Exp Brain Res (2010) 206:257–269
DOI 10.1007/s00221-010-2404-2

RESEARCH ARTICLE

How automatic is the hand's automatic pilot?

Evidence from dual-task studies

Robert D. McIntosh · Amy Mulroue ·
James R. Brockmole

Received: 14 July 2010 / Accepted: 19 August 2010

Abstract The ability to correct reaching movements for changes in target position has been described as the hand's 'automatic pilot'. These corrections are preconscious and occur by default in double-step reaching tasks, even if the goal is to react to the target jump in some other way, for instance by stopping the movement (STOP instruction). Nonetheless, corrections are strongly modulated by conscious intention: participants make more corrections when asked to follow the target (GO instruction) and can suppress them when explicitly asked not to follow the target (NOGO instruction). We studied the influence of a cognitively demanding (auditory 1-back) task upon correction behaviour under GO, STOP and NOGO instructions. Correction rates under the STOP instruction were unaffected by cognitive load, consistent with the assumption that they reflect the default behaviour of the automatic pilot. Correction rates under the GO instruction were also unaffected, suggesting that minimal cognitive resources are required to enhance online correction. By contrast, cognitive load impeded the ability to suppress online corrections under the NOGO instruction. These data reveal a constitutional bias in the automatic pilot system: intentional suppression of the default correction behaviour is cognitively demanding, but enhancement towards greater responsiveness is seemingly effortless.

Keywords Visuomotor · Online correction · Attention · Automatic

Introduction

The elegance and efficiency of human action owes much to our ability to compensate for initial motor programming inaccuracies and environmental perturbations. This online correction has often been modelled via 'double-step' reaching tasks, in which the target of the action is jumped to a new location once the reach is underway. Compensatory re-accelerations can be detected within about 110 ms of the jump, and the spatial path of the hand may deviate unambiguously towards the new target within ~200 ms (Brenner and Smeets 1997; Castiello et al. 1991). This facility for fast in-flight correction depends critically upon the dorsal posterior parietal cortex (Desmurget et al. 1999; Grea et al. 2002; Pisella et al. 2000) and has been described memorably as the hand's 'automatic pilot' (Pisella et al. 2000).

There are several good reasons to characterise online reach corrections as automatic. Most obviously, they are too rapid to be mediated consciously. Castiello et al. (1991) found that participants could modify their reaches within ~110 ms, but required more than 400 ms to vocalise awareness of the target jump, a difference too great to be ascribed simply to the differing output modalities. Goodale et al. (1986; see also Pelisson et al. 1986) demonstrated that awareness of the perturbation is not necessary for online correction in reaching tasks, since participants correct their reaches even if the jump occurs during saccadic suppression. Under such conditions, in the absence of other visual landmarks, participants are at chance in guessing whether or not the target was moved, yet their reaching movements

---

R. D. McIntosh (✉) · A. Mulroue
Human Cognitive Neuroscience, Psychology,
University of Edinburgh, 7 George Square,
Edinburgh EH8 9JZ, UK
e-mail: r.d.mcintosh@ed.ac.uk

J. R. Brockmole
Department of Psychology,
University of Notre Dame, IN, USA

can land at the jumped location with no movement time cost relative to direct reaches to the same location (Goodale et al. 1986; Pelisson et al. 1986).

Pisella et al. (2000) introduced alternative versions of the double-step reaching task, varying instructions for different participant groups. The GO task, in which participants were required to follow target jumps, corresponded to the standard demand. In the STOP task, participants were instead required to stop their movement immediately upon detecting a target jump. Movement endpoints were collected via a touch screen, and participants were paced to produce different duration movements in different blocks. In the GO task, some movements as brief as 200 ms landed towards the jumped target, and movements longer than ~250 ms invariably did so. In the STOP task, participants required about 300 ms to stop their reaches in response to a target jump, with shorter duration movements reaching the screen despite the STOP instruction. Critically, provided that they were longer than 200 ms, these unstopped movements often landed near the jumped target.

Corrections in the STOP task have sometimes been taken to show that participants cannot suppress online corrections. We think that this characterisation is misleading; such a conclusion would require the persistence of corrections in the face of an explicit instruction to suppress them. By contrast, the STOP instruction simply asks participants to terminate their reach in response to a target jump. This is a relatively late voluntary response, and forward momentum must be overcome, so the reach will inevitably continue for some time after the jump but before the movement is stopped. Participants are given no instructions about what the hand should do whilst the STOP response is pending, so it may be assumed that whatever it does will be the default (uninstructed) early response of the hand to the jump. Whether the hand veers in the direction of the jump or retains its initial trajectory prior to the STOP response is strictly irrelevant to successful compliance with the task. Thus, in our view, correction behaviour in the STOP task can be construed as the default behaviour of the automatic pilot (i.e. that which occurs in the absence of explicit instructions). In fact, observers do still make corrections in the STOP task, albeit at a reduced rate relative to the GO task. This basic observation was confirmed by Cressman et al. (2006), who used trajectory analyses to show early deviations towards the jumped target in a STOP task, even for trials that were successfully stopped. Their analyses estimated that ~82% of jump trials in the GO task, and ~42% of jump trials in the STOP task were corrected, even for brief paced movements of around 200 ms.

Another variant of the double-step task was reported by Day and Lyon (2000), who asked participants to respond to a target jump by diverting their movement *in the opposite direction*. Like Pisella et al.'s (2000) STOP task, this requires a voluntary response to the jump that differs from the more usual requirement to follow the target. A trajectory analysis showed similar outcomes, in that short-latency corrections, in the direction of the target jump, occurred prior to the instructed ‘anti-corrections’ (see also Johnson et al. 2002). Nonetheless, Day and Lyon noted that early corrections towards the target were less frequent and less vigorous under the anti-correction instruction, echoing reduced rates of fast online correction during STOP tasks (Cressman et al. 2006; Pisella et al. 2000). The occurrence of in-flight corrections, even when not required by task instructions, clearly implies some degree of automaticity; at the same time, the reduced frequency of correction under such conditions suggests that the behaviour is modifiable by volition. In more formal terms, online correction is probably *weakly* but not *strongly* automatic (Jonides et al. 1985). According to this distinction, any process that operates when not required by task goals may be weakly automatic, but to be strongly automatic it must be both immune to voluntary suppression (intentionality criterion) and unaffected by concurrent cognitive load (load criterion).

The weakly automatic status of online correction has recently received confirmation from an explicit, direct test of the intentionality criterion. In addition to GO and STOP double-step reaching tasks, Cameron et al. (2009) introduced an IGNORE task in which participants were explicitly told to ignore target jumps and to continue to the target's initial location. Participants managed to suppress corrections almost completely, deviating towards the new target on only ~7% of jump trials in the IGNORE task, compared with ~41% and ~36% in the GO and STOP tasks respectively. One slight anomaly of these data is the lack of reliable difference between correction rates in the STOP and GO tasks (cf. Cressman et al. 2006; Pisella et al. 2000). This may owe to the fact that the GO task always followed the IGNORE task, an ordering imposed to avoid transfer effects from the GO to IGNORE tasks, but which may have promoted transfer in the opposite direction. That is, participants may have produced relatively low rates of correction in the GO task given prior experience of the IGNORE task. Nonetheless, their ability to suppress corrections when explicitly asked to, demonstrates that online correction in double-step tasks does not meet the intentionality criterion, and should be classed as weakly automatic.

