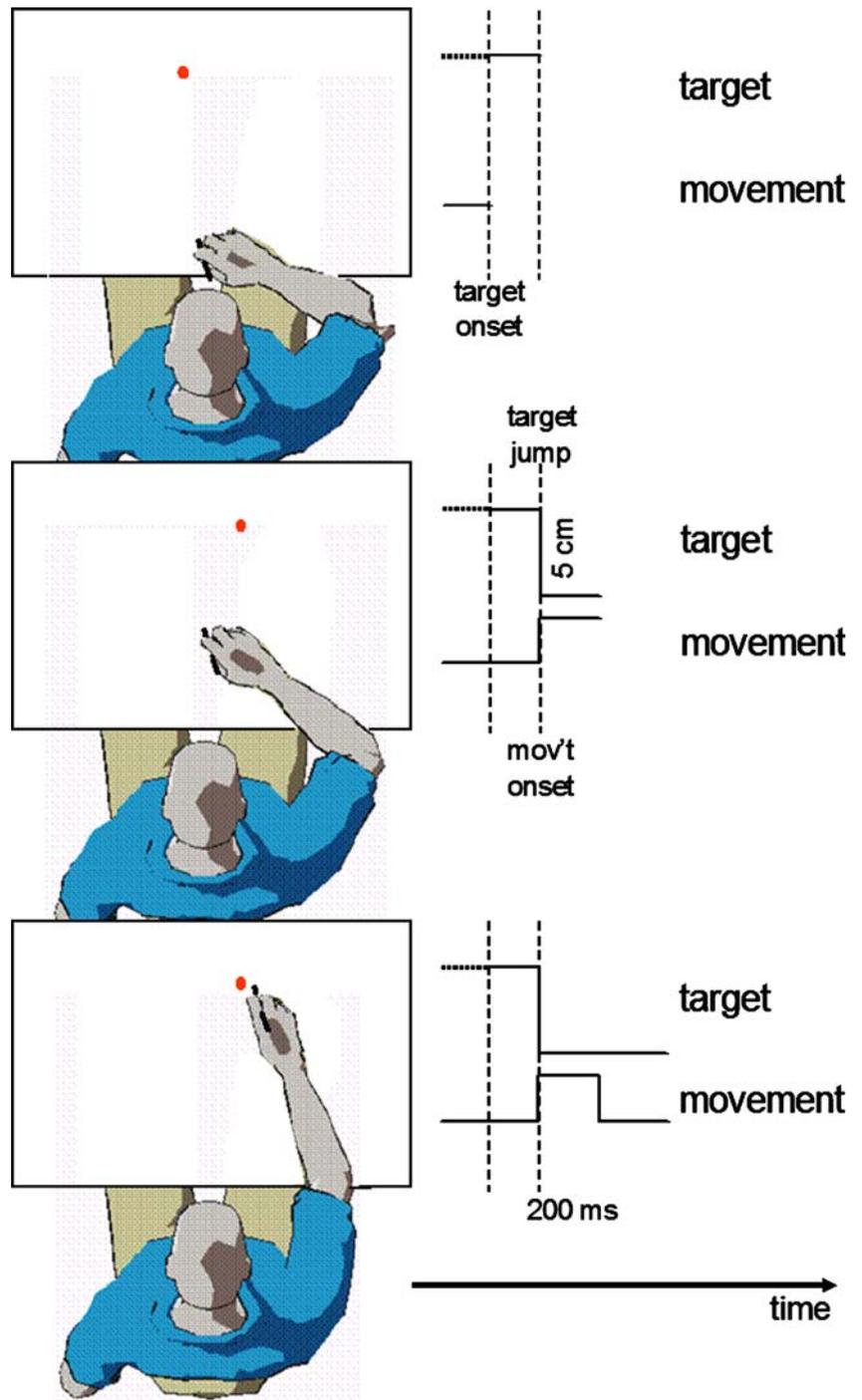
Analyses and results

Classification of pointing responses

Pointing responses were classified in one of three ways: pointing completed to the initial target position (T1),

pointing completed to the new target position (T2) or stopped responses (SR). Following Pisella et al. (2000), the classification of T1 and T2 responses required the calculation of a 95% confidence interval in horizontal accuracy for the initial target position. Pointing responses, in which participants' touched down, were counted as T2 responses if the endpoint fell outside of the 95% confidence interval in the direction of the second target position. Pointing responses that did not make contact with the display panel were classified as SR.

Fig. 1 Timeline of trial events. Panels depict a perturbed trial under the location go condition



Pointing movement time and accuracy

Pointing on the 80% of unperturbed target trials in each of the four conditions (LG, LS, CG and CS) was classified as T1 on approximately 95% of the trials. Mean movement time and radial error on these trials are shown in Table 1. These data show that participants completed their movements to unperturbed target locations within the goal criterion (204.5 ms) and with reasonable accuracy (overall radial error = 9.8 mm). Repeated measures ANOVA revealed no significant differences between Conditions (LG, LS, CG and CS) for either movement time, $F_{(3, 24)} = 1.763$, $P = 0.181$, or radial error, $F_{(3, 24)} = 0.512$, $P = 0.678$.

Pointing movements that were adjusted toward the new target location on the 20% of perturbed trials were classified as T2. The percentage of these responses for “go” instructions was reduced relative to the high rate of T1 responses on unperturbed trials, and there were relatively few T2 responses in the “stop” instructions on perturbed trials, as will be discussed below. As a result, mean movement time, and accuracy were analysed only for the successfully completed responses in the “go” condition, as shown in Table 1. ANOVA revealed that pointing to perturbed targets indeed took longer to complete than to unperturbed targets, $F_{(1, 8)} = 22.478$, $P = 0.0015$. Moreover, the movement times on perturbed trials were longer in the CG than the LG condition, $F_{(1, 8)} = 19.008$, $P = 0.0024$. Pointing movements to perturbed targets were marginally less accurate than to unperturbed targets, $F_{(1, 8)} = 5.111$, $P = 0.0537$, but there was no reliable difference in movement accuracy between Location and Colour conditions, $F < 1$.

Pointing on perturbed trials

Successful pointing responses on the 20% of trials in which the target was perturbed were expected to be classified as T2 in “go-instruction” conditions and SR in the “stop-instruction” conditions. The frequency of these two responses are shown in Fig. 2 (T2 responses) and Fig. 3 (SR responses).

Inspection of the T2 responses in Fig. 2 shows that successful corrections in pointing to the new target location occurred on 84% of trials in the LG and 45% of trials in the CG conditions.¹ To analyse these data statistically, the proportions were first submitted to an arcsin-squareroot transform and then subjected to a

repeated measures ANOVA involving condition (Location, Colour) and trial type (Go, Stop). The analysis revealed significantly more T2 responses for location than colour changes, $F_{(1, 8)} = 19.749$, $P = 0.0022$, and more T2 responses following “go” than “stop” instructions, $F_{(1, 8)} = 28.203$, $P = 0.0007$. The interaction between these two factors was also significant, $F_{(1, 8)} = 7.456$, $P = 0.0258$.

Inspection of the SR responses in Fig. 3a shows that participants were able to successfully stop their pointing actions, when instructed to do so, 84% when the target changed location and 52% when it changed colour, $F_{(1, 8)} = 19.975$, $P = 0.0021$. Figure 3b shows that when failures to stop pointing occurred, they were very infrequent (less than 16%) and evenly distributed among the two target locations in the Location Change condition. In contrast, stopping failures were much greater and biased toward the first target location in the Colour Change condition (44%). This interaction between the factors of Condition and Target Location was significant, $F_{(1, 8)} = 31.989$, $P = 0.0005$.

Kinematic analysis of pointing trajectories

The foregoing analysis was based entirely on endpoint accuracy of pointing, following Pisella et al. (2000). As outlined in the Introduction, this analysis may mask important information regarding on-line control. In order to examine the trajectories of pointing movements in this experiment, an average spatial trajectory in the 2D plane of the movement was first calculated for each participant from all unperturbed trials. The 2D plane of movement was defined by display coordinates such that the target stimulus was located 27 cm forward (y -direction) and 2.5 cm to the left or right (x -direction) of the starting position. The points in this trajectory were obtained by deriving the mean spatial position in the x - y plane for every 2 mm of forward movement progression in the y -direction. If a trajectory did not have a position value at the exact spatial location required, one was obtained by linear interpolation from the closest data points within a maximum distance of 1 mm. In addition, for each point, the standard deviation of the mean position in the x -direction was also calculated. The resulting mean spatial trajectory, together with its two standard deviation bandwidth, then became the standard against which pointing on perturbed trials could be assessed.