Striemer et al. (2010) subsequently used a similar task, instructing participants not to correct the movement if the target jumped, but to continue reaching to the initial target position. They referred to this as a NOGO instruction. We will adopt the same NOGO terminology here, as it captures the key requirement to suppress a motor reaction to the target jump, without implying that this is necessarily achieved by ignoring the jump outright. The NOGO instruction led to a substantial reduction of corrections relative to a GO task (32 vs. 64%), confirming that autopilot behaviour can be voluntarily modulated. However, whereas Cameron et al. had achieved a near-total elimination of corrections (7%), Striemer et al. found an appreciable residual rate (32%), suggesting that corrections are hard to suppress entirely. Striemer et al. also confirmed that experience can alter correction behaviour, in that prior experience of the GO task increased correction rates in the NOGO task, and prior experience of the NOGO task decreased correction rates in the GO task. These order effects were not simple performance costs of switching between instructions, but arose despite the different instruction blocks being completed on different days, and each preceded by a practice block of 40 trials. The responsiveness of the automatic pilot thus seems to be shaped by prior experience, as well as current goals.

The present study is complementary to those that have assessed the influence of intentionality (explicit instruction) upon correction behaviour. The aim is to assess the status of online correction behaviour with respect to the load criterion, which states that strongly automatic behaviours should be unaffected by concurrent cognitive load. The existing data suggest that the hand’s automatic pilot operates at a certain default level in the absence of any explicit correction strategy (STOP task) but, being weakly automatic, is amenable to voluntary modification. This can be enhancement, yielding higher correction efficiency in GO tasks, or suppression, leading to lower correction rates in NOGO tasks. We will study how a cognitively demanding secondary task influences correction behaviour under GO, STOP and NOGO instructions. Our secondary task requires auditory monitoring of a stream of digits for sequential repetitions (auditory 1-back task) and has previously been found to eliminate the capture of visual attention by a sudden onset distractor during visual search (Boot et al. 2005).

It is important to distinguish our secondary task from a visuomotor secondary task, which could compete directly for the dorsal stream processes supporting online correction. Cameron et al. (2007) neatly demonstrated that correction efficiency is reduced when participants reach in sequence to two visual targets, either of which can jump at sequence onset. Here, the reduced responsiveness of the automatic pilot reflects increased *visuomotor* processing load in dual-target, relative to single-target conditions. By contrast, we are interested in how a non-visual, non-motor, cognitive task influences correction behaviour. Our predictions are straightforward. First, if corrections in the STOP task are taken to reflect the default (uninstructed) behaviour of the automatic pilot, then this level of performance should be effortless, and robust to interference from the secondary task. By contrast, if compliance with the other reaching instructions requires cognitive resources, then the secondary task should in each case push correction rates towards this default level. Thus, the secondary task should reduce correction rates under the GO instruction (i.e. impair the ability to make corrections), but increase correction rates under the NOGO instruction (i.e. impair the ability to *suppress* corrections). A lack of such effects, in either case, would suggest a relative independence from ongoing cognitive control, thus stronger automaticity.

Experiment 1: Methods

Participants

Twenty-four volunteers (18 women, 6 men; mean age 21.2 years, SD 2.2) took part, with approval from the Research Ethics Committee of the School of Philosophy, Psychology and Language Sciences, University of Edinburgh. All participants were right-handed by self-report, with no visual or motor deficits.

Procedure

Participants were allocated, in rotating order, to one of three groups, each of which performed a double-step reaching task under a different instruction: GO, STOP or NOGO. Each participant performed the allocated reaching task in two blocks of 100 trials. One block was performed in a single-task condition, and one in a dual-task condition with a concurrent auditory 1-back task, with block order counterbalanced within each group. The reaching task and auditory task are described in the following sections.

Reaching task

The participant sat at a table in a dimly lit room, with their left hand resting on their lap, and their right index finger resting on a start button ~100 mm in front of them. Stimuli were presented on a 17 in. LCD touch screen (3 M MicroTouch$^{\text{TM}}$ M170; active display area 340 × 270; resolution 1,024 × 768, 60 Hz) placed so that the straight-line distance from start button to screen centre was 505 mm. Each trial was preceded by a blank screen, and the participant initiated the trial by depressing the start button. After a delay that varied randomly from 1,000 to 1,500 ms, a 10 mm white dot (target 1) was presented 27 mm to the left or right of the screen centre. The participant was required to initiate a reaching movement towards the dot as soon as it appeared. Button release at movement onset triggered the replacement of target 1 by target 2 in the next monitor refresh cycle. Target 2 was identical to target 1 and was either in the same position as target 1 (static trials), or at the target position on the opposite side (jump trials). Target 2 remained onscreen for 350 ms. Finally, 4,000 ms after trial initiation, a dialog box appeared in the centre of the screen, to collect a touch-screen response to end the trial. Once the participant had given their response, the screen went blank, and the hand was returned to the start position for the next trial. Each block of 100 trials comprised 70 static trials (35 left, 35 right) and 30 jump trials (15 jump left, 15 jump right).

The instruction for the reaching task differed between the three participant groups. The GO condition instructed participants to aim for the final target position, even if the target jumped. The STOP condition instructed participants to pull their hand back to rest on the start button as soon as they detected a target jump. This differed slightly from previous versions of the STOP task (e.g. Cressman et al. 2006; Pisella et al. 2000), but not in any important sense: to pull back the hand is just to stop its forward movement and reverse it, and no explicit instruction pertaining to reach corrections was given. By contrast, the NOGO condition instructed participants always to aim for the original target location, even if the target jumped to another location, thus explicitly requiring the suppression of corrections.

Prior to the experimental trials, performed with the auditory task, participants received a practice block of 30 static trials, with a high tone 350 ms after movement onset. Participants were required to try to finish their reaching movement in synchrony with the high tone. The purpose of this training was to provide experience of the required pace of movement for the experimental trials. Pacing tones were not provided during the experiment, to avoid interference with the auditory task.

Auditory task

The auditory 1-back task was adapted from Boot et al. (2005), using the same sound files, which were played at clearly audible volume through loudspeakers positioned behind the touch screen. On each trial, a digitised voice recited a sequence of eight digits (from 1 to 9) at a rate of two per second for 4 s. The sequences were generated randomly, except that each contained one, two or three ‘pairs’, in which adjacent digits were the same. The sequence was initiated by the depression of the start button at the beginning of each trial. At the end of the sequence, a dialog box appeared in the centre of the screen. In the dual-task condition, the dialog box asked ‘How many pairs?’, and the participant was required to touch the appropriate numbered button (1, 2 or 3). If they responded incorrectly, a low error tone was sounded, and the trial was discarded and recycled to the end of the block with a novel digit string. Participants were aware that error trials would be recycled. In the single-task condition, participants were instructed to ignore the digit sequence; at the end of each trial, the dialog box contained one button, labelled ‘OK’, which they were required to press.