Figure 4 shows examples of mean pointing trajectories for unperturbed target trials (circles) and for individual perturbed trials (+). Pointing movements that deviated toward the perturbed target location by crossing the mean spatial trajectory’s variability bandwidth were classified as T2 responses. In addition, a conservative estimate of the time at which the movement began to deviate toward the new target location was calculated. This estimate was defined as the point in time at which the displacement in the lateral axis of the movement

¹In Pisella et al. (2000) participants corrected their movements to T2 only 30% of the time in the Location-Go condition, in contrast to the 84% reported here. We suspect two reasons for this difference. First, our participants received more opportunity to practice the task, with some completing over 700 pointing trials before even starting in the location-go condition. Second, our strict movement time criterion of 200 ms likely encouraged movement initiation based solely on dorsal stream information (rather than on ventral information that may be slower and less likely to detect the new target position). We also note that this high level of correction is consistent with the study by Day and Lyon (2000).

Table 1 Mean (SD) movement time (ms) and radial error (mm) of pointing movements

	Location		Colour	
	Go	Stop	Go	Stop
Unperturbed targets				
Movement time	201.6 (7.9)	204.2 (7.7)	206.3 (4.1)	205.3 (4.7)
Radial error	10.3 (2.8)	9.6 (2.4)	10.0 (2.2)	9.3 (1.4)
Perturbed targets				
Movement time	318.1 (88.8)	–	378.6 (93.9)	–
Radial error	17.8 (11.8)	–	20.0 (12.7)	–

showed a reversal toward the opposite direction. Note that the classification of pointing responses based on the movement trajectory does not require that the movement actually be executed to completion (i.e., to touch down on the display panel). Thus, we were also able to assess what happened in pointing movements that were

successfully stopped when participants were instructed to do so.

Figure 5 shows the mean proportion of T2 responses on perturbed trials, assessed using mean pointing trajectories. A comparison with the endpoint data in Fig. 2 indicates that these two ways of examining the data are

Fig. 2 Proportion of perturbed trials classified as T2 responses for (a) Location Go and Location Stop; (b) Colour Go and Colour Stop. *Error bars* = standard error