Data recording

Reaching movements were recorded by the Optotrak Certus system (Northern Digital Inc.), which sampled the position of an infra-red emitting diode, attached to the nail of the right index finger, at a frequency of 200 Hz.

Data processing and analysis

Kinematic data were coded within a spatial reference frame having the start button as its origin, in which a straight-line path from start button to screen centre defined increasing depth displacement (*Y*-axis), and a straight line between the left and right target positions defined increasing lateral displacement (*X*-axis). Raw kinematic data were filtered by a dual pass through a Butterworth filter with a cut-off of 20 Hz. Button release triggered movement recording and defined movement onset. Movement offset was defined as the final frame before which forward (*Y*) velocity fell to zero. In the STOP task, the end of the movement was defined in the same way, and the movement was classified as a successful STOP response if *Y*-velocity reversed rapidly thereafter, falling below $-50\ \text{mms}^{-1}$ within at least 50 ms.

The following movement variables were extracted to characterise performance on static trials: reaction time (RT) from target presentation to button release; movement time (MT) from movement onset to offset; peak speed (PS); time to peak speed (TPS) from movement onset; lateral angular error (LAE) of the endpoint from the second target position, calculated with respect to the start button. Since static trials were identical, regardless of reaching instruction, initial analyses of these movement characteristics should identify any strategic changes in baseline reaching behaviour across the different instruction conditions. Additionally, these analyses should identify any overall changes in reaching between the single- and dual-task conditions, which might affect our ability to compare online correction behaviour across task conditions.

The analysis of online corrections in individual jump trials was based upon deviations of the spatial trajectory from the average trajectory for static trials in the same block (see Fig. 1). First, the trajectories for all static trials were normalised to 1-mm increments along the depth axis. Second, for each participant, for each trial block, the average lateral coordinate of static trials and its standard deviation were calculated at each depth increment, and

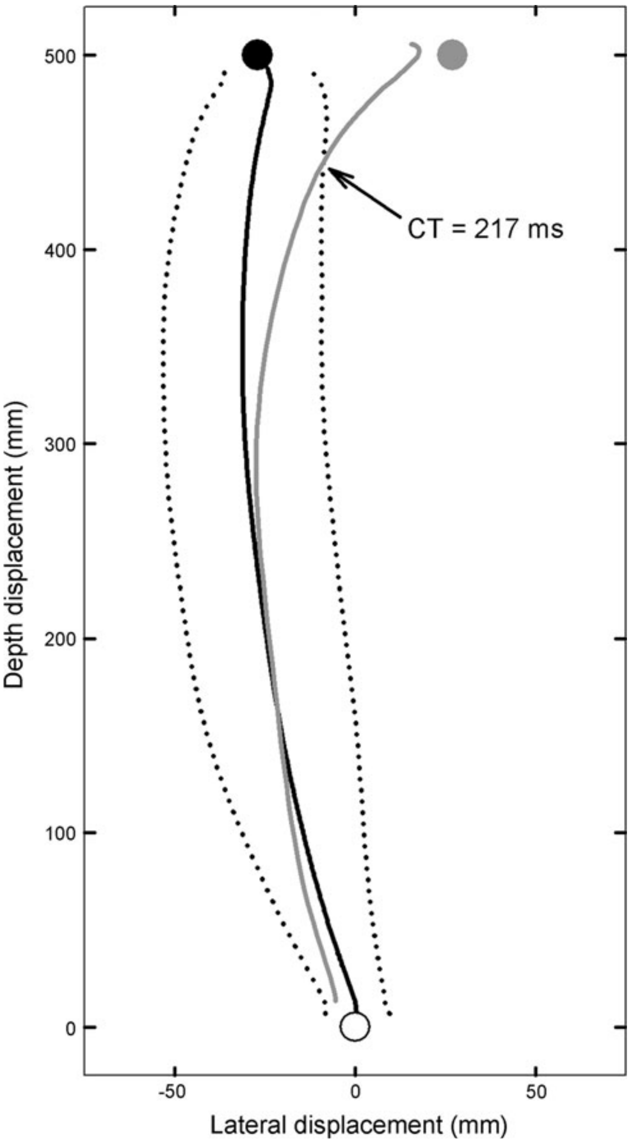

Fig. 1 Analysis of online correction in a single jump trial. The *solid black* trajectory is the average *XY* path of all of this participant's reaches to static targets on the left of the midline (*black circle*) in a given reaching condition (e.g. single task, GO instruction). The *dotted lines* mark a 'bandwidth' of 2.81 SD either side of the average at each depth increment. The *grey* trajectory is the spatial path of a reach to a target on the left (*black circle*) that jumps to the right (*grey circle*) at reach onset. At each time frame, the reach is classed as 'corrected' if it falls outside the bandwidth of static trials, *in the direction of the jump*. In this example, the reach is in a corrected position in its terminal frame, so it is classed as a corrected reach. The correction time (*CT*) is estimated from the time of the last transition from uncorrected to corrected status (217 ms). The example illustrates that CT is not a direct estimate of when the correction is initiated (in fact, the trajectory begins to deviate towards the right about 100 ms earlier); it simply indexes the earliest time at which the correction can be reliably identified, for this jump trial, from the spatial position of the hand

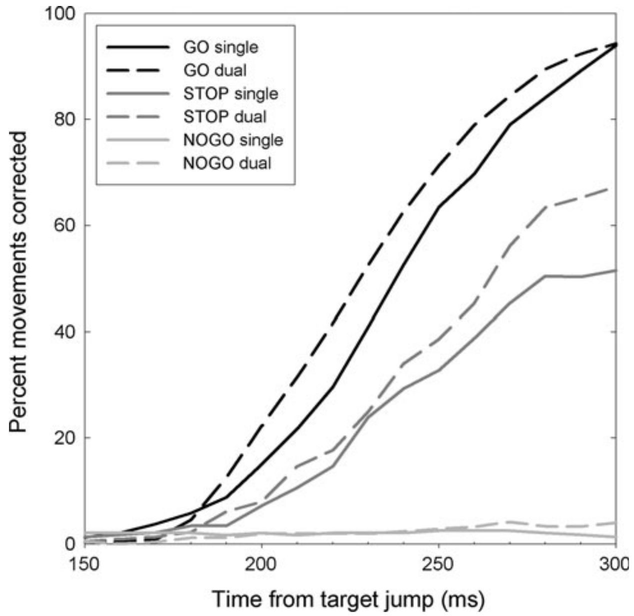

Fig. 2 Percent movements corrected against time from target jump for each combination of reach instruction and task condition in Experiment 1. Note that these profiles reflect the number of movements classified as corrected at each point in time expressed as a proportion of the total number of movements ongoing at that time. These are therefore not cumulative rates of correction, but separate estimates of correction rate for each represented time. The plots do not extend beyond 300 ms because too few movements were represented beyond this time to allow reliable estimates of correction rate (for at least one participant, more than 50% of jump trials had terminated). Accordingly, the latest correction rates plotted here (at 300 ms) are not the same as the terminal correction rates reported in Table 2

cut-offs were set at 2.81 standard deviations either side of the average. Third, for each jump trial, in each time frame, the movement was classed as corrected if it fell beyond the cut-offs *in the direction of the jump*, being otherwise classed as uncorrected (each comparison thus approximates a one-tailed comparison at alpha ~ 0.0025). Each jump trial was overall classed as 'corrected' only if it was classed as corrected in the terminal frame of the movement. For these trials, correction time (CT) was estimated as the time at which the last transition from uncorrected to corrected status occurred. (Note that our system allows that a reach could be 'corrected' during part of its time-course, yet be classed as 'uncorrected' overall if its terminal position fell within the bandwidth of the static trials. If such trials were common, we should see a temporary rise in correction rates during the course of the movement, which did not occur in any condition in either Experiment 1 or 2.).

Correction performance on jump trials was characterised first by the profile of correction rate against time since target jump (Fig. 2), allowing for the progressive emergence of corrections to be visualised. The formal analysis of correction behaviour referred to several specific indicators of correction efficiency, the most global of which was terminal correction rate (TCR): the percentage of jump trials that ended in a corrected state. If there were sufficient numbers of corrected trials to support further analyses (at least one trial per participant for every combination of jump direction, reach instruction and task condition), then we also examined correction time (CT), and lateral angular error (LAE), with respect to target 2, of these trials. If there were too few corrected trials to support these analyses, then we examined (LAE) of uncorrected trials with respect to target 1, in order to look for evidence of more subtle deviation towards the target 2 position.

Finally, though half of our jump trials were left-to-right, and half were right-to-left, we do not report our analyses split by this factor. Preliminary analyses established that jump direction had a consistent influence across participants and experiments, such that corrections for left-to-right jumps were advantaged, emerging earlier in the spatial trajectories. For instance, in Experiment 1, across GO and STOP instructions, and across dual-task conditions, mean CT was 240.3 ms and 259.6 ms for left-to-right and right-to-left jumps respectively ($F_{1,14} = 13.87$, $P < 0.005$). However, this asymmetry did not interact with other factors in ways that were relevant to our main hypotheses. Although the asymmetry is worthy of future investigation in its own right, we tested participants' right hand reaching only, so we cannot presently exclude simple biomechanical and/or hemispheric compatibility effects, privileging ipsilateral over contralateral movements (e.g. Fisk and Goodale 1985). For present purposes, the exposition of results is facilitated by excluding this factor.

Experiment 1: Results

The key outcomes of Experiment 1 are illustrated by Fig. 2, which shows the development of correction rates over time (up to 300 ms) for jump trials in each secondary task condition and under each reach instruction. The correction profiles are strongly modulated by reach instruction, with high rates of correction in the GO condition, intermediate rates in the STOP condition, and almost no corrections in the NOGO condition. This pattern supports previous demonstrations that online corrections are modified by top–down influences (e.g. Cameron et al. 2009; Striemer et al. 2010). The addition of a dual task does not decrement performance in any of the reach conditions. Indeed, if anything, correction efficiency is slightly *enhanced* in the GO and STOP conditions, perhaps because the dual task induced a higher state of arousal. Experiment 1 shows no detrimental effect of attentional load upon the ability to make, or to resist making, corrections to target jumps. However, it is possible, at least in the GO and NOGO conditions, that any influence of the secondary task might have been masked by ceiling levels of performance in the basic reaching task. These key outcomes are elaborated by the formal statistical analyses presented in the following sections.

Auditory task

Reaching trials with errors in the auditory 1-back task were excluded and recycled. On average, 127 trials (SD 11.81) were completed per participant in the dual-task condition, in order to yield 100 trials with correct auditory task performance (i.e. 21.3% error rate). These sub-ceiling levels of performance confirm that the auditory task was cognitively demanding. A mixed-model ANOVA was performed on arcsine-transformed percentage error rates, to examine the influence of reach instruction (GO, STOP, NOGO) and trial type (static, jump). The main effect of trial type was significant, with higher error rates on jump trials (24.9%, SD 1.0) than on static trials (18.5%, SD 7.0) ($F_{1,21} = 48.37$, $P < 0.0005$). This effect interacted significantly with reach instruction ($F_{1,21} = 3.85, P < 0.05$), as the increase of error rate in jump trials was greater under the STOP instruction (10.2%, SD 6.4) than under GO (4.7%, SD 3.7) or NOGO (4.6%, SD 2.8) instructions. The differentially greater interference on jump trials under the STOP instruction is consistent with an increased cognitive load associated with the voluntary stop response relative to the GO and NOGO conditions. Importantly, the main effect of reach instruction did not approach significance ($P = 0.56$), indicating that comparable cognitive resources were allocated to the auditory task across reach conditions.

Reaching task: static trials (Table 1)

Movement characteristics on static trials were used to characterise baseline reaching behaviour. For each movement variable, a mixed-model ANOVA assessed the influence of reach instruction (GO, STOP, NOGO) and task condition (single, dual). Reach instruction had a significant influence only upon LAE ($F_{2,21} = 5.07$, $P < 0.05$). Bonferroni-corrected post hoc *t*-tests confirmed that participants laterally undershot the target in the GO relative to the other conditions (GO vs. NOGO, $P < 0.05$; GO vs. STOP, $P < 0.05$; NOGO vs. STOP, ns). This may reflect a strategy to facilitate corrections in the GO condition, as participants veered slightly towards the likely location of the target jump. This pattern implies that participants acquired implicit or explicit knowledge that targets jumps were always across the midline (i.e. leftward for targets on the right and rightward for targets on the left). LAE was also affected by task condition, with a reduced tendency to undershoot in the dual-task condition ($F_{1,21} = 16.34$, $P < 0.005$). Task condition also affected RT, with participants taking on average 90 ms longer to initiate their reach following target onset in the dual-task condition ($F_{1,21} = 22.62$, $P < 0.0005$). There

Table 1 Group descriptive data for Experiment 1 static trials, by reach instruction (GO, STOP, NOGO) and secondary task (single, dual), for movement variables: reaction time (RT); movement time (MT); peak speed (PS); time to peak speed (TPS); lateral angular error (LAE)

	GO		STOP		NOGO	
	Single	Dual	Single	Dual	Single	Dual
Mean (SD) RT (ms)	372.0 (129.4)	401.6 (45.6)	327.1 (53.1)	437.4 (71.6)	339.7 (55.3)	471.5 (142.8)
Mean (SD) MT (ms)	383.1 (28.0)	383.9 (31.3)	414.1 (38.3)	410.8 (28.0)	397.5 (51.2)	385.6 (37.6)
Mean (SD) PS (m ms^{-1})	2498.0 (228.5)	2532.7 (253.1)	2414.4 (368.3)	2461.0 (295.5)	2301.9 (254.7)	2291.8 (90.24)
Mean (SD) TPS (ms)	98.3 (16.9)	99.1 (12.3)	104.5 (29.8)	110.8 (21.18)	110.6 (21.2)	112.0 (18.9)
Mean (SD) LAE (°)	−0.18 (0.13)	−0.11 (0.12)	−0.05 (0.15)	0.00 (0.14)	−0.01 (0.08)	0.09 (0.13)

Jump trials were included for calculation of RT, since this measure precedes the target jump