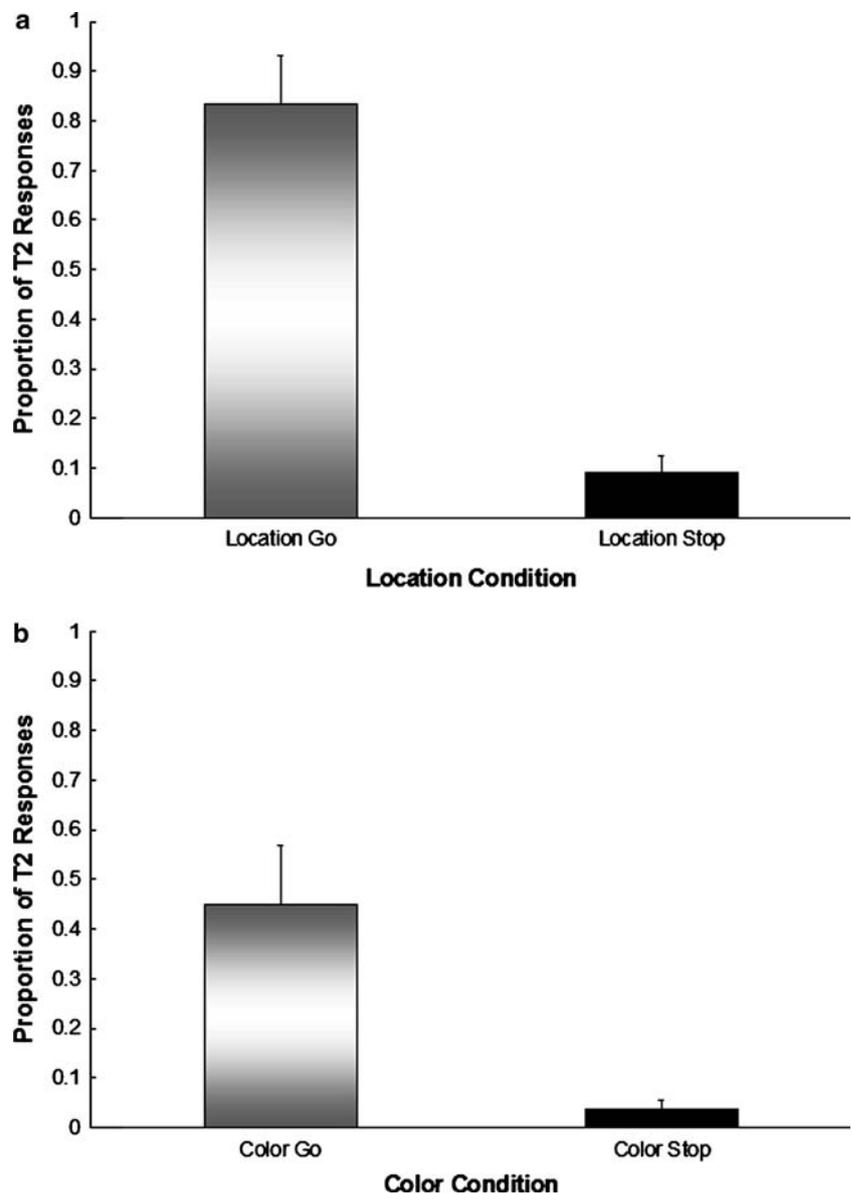
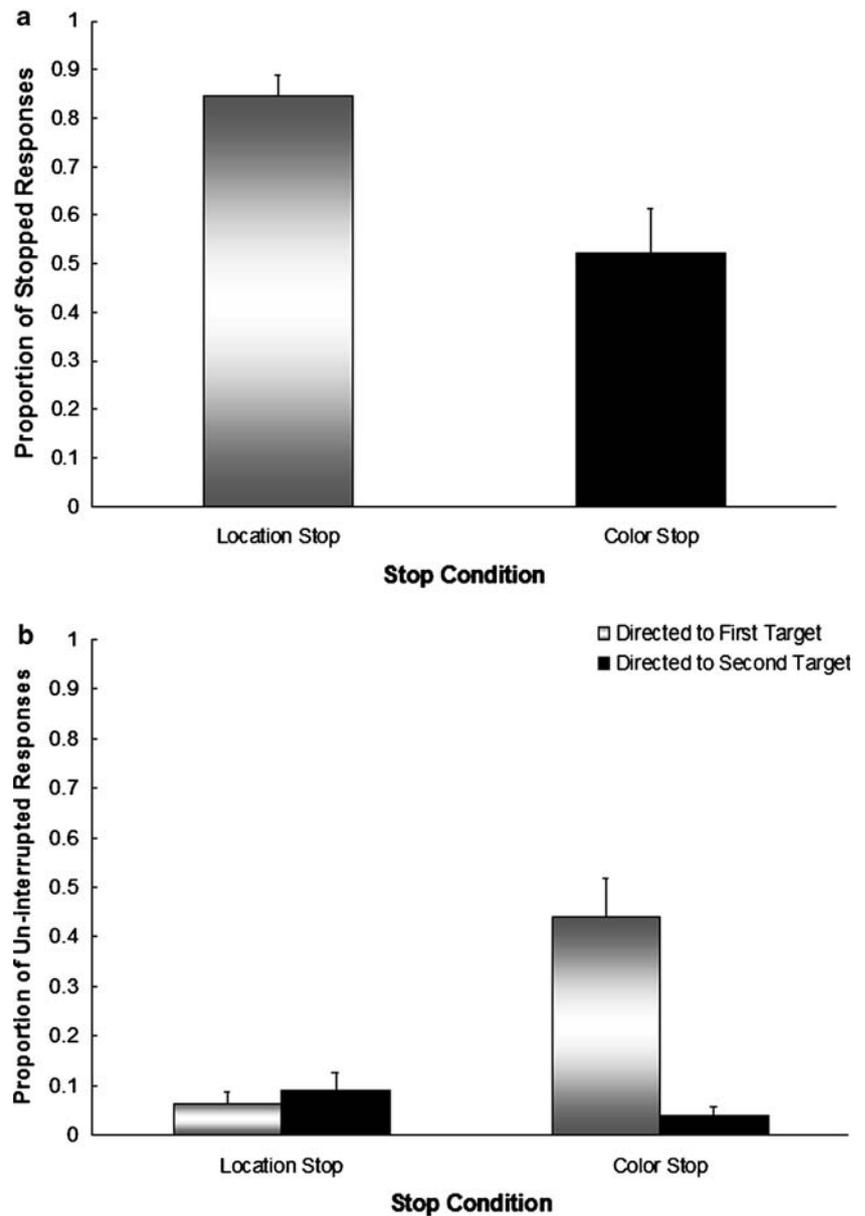