Table 2 Group descriptive data for Experiment 1 jump trials, by reach instruction (GO, STOP, NOGO) and secondary task (single, dual), for correction variables: terminal correction rate (TCR); correction time (CT); lateral angular error (from target 2) of corrected movements (LAEc); lateral angular error (from target 1) of uncorrected movements (LAEu)

	GO		STOP		NOGO	
	Single	Dual	Single	Dual	Single	Dual
Median (IQR) TCR (%)	98.3 (10.0)	100.0 (7.0)	68.3 (38.7)	82.7 (35.1)	0.0 (1.7)	1.7 (7.1)
Mean (SD) CT (ms)	236.6 (16.7)	223.6 (16.2)	257.3 (29.5)	249.0 (26.2)		
Mean (SD) LAEc (°)	−10.27 (0.31)	−0.28 (0.27)	−2.32 (0.98)	−1.89 (1.01)		
Mean (SD) LAEu (°)					0.09 (0.22)	0.31 (0.30)

Non-parametric measures (median, IQR) are given for TCR, as compression effects created non-normality in the GO and NOGO conditions (see text)

were no other significant outcomes. This relative consistency of baseline reaching performance across task conditions provides an adequate basis for assessing the effect of the secondary task on autopilot efficiency in jump trials.

Reaching task: jump trials (Fig. 2; Table 2)

As illustrated in Fig. 2, in the GO and STOP conditions, the earliest corrections could be identified within the spatial path of movements by around 180–190 ms after the target jump (i.e. after movement onset); thereafter, corrections accumulated more rapidly in the GO than in the STOP condition. In the STOP condition, participants managed to pull their hand back before touching the screen on 93% (SD 6.6) of jump trials, but the average time taken for the forward movement to end was 333 ms (SD 35.3), giving ample time for corrections to appear in the trajectory prior to the STOP response. Task condition influenced neither the rate ($t_7 = 0.22$, $P = 0.83$) nor the latency ($t_7 = 1.17$, $P = 0.28$) of STOP responses.

Correction behaviour was formally analysed in terms of several dependent variables, summarised in Table 2. First, TCR mirrors the patterns evident in Fig. 2. Ceiling levels of performance for some participants in the GO and NOGO conditions (i.e. maximum and minimum TCR respectively) precluded parametric comparisons between groups, but non-parametric comparisons confirmed higher TCR in the GO compared with the STOP condition (Mann–Whitney $U = 8.00$, $P < 0.05$) and in the STOP compared with the NOGO condition (Mann–Whitney $U = 0.00$, $P < 0.0005$). The distributions of paired differences between single and dual-task conditions did not violate normality, so paired *t*-tests were used to compare single and dual-task performance within each reaching condition. Differences were non-significant for the GO ($t_7 = 0.40$, $P = 0.70$) and NOGO conditions ($t_7 = 0.19$, $P = 0.11$), and just non-significant for the STOP condition ($t_7 = 2.07$, $P = 0.07$). Of course, the occurrence of ceiling effects in the GO and NOGO groups may have masked performance differences between task conditions in these groups, an issue which will be addressed further in Experiment 2.

For the GO and STOP conditions, for those movements that were corrected, a mixed-model ANOVA was performed upon CT. Corrections tended to emerge earlier in the GO than in the STOP condition, though this difference failed to reach clear significance ($F_{1,14} = 4.48$, $P = 0.052$). More surprisingly, corrections emerged significantly earlier in the dual- than in the single-task condition ($F_{1,14} = 9.25$, $P < 0.01$). An analysis of LAE, with respect to target 2, confirmed that corrected movements finished closer to the target (i.e. corrections were more complete) in the GO than in the STOP condition ($F_{1,14} = 30.15$, $P < 0.0005$), but these errors were not significantly affected by the dual task. Finally, for the NOGO condition, sufficient *uncorrected* jump trials were available to allow for a repeated-measures ANOVA of LAE, with respect to target 1, with the factors of task condition (single, dual) and trial type (static, jump). As can be seen from a comparison of Tables 1 and 2, reaching movements showed greater lateral overshoot in jump trials than in static trials ($F_{1,7} = 19.29, P < 0.005$); this may be an exaggerated inhibition of automatic deviations towards the new target location on jump trials, consistent with the idea that participants must actively suppress trajectory corrections in the NOGO condition. The only effect of the dual task, as already noted for static trials, was to bias angular errors towards lateral overshoot ($F_{1,8} = 19.06, P < 0.005$).

Experiment 1: Discussion

The full analyses support the patterns evident in Fig. 2. Participants could comply with requests either to make or to resist trajectory corrections, confirming that the automatic pilot is amenable to top–down modulation. The addition of the secondary task did not harm performance under any of the reach instructions. In fact, correction efficiency under the GO and STOP instructions was slightly enhanced in the dual-task condition, as shown by earlier correction times, and (non-significant) trends towards higher correction rates. This enhancement may owe to increased arousal associated with the dual-task demand, but gives no hint that online correction in STOP or GO conditions is cognitively demanding. The NOGO task yielded an interesting pattern of target overshoot on jump trials, indicative of veering *away* from the jump, suggesting active inhibition of corrections. Even so, these errors, and all other measures of correction behaviour, were unaffected by the secondary task. Overall, dual-task decrements were strikingly absent in Experiment 1, providing no evidence that either making or suppressing in-flight corrections is cognitively demanding. An important caveat, however, is that Experiment 1's ability to detect dual-task decrements may have been blunted by ceiling levels of performance, as several participants achieved maximal (or near-maximal) rates of correction in the GO task, and minimal (or near-minimal) rates in the NOGO task. A more definitive test of the load criterion would be afforded by sub-ceiling levels of performance in single-task conditions, an objective to be addressed in Experiment 2.

First, however, it is worth considering Experiment 1 in relation to the two previous studies that have used the NOGO instruction. As noted in the Introduction, Cameron et al. (2009) found that participants could suppress corrections almost entirely, whereas Striemer et al. (2010) found non-negligible rates (~32%) of unsuppressed corrections in their NOGO condition. They suggested that this may have been due to differing movement durations: their participants were paced to reach 300 mm within 300 ms, whereas Cameron et al.'s participants were paced to cover 270 mm within ~200 ms. Striemer and colleagues suggested that it takes time for automatic processes to override the intention to ignore a target jump, so that unsuppressed corrections emerge only at longer durations (>200 ms). Our data suggest otherwise, since our participants moved at similar average speeds to Striemer et al.'s for a greater distance (505 mm), resulting in reaches of even longer duration (average of ~412 ms for static trials in the NOGO condition), yet they suppressed corrections entirely. Moreover, since we analysed the whole trajectory, we can exclude any temporary rise of unsuppressed corrections between 200 and 300 ms (see Fig. 2). The data therefore do not support the idea of an inhibitory task set yielding over time to a prepotent automatic pilot; the reverse picture of active inhibition overriding automatic corrections seems at least as plausible.