Fig. 3 a Proportion of SR responses during perturbed trials under the Location Stop and Colour Stop conditions. **b** Proportion of un-interrupted responses during perturbed trials under the Location Stop and Colour Stop conditions



largely in agreement, with one notable exception. Although participants in the LS condition were able to successfully abort their pointing to perturbed targets most of the time (less than 10% of T2 responses in Fig. 2a), the kinematic analysis shows that they were nonetheless directing their actions (both incorrectly completed ones and correctly stopped ones) toward the new target location at a much higher rate (42% of T2 responses in Fig. 5a). ANOVA showed that this difference was significant, $F_{(3, 24)} = 18.886$, $P < 0.0025$. Equally important, participants in the CS conditions successfully aborted their pointing movements to perturbed targets, both when assessed by the endpoint analysis (Fig. 2b) and by the pointing trajectories (Fig. 5b), $F < 1$.

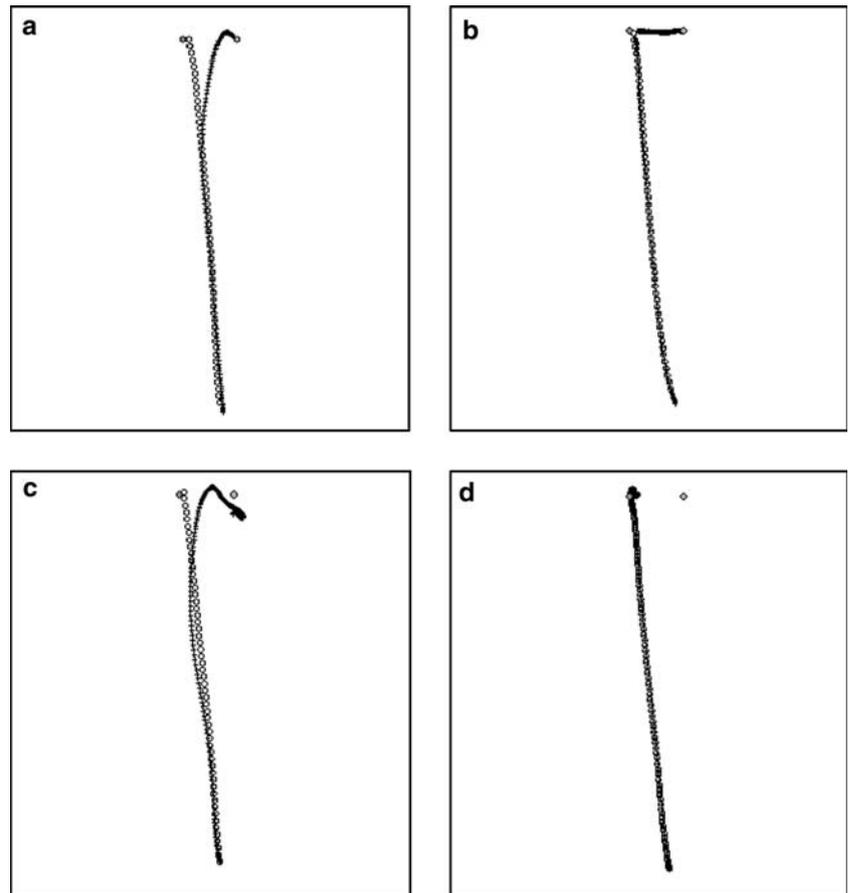
The time it took for pointing trajectory deviations to occur was only examined for the three conditions in which significant path deviations from T1 were observed

(LG, LS and CG). These trajectory adjustments occurred much later in the Colour Go condition ($194 \text{ ms} \pm 7.5 \text{ SE}$) than in either the LG ($152 \text{ ms} \pm 4.6 \text{ SE}$) or LS conditions ($147 \text{ ms} \pm 4.2$). ANOVA showed that these differences were significant, $F_{(2, 12)} = 29.029$, $P < 0.0001$, and Tukey's HSD test revealed that the time to deviation in the CG condition was significantly different from the other two conditions, which did not differ from one another (cf. Fig. 4a, b).