An alternative account for the differing rates of unsuppressed corrections is that these studies differed in the predictability of the jumped target location. Our study, like Cameron et al.'s (2009), used two target locations only, so a target on the left could only jump to the right and vice versa. In Striemer et al.'s (2010) design, by contrast, any target could jump either left or right, and much higher rates of unsuppressed corrections were observed. If the NOGO task is solved by inhibiting orienting responses to the jumped target, this may be better achieved when its location is predictable, as only one location need be inhibited. If spatial predictability does aid the suppression of corrections, then tasks such as ours will tend to overestimate how easily the automatic pilot can be disengaged, at least relative to real-world situations in which target movements are unlikely to be so predictable.

Despite this shortcoming, Experiment 2 will continue to use the basic double-step paradigm from Experiment 1, adapting it to discourage ceiling effects that may have prevented a fair assessment of dual-task decrements. To this end, we apply another insight gained from Striemer et al. (2010), which is that the ability to comply with GO and NOGO instructions is modulated by prior experience. Rather than manipulating task instruction between-subjects, as in Experiment 1, Experiment 2 will test all participants under both instructions, forcing them to switch repeatedly between them. The intermingling of opposing instructions should bias performance in both tasks away from ceiling levels, allowing for a stronger test of whether the implementation and/or the suppression of reach corrections is sensitive to cognitive load.

Experiment 2: Methods

Sixteen new volunteers (9 women and 6 men, mean age 22.2 years, SD 4.0) took part, with approval from the

Research Ethics Committee of the School of Philosophy, Psychology and Language Sciences, University of Edinburgh. All participants were right-handed by self-report, with no visual or motor deficits.

Procedure

Each participant performed the reaching task in single- and dual-task conditions, and under GO and NOGO instructions. Each participant performed two blocks of 100 trials in one task condition (single or dual), followed by two blocks in the other. Each block comprised five sub-blocks of 20 trials, with the reach instruction alternating between sub-blocks. Within each task condition, one block began with a GO sub-block, and the other with a NOGO sub-block, and the same order of sub-blocks was used for both task conditions per participant. The two orders of task conditions were crossed with the two orders of sub-blocks to create four block orders, which were rotated between participants, and thus counterbalanced across the 16 participants. The reaching task and auditory 1-back task are described in the following sections.

Reaching task

The reaching task was identical to that of Experiment 1, except that each sub-block of 20 trials was preceded by a written instruction at the centre of the screen which read ‘FOLLOW’ or ‘DON’T FOLLOW’ for GO and NOGO sub-blocks respectively. Additionally, the stimulus dot itself provided a reminder of the task instruction on each trial. The participant initiated each trial by depressing the start button, and a target dot appeared immediately, and was green in GO sub-blocks, and red in NOGO sub-blocks. After a delay that varied randomly from 1,000 to 1,500 ms, the dot turned white, and the participant was required to initiate a reaching movement as soon as it did so. Within each sub-block of 20 trials, there were 14 static trials (7 left, 7 right) and 6 jump trials (3 jump left, 3 jump right). Trial order within sub-blocks was pseudo-random, with the constraint that the first six and the last six trials within each sub-block each contained one jump left and one jump right trial, with the remaining two jump trials occurring within the middle eight trials in the sub-block. Across the four blocks, each participant completed a total of 100 trials for each combination of task condition and reach instruction, comprising 70 static trials (35 left, 35 right) and 30 jump trials (15 jump left, 15 jump right).

Prior to the experimental trials, participants received a practice block of 10 trials in the GO condition and 10 trials in the NOGO condition, with a 30% perturbation rate. A high tone was sounded 350 ms after movement onset, and participants were required to try to finish their reaching movement in synchrony with the high tone. The purpose of this training was to ensure understanding of the two reaching instructions and to provide experience of the required pace of movement for the experimental trials. Pacing tones were not provided during the experiment, to avoid interference with the auditory task.

Auditory task

The auditory 1-back task was identical to that used in Experiment 1. The only difference was that reaching trials were not recycled if an error was made in the dual-task condition, as trial recycling was incompatible with the regular sub-blocked trial sequence required for Experiment 2.

Data recording

Reaching movements were recorded by the Optotrak Certus system (Northern Digital Inc.), which sampled the position of an infra-red emitting diode, attached to the nail of the right index finger, at a frequency of 200 Hz.

Data processing

Data processing was identical to Experiment 1, except that, for the analysis of individual corrections, trials were grouped separately for each combination of reaching instruction (GO, NOGO) and dual task (single, dual). Thus, for example, jump trials in the GO-single condition were evaluated with respect to cut-offs derived from static trials across all sub-blocks in the GO-single condition.

Experiment 2: Results

The key outcomes of Experiment 2 are well illustrated by Fig. 3, which shows the development of correction rates over time (up to 350 ms) for jump trials in each secondary task condition under GO and NOGO reach instructions. Comparison of Fig. 3 against Fig. 2 (note the differently scaled abscissa) suggests that the task switching demand of Experiment 2 yielded some global differences from Experiment 1, including a slightly later emergence of corrections (200–210 ms), and off-ceiling levels of performance in both the GO and NOGO conditions (i.e. below-maximum and above minimum correction rates respectively), creating ideal conditions for the assessment of dual-task effects. Crucially, the addition of the dual task did not affect correction rates in the GO condition, but had a clear impact in the NOGO condition, with participants less able to resist making corrections. This pattern implies that more cognitive resources are needed to comply with the NOGO than with the GO instruction, suggesting that

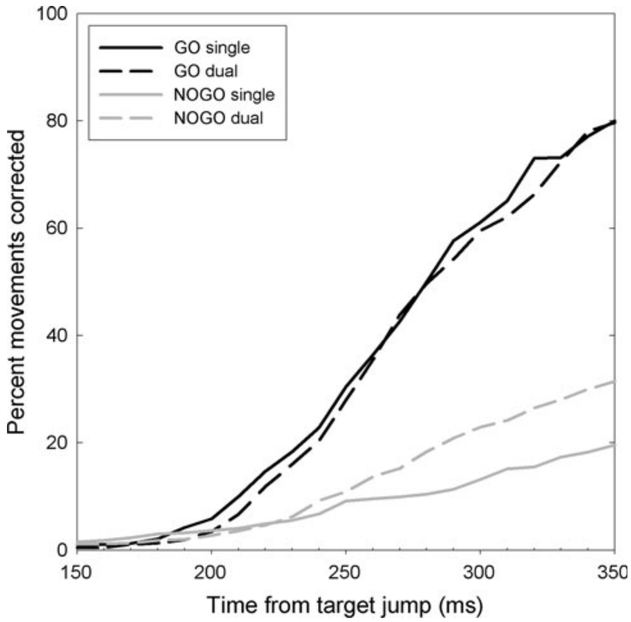

Fig. 3 Percent movements corrected against time from target jump for each combination of reach instruction and task condition in Experiment 2. As for Fig. 2, these profiles reflect the number of movements classified as corrected at each point in time expressed as a proportion of the total number of movements ongoing at that time. The plots do not extend beyond 350 ms because too few movements were represented beyond this time to allow reliable estimates of correction rate (for at least one participant, more than 50% of jump trials had terminated). Accordingly, the latest correction rates plotted here (at 350 ms) are not the same as the terminal correction rates reported in Table 4

the automatic pilot can be disengaged only with some sustained effort. These patterns are elaborated by the formal analyses in the following sections.