Discussion

The present experiment used kinematic analyses to examine the degree to which rapid visually guided actions can resist automatic control. But to put the "automatic pilot" into proper context, it was first

Fig. 4 Examples of mean unperturbed spatial trajectories (*circles*) and individual perturbed spatial trajectories (+) under each of the four movement conditions. Note the earlier deviation toward the new target position under the Location Go (**a**) compared to the Colour Go (**b**) condition. Note also the trajectory deviation that occurred prior to interruption of the response under the Location Stop (**c**) condition. No such deviation was observed in the Colour Stop (**d**) condition



important to establish the degree of volitional control that participants had under the particular experimental conditions we tested. Our analysis of participants' ability to modify their pointing actions on-line, in response to a change in target position, indicated that a large number of pointing movements were correctly modified (LG = 82%, CG = 45%). Similarly, participants were able to intentionally abort their movements in response to these same changes in target position a majority of the time (LS = 82%, CS = 52%). This established for the present study what others have reported previously (Brenner and Smeets 2003; Schmidt 2002), namely, that target characteristics such as location, luminance, and colour can be processed quickly in the intentional control of rapid aiming movements.

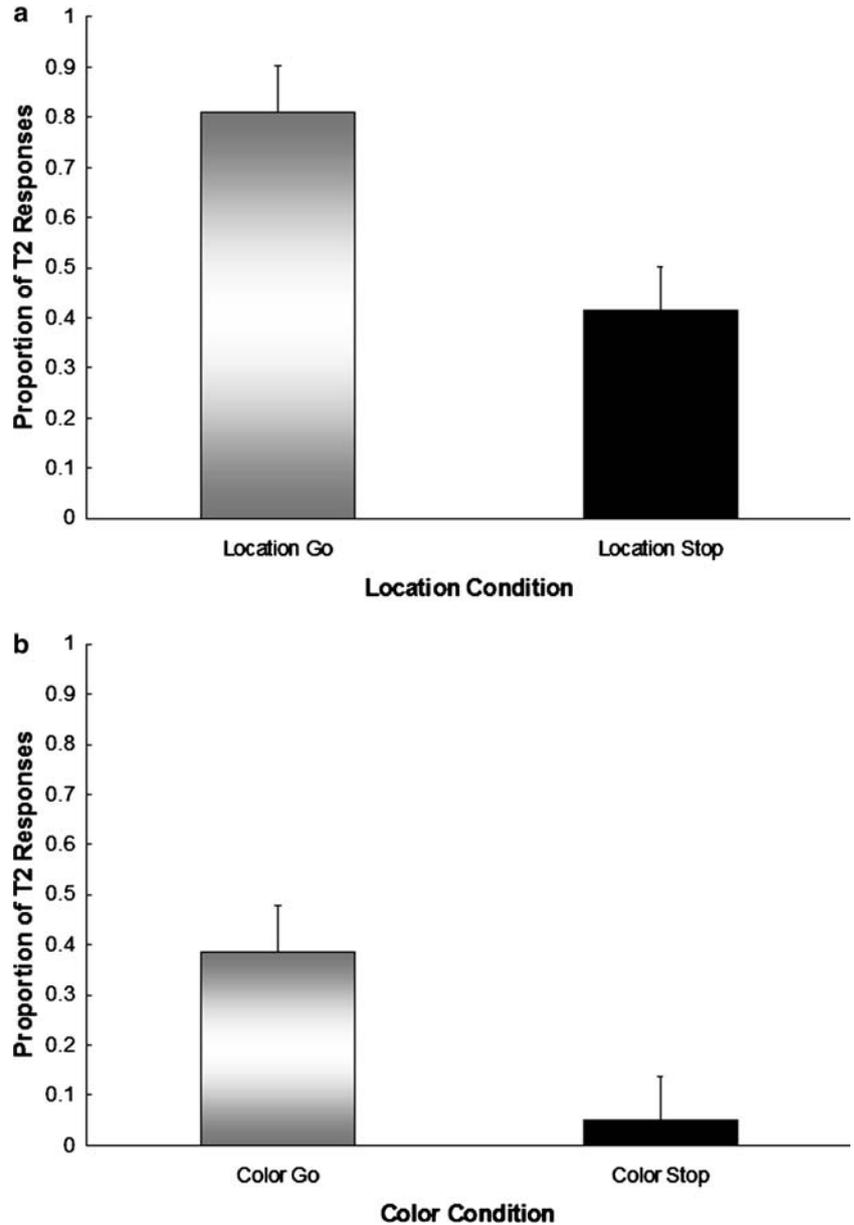
Yet, the differences seen in successful intentional pointing to new target locations cued by location and colour indicate that these signals are not processed with equal efficiency. In particular, target jumps cued by colour were detected much less efficiently than location changes, as seen in (1) the reduced success rate of intentional modifications to colour changes (a difference of 35% or more), (2) the high-failure rate in aborting movements to the original target location when instructed to "stop" when a colour change was detected (approximately 50%), (3) by the longer average time needed to complete a movement in response to a colour