Auditory task

Error rates in the auditory 1-back task were overall higher than those in Experiment 1 (GO 29.2%, NOGO 30.6%), consistent with the greater cognitive demand imposed by the changing reach instruction. A mixed-model ANOVA was performed on arcsine-transformed percentage error rates to examine the influence of reach instruction (GO, NOGO) and trial type (static, jump). No effects approached significance ($P \geq 0.17$). Unlike in Experiment 1, then, the target jump did not interfere with performance of the auditory task; the distracting influence of the jump may have been masked by the overall greater cognitive demand in Experiment 2. As in Experiment 1, the lack of main effect of reach instruction indicates that comparable cognitive resources were allocated to the auditory task across reach conditions. Unlike in Experiment 1, reaching trials with errors in the auditory task were not excluded, since $\sim$ 30% of observations would have been lost; however, exploratory analyses performed without these trials gave similar results.

Reaching task: static trials (Table 3)

Table 3 shows broadly comparable movements to static targets across conditions. However, as in Experiment 1, participants showed increased RTs in the dual-task condition ($F_{1,15} = 49.25$, $P < 0.0005$); more surprisingly, they also tended to react more slowly in the GO than in the NOGO condition ($F_{1,15} = 53.19$, $P < 0.0005$). Reach instruction also affected LAE, with lateral undershoot in the GO, and lateral overshoot in the NOGO condition ($F_{1,15} = 23.56$, $P < 0.0005$). These opposing biases represent veering towards and away from the probable jump location, and may reflect readiness to implement, or to inhibit, corrections in the anticipated direction for the GO and the NOGO conditions respectively.

Reaching task: jump trials (Fig. 3; Table 4)

Figure 3 clearly suggests that the dual task induces increased rates of correction in the NOGO condition, but does not affect performance in the GO condition. This is formally confirmed by the analysis of TCR (Table 4), which shows a main effect of reach instruction ($F_{1,15} = 171.463$, $P < 0.0005$), interacting significantly with task condition ($F_{1,15} = 16.853$, $P < 0.005$). Task condition did not modify CT or LAE (with respect to target 2) on corrected trials for the GO condition. For the NOGO condition, a repeated-measures analysis of LAE (with respect to target 1) was performed on uncorrected trials, with the factors of task condition (single, dual) and trial type (static, jump). This revealed only a significant main effect of trial type ($F_{1,15} = 10.7$, $P < 0.01$), with greater lateral overshoot on jump trials; as in Experiment 1, the additional deviation away from the jumped target may reflect active suppression of corrections.

As a final analysis, we considered the extent to which correction rates in each task were shaped by short-term performance costs of switching between GO and NOGO instructions. Such switch costs should strongly affect the trials immediately following a change of instruction, but not those at the end of the instruction block. The trial orders were designed to facilitate the investigation of switch costs, as each sub-block of 20 trials contained two ‘early’ jump trials (one left, one right) within the first six trials of the block, and two ‘late’ jump trials (one left, one right) within the last six trials. Correction rates for ‘early’ and ‘late’ jump trials were calculated per participant, per condition, excluding the first sub-block within each block of five, as this initial sub-block did not follow a change of reaching instruction. A repeated-measures ANOVA confirmed the main effect of reaching instruction ($F_{1,15} = 198.6$, $P < 0.0005$), modulated by task condition ($F_{1,15} = 14.3$, $P < 0.005$), as already reported earlier, but

Table 3 Group descriptive data for Experiment 2 static trials, by reach instruction (GO, NOGO) and secondary task (single, dual), for movement variables: reaction time (RT); movement time (MT); peak speed (PS); time to peak speed (TPS); lateral angular error (LAE)

	GO		NOGO	
	Single	Dual	Single	Dual
Mean (SD) RT (ms)	346.9 (60.3)	421.8 (89.4)	305.0 (51.7)	387.5 (74.9)
Mean (SD) MT (ms)	443.9 (89.3)	445.2 (98. 1)	442.0 (89.6)	440.1 (88.1)
Mean (SD) PS (m ms^{-1})	2129.6 (393.1)	2132.3 (374.2)	2122.0 (389.0)	2132.0 (362.9)
Mean (SD) TPS (ms)	134.2 (47.7)	139.3 (48.8)	134.7 (46.8)	135.6 (38.5)
Mean (SD) LAE (°)	−0.12 (0.18)	−0.10 (0.22)	0.08 (0.19)	0.09 (0.21)

Jump trials were included for calculation of RT, since this measure precedes the target jump

Table 4 Group descriptive data for Experiment 2 jump trials, by reach instruction (GO, NOGO) and secondary task (single, dual), for correction variables: terminal correction rate (TCR); correction time (CT); lateral angular error (from target 2) of corrected movements (LAEc); lateral angular error (from target 1) of uncorrected movements (LAEu)

	GO		NOGO	
	Single	Dual	Single	Dual
Mean (SD) TCR (%)	89.3 (9.4)	85.1 (13.8)	16.2 (13.5)	31.1 (26.5)
Mean (SD) CT (ms)	290.7 (46.2)	293.4 (43.0)		
Mean (SD) LAEc (°)	−0.33 (0.28)	−0.29 (0.44)		
Mean (SD) LAEu (°)			0.32 (0.28)	0.39 (0.51)

no effects involving the factor of jump trial stage (early, late) approached significance ($P > 0.19$). Therefore, short-term switch costs do not influence the present findings to any appreciable degree.

Experiment 2: Discussion

Exposing participants to alternating sub-blocks under the GO and NOGO instructions produced the desired effect of pulling performance away from the ceiling levels obtained in Experiment 1. In the single task, participants failed to correct on ~10% of jump trials under the GO instruction, and failed to suppress corrections in ~16% of jump trials under the NOGO instruction. Comparison of Figs. 2 and 3 (note the differently scaled abscissa) shows that corrections emerged slightly later in Experiment 2 (~200–210 ms), rising in frequency with a more shallow slope. These changes were not attributable to switch costs immediately following a reversal of instruction, since they were not differentially expressed in the early trials of each sub-block. They seem to reflect more global changes in task set associated with exposure to the two different instructions, confirming that prior experience can substantially modify automatic pilot settings (Striemer et al. 2010).

Off-ceiling levels of performance provided favourable conditions for assessing dual-task effects. The auditory task had no reliable effect under the GO instruction, but a highly significant influence under the NOGO instruction, nearly doubling the rate of unsuppressed corrections. Thus, whilst voluntarily biasing the automatic pilot towards greater responsiveness requires few or no cognitive resources, beyond the voluntary decision itself, disengagement of the automatic pilot would seem to take sustained effort. This conclusion might not surprise our participants, several of whom commented informally that the NOGO task felt ‘difficult’ or ‘unnatural’.

General discussion

Fast in-flight correction of reaching movements is a default response that occurs even without instruction (Day and Lyon 2000; Pisella et al. 2000), and which can be preconscious (e.g. Castiello et al. 1991; Goodale et al. 1986). These corrections are not sufficiently reflexive to meet criteria for strong automaticity, but are modifiable by a variety of implicit influences, such as expectancy and prior experience, and by explicit instruction. Participants can voluntarily increase the frequency and vigour of online corrections from the default level if their task is to track the target (Cressman et al. 2006; Day and Lyon 2000; Pisella et al. 2000). Conversely, they can resist corrections if told to aim for the original target location (Cameron et al. 2009; Striemer et al. 2010). The present study adds further detail to this picture, showing that the suppression of online corrections is cognitively demanding, whilst their enhancement is seemingly effortless.