change (60 ms or more) and (4) by the increased latency with which pointing corrections were detected in the kinematic analyses (40 ms or more). These findings indicate that colour changes are simply not detected as early or as reliably as location changes and so any differences in the "automatic pilot" to changes to colour versus location must take this baseline difference in detectability into account.

Indeed, one reasonable interpretation of these differences in change detection is that the apparently reduced sensitivity of the automatic pilot to colour change is not due to inherent differences in the way the dorsal stream processes location versus colour, as concluded by Pisella et al. (2000), but rather due only to the increased latency with which colour is processed. Perhaps it is this increase in the amount of time that elapses, rather than the fact that change is signaled through colour, that permits the conscious ventral stream to arrest control of action away from the unconscious dorsal stream (Rossetti et al. 2000; Rossetti and Pisella 2002). But this is where the kinematic data collected in the present study contribute uniquely, because they are able to reveal influences on action that can be measured prior to the final outcome of the pointing movement.

When we compared the movement endpoint analysis (Fig. 2) with the kinematic analysis (Fig. 5) there was a very high level of agreement on the rate of intentional

Fig. 5 Mean proportion of T2 responses for perturbed trials under the two Location conditions (a) and two Colour conditions (b) as determined by kinematic analysis. Note the significant proportion of responses that were directed to the new target position under the Location Stop condition, in which participants successfully stopped their pointing movements in response to the target perturbation (cf. Fig. 2)



modifications of action in response to a change in location (82 and 81%, respectively) and in response to a change in colour (45 and 42%, respectively). However, the same kind of comparison revealed much less agreement on the frequency of automatic modifications in response to a change in location (<10% for endpoint, >40% for kinematic). Thus, the endpoint analysis of Pisella et al. (2000) seriously underestimates the prevalence of action modifications occurring under “automatic pilot” when a target jump is signalled by a change in spatial location. At the same time, the kinematic measures used in the present study were unable to pick up any evidence for “automatic pilot” responses in regard to colour changes (both measures <5%). We therefore, interpret these results as agreeing with and strengthening Pisella et al.’s (2000) proposal of a

strongly automatic pilot. Based on the present results, we conclude that this on-line control system is engaged during rapid visually guided actions to spatially defined targets, and that automatic movement corrections can be elicited by changes in the spatial location of targets.

The strongest evidence in support of this conclusion comes from the analysis of the hand trajectories (Fig. 4), which shows how qualitatively different they are in response to changes in location and colour. In addition to showing that the colour change is detected later than the location change, they show no evidence that pointing in response to colour is ever influenced outside of the awareness of the participant. Trajectory modifications toward the new target position in the CS condition were at the same low baseline levels in both the kinematic and in the endpoint analyses.

In conclusion, our results provide additional support for the existence of a highly automatic system, often escaping intentional control, that is engaged during on-line movement execution in response to a change in target location (Day and Lyon 2000; Pisella et al. 2000). Moreover our kinematic analysis clearly demonstrates that this automatic system is not engaged when the same change in target location is cued through a colour switch. Following the dual systems theory (Milner and Goodale 1995) we assume this automatic system resides in the dorsal visual stream and that it can be overridden by visual processes leading to conscious awareness within approximately 200 ms.

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