Suppression of online correction may depend upon active inhibition of orienting to the jumped location, biasing movement endpoints in the opposite direction. This recalls a family of similar effects in which participants veer away from attention-attracting non-targets in saccadic (e.g. Doyle and Walker 2001; McSorley et al. 2004; Van der Stigchel and Theeuwes 2005) and manual reaching tasks (Meegan and Tipper 1998; Tipper et al. 1997; Welsh and Elliott 2004, 2005; Welsh et al. 1999). Inhibition may be more successful if the jumped target location is predictable, as suggested by the higher rates of unsuppressed corrections with more than one possible jump location (Striemer et al. 2010). However, it must be noted that the voluntary suppression of online corrections has so far been studied only using double-step reaching tasks, with the target displaced in free vision. Here, the target jump is a highly salient visual event, making the control of visual attention especially critical to performance. This may model ecological situations of reaching for mobile targets, but might not be representative of online correction behaviour more generally. If a participant were instead asked to suppress corrections to target jumps applied during saccadic suppression, or in a task in which motor errors were induced by perturbation of reach programming (e.g. using optical prisms) or execution (e.g. by applying force to the limb), it is hard to see how the same strategy of active inhibition could be used. Indeed, it is an open question whether participants could suppress their natural tendency to online correction at all under such conditions.

The present study deepens our understanding of what ‘automatic’ should be taken to imply for the hand’s automatic pilot, at least within the context of the widely used double-step reaching task. For ease of exposition, we have framed this question in terms of a dichotomy between weak and strong automaticity (Jonides et al. 1985), but these categories are in reality broad, probably representing an underlying continuum (e.g. James 1890; MacLeod and Dunbar 1988). For a weakly automatic process, such as the automatic pilot, a fuller description is therefore both possible and useful, and our data help to furnish one. The default setting of the automatic pilot is a state of moderate responsiveness, as shown by intermediate correction rates in STOP tasks, but the system is flexible, being sensitive to both implicit and explicit top–down modulation. It can be adjusted by voluntary intention to meet task goals, but shows a clear preference for adjustment towards greater, rather than lesser responsiveness. This is fully consistent with the evolved role of the automatic pilot as a mechanism to improve motor accuracy.

Acknowledgments A.M. was supported by a studentship from the UK Economic and Social Research Council.

References

Boot WR, Brockmole JR, Simons DJ (2005) Attention capture is modulated in dual-task situations. Psychon Bull Rev 12(4):662–668

Brenner E, Smeets JBJ (1997) Fast responses of the human hand to changes in target position. J Motor Behavior 29(4):297–310

Cameron BD, Franks IM, Enns JT, Chua R (2007) Dual-target interference for the ‘automatic pilot’ in the dorsal stream. Exp Brain Res 181(2):297–305

Cameron BD, Cressman EK, Franks IM, Chua R (2009) Cognitive constraint on the ‘automatic pilot’ for the hand: movement intention influences the hand’s susceptibility to involuntary online corrections. Conscious Cogn 18(3):646–652

Castiello U, Paulignan Y, Jeannerod M (1991) Temporal dissociation of motor-responses and subjective awareness—a study in normal subjects. Brain 114:2639–2655

Cressman EK, Franks IM, Enns JT, Chua R (2006) No automatic pilot for visually guided aiming based on colour. Exp Brain Res 171(2):174–183

Day BL, Lyon IN (2000) Voluntary modification of automatic arm movements evoked by motion of a visual target. Exp Brain Res 130(2):159–168

Desmurget M, Epstein CM, Turner RS, Prablanc C, Alexander GE, Grafton ST (1999) Role of the posterior parietal cortex in updating reaching movements to a visual target. Nat Neurosci 2(6):563–567

Doyle D, Walker R (2001) Curved saccade trajectories: voluntary and reflexive saccades curve away from irrelevant distractors. Exp Brain Res 139(3):333–344

Fisk JD, Goodale MA (1985) The organization of eye and limb movements during unrestricted reaching to targets in contralateral and ipsilateral visual space. Exp Brain Res 60(1): 159–178

Goodale MA, Pelisson D, Prablanc C (1986) Large adjustments in visually guided reaching do not depend on vision of the hand or perception of target displacement. Nature 320(6064):748–750

Grea H, Pisella L, Rossetti Y, Desmurget M, Tilikete C, Grafton S et al (2002) A lesion of the posterior parietal cortex disrupts on-line adjustments during aiming movements. Neuropsychologia 40(13):2471–2480

James W (1890) The principles of psychology. Dover, New York

Johnson H, van Beers RJ, Haggard P (2002) Action and awareness in pointing tasks. Exp Brain Res 146(4):451–459

Jonides J, Navehbenjamin M, Palmer J (1985) Assessing automaticity. Acta Psychol 60(2–3):157–171

Macleod CM, Dunbar K (1988) Training and Stroop-like interference—evidence for a continuum of automaticity. J Exp Psychol—Learn Mem Cogn 14(1):126–135

McSorley E, Haggard P, Walker R (2004) Distractor modulation of saccade trajectories: spatial separation and symmetry effects. Exp Brain Res 155(3):320–333

Meegan DV, Tipper SP (1998) Reaching into cluttered visual environments: spatial and temporal influences of distracting objects. Q J Exp Psychol Sect A—Human Exp Psychol 51(2):225–249

Pelisson D, Prablanc C, Goodale MA, Jeannerod M (1986) Visual control of reaching movements without vision of the limb. 2. Evidence of fast unconscious processes correcting the trajectory of the hand to the final position of a double-step stimulus. Exp Brain Res 62(2):303–311

Pisella L, Grea H, Tilikete C, Vighetto A, Desmurget M, Rode G et al (2000) An ‘automatic pilot’ for the hand in human posterior parietal cortex: toward reinterpreting optic ataxia. Nat Neurosci 3(7):729–736

Striemer CL, Yukovsky J, Goodale MA (2010) Can intention override the "automatic pilot"? Exp Brain Res 202(3):623–632

Tipper SP, Howard LA, Jackson SR (1997) Selective reaching to grasp: evidence for distractor interference effects. Vis Cogn 4(1):1–38

Van der Stigchel S, Theeuwes J (2005) The influence of attending to multiple locations on eye movements. Vis Res 45(15):1921–1927

Welsh TN, Elliott D (2004) Movement trajectories in the presence of a distracting stimulus: Evidence for a response activation model of selective reaching. Q J Exp Psychol Sect A – Human Exp Psychol 57(6):1031–1057

Welsh TN, Elliott D (2005) The effects of response priming on the planning and execution of goal-directed movements in the presence of a distracting stimulus. Acta Psychol 119(2):123–142

Welsh TN, Elliott D, Weeks DJ (1999) Hand deviations toward distracters—evidence for response competition. Exp Brain Res 127(2):207–212