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Christopher Striemer, Julia Yukovsky, Melvyn Goodale

The final publication is available at Springer via

http://dx.doi.org/doi:10.1007/s00221-010-2169-7

Permanent link to this version http://roam.macewan.ca/islandora/object/gm:738

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Can intention override the "automatic pilot"?

Christopher L. Striemer, Julia Yukovsky & Melvyn A. Goodale*

Department of Psychology, Centre for Brain and Mind,
University of Western Ontario,
London, Ontario, Canada, N6A 5C2

Accepted for publication in *Experimental Brain Research* (Jan 13, 2009).

*Corresponding author:
Melvyn A. Goodale, Ph.D., F.R.S.C.
Canada Research Chair in Visual Neuroscience
Department of Psychology
Social Sciences Centre
University of Western Ontario
London Ontario N6A 5C2, CANADA
Email: mgoodale@uwo.ca
Phone: +1 519 661 2070
Fax: +1 519 661 3961

Abstract

Previous research has suggested that the visuomotor system possesses an “automatic pilot” which allows people to make rapid online movement corrections in response to sudden changes in target position. Importantly, the automatic pilot has been shown to operate in the absence of visual awareness, and even under circumstances in which people are explicitly asked *not* to correct their ongoing movement. In the current study, we investigated the extent to which the automatic pilot could be “disengaged” by explicitly instructing participants to ignore the target jump (i.e., “NO-GO”), by manipulating the order in which the two tasks were completed (i.e., either “GO” or NO-GO first), and by manipulating the proportion of trials in which the target jumped. The results indicated that participants made fewer corrections in response to the target jump when they were asked not to correct their movement (i.e. NO-GO), and when they completed the NO-GO task *prior* to the task in which they were asked to correct their movement when the target jumped (i.e., the GO task). However, increasing the proportion of jumping targets had only a minimal influence on performance. Critically, participants still made a significant number of unintended corrections (i.e., errors) in the NO-GO tasks, even under explicit instructions not to correct their movement if the target jumped. Overall these data suggest that, while the automatic pilot can be influenced to some degree by top-down strategies and previous experience, the pre-potent response to correct an ongoing movement cannot be completely disengaged.

Introduction

Previous research has shown that the visuomotor system can utilize fast sensory feedback loops in order to make rapid online corrections to reaching movements in response to sudden changes in target position (Paulignan et al. 1991). Amazingly, these rapid corrections occur even though participants may be totally unaware of the target jump (Goodale et al. 1986; Pelisson et al. 1986; Cameron et al. 2009b). In addition, under circumstances where people *are* aware of the change in target position, the correction *precedes* awareness of the target jump (Castiello et al. 1991; Johnson and Haggard 2005). These data constitute some of the earliest behavioural evidence in humans suggesting that the neural systems supporting visually guided action are separate from those controlling conscious vision (Goodale and Milner 1992; Milner and Goodale 2006).

In an elegant study, Pisella and colleagues (Pisella et al. 2000) investigated participants' ability to correct their movements in response to a target jump (i.e., the "GO" condition) and their ability to *suppress* the same corrections in response to a target jump by stopping their movement (i.e. the "STOP" condition) over a range of movement times (MT; i.e., the time between the initiation and completion of the movement). In the GO condition, healthy participants were able to correct their movements in response to the target jump, even with MTs as fast as 200ms[1]. Furthermore, for the same 200ms MT duration, healthy participants also had difficulty *suppressing* these rapid movement corrections when they were explicitly asked to STOP their movements if the target jumped (i.e., the STOP condition; see also, Day and Lyon 2000; Cressman et al. 2006). The earliest MT for which there was a differential effect of instructions on movement corrections (i.e., with a greater number of corrections in the GO vs. the STOP condition) was approximately 240ms. While this may be taken to imply that trials with

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[1] Previous work by Cressman et al. (2006) and Cameron et al. (2009a) has shown that reach trajectories begin to deviate toward the jumped target as early as 130-150ms after the target jump.

MTs greater than 240ms were under conscious “intentional” control, this explanation seems unlikely. Specifically, in the STOP condition participants continued to produce a significant number of unintended corrections for MTs up to (and including) 300ms, suggesting that movements completed within 300ms were still not completely under intentional control. In contrast, movements with MTs longer than 300ms rarely produced unintended corrections in the STOP condition. This suggests that the temporal window in which “automatic” movement corrections are likely to escape intention is rather narrow (i.e., 200-300ms).[2] Furthermore, rather than having an absolute time point at which there is an abrupt shift from automatic control to “conscious” control these data imply that this shift is a gradual one that is likely influenced by the speed with which sensory feedback loops can sample information from an ongoing movement in order to accurately guide the hand to the target (for a review see Desmurget and Grafton 2000).

In a second experiment, Pisella and colleagues demonstrated that a patient with bilateral lesions of the dorsal posterior parietal (PPC) cortex was unable to initiate any *rapid* online corrections (i.e., for movements with MTs faster than 300ms) in response to changes in target position. Furthermore, the same patient also made no rapid corrections when she was asked *not* to correct her movements to the target jump (i.e., the opposite of healthy controls). Based on these data, Pisella and colleagues suggested that the visuomotor system in the PPC possesses an “automatic pilot” that allows people to rapidly modify ongoing movements in order to accurately guide their hand to a target (see also Desmurget et al. 1999; Grea et al. 2002; Blangero et al. 2008).

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[2] This temporal window should not be seen as absolute limit, but as a rough guideline. These time limits will undoubtedly be influenced by factors such as movement velocity, reach distance, and individual differences in visuomotor processing speed.

Although the automatic pilot in the PPC can rapidly correct movements online, several important questions remain unanswered. One particularly interesting question centres on understanding the extent to which the automatic pilot can be considered to be highly automatic[3]. To address this question in the current study, we examined what factors might influence the performance of the automatic pilot. First, whereas previous studies have contrasted situations in which the participant is told to correct their movement (i.e. GO) or to abort their movement (i.e. STOP) in response to the target jump, in the present study we were interested in whether or not participants could actively *ignore* the target jump and reach to the initial target location (i.e., the NO-GO condition). That is, we were interested in whether a participant’s intention to ignore the target jump could effectively disengage the automatic pilot and override the tendency to correct their movement in response to the target jump.

Second, we were also interested in whether or not the automatic pilot could be influenced by prior experience. That is, if we had participants complete a large number of trials in which they were explicitly asked *not* to correct their movement on one testing day, would that experience influence their ability to initiate corrections when they were explicitly asked to *correct* their movements on a subsequent testing day? If the automatic pilot is influenced by previous experience, then that would tend to indicate that it is not as highly automatic as has been suggested previously.

Finally, we wanted to examine whether or not the automatic pilot is sensitive to the probability that a target would change position on a given trial. In order to examine this question

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[3] We use the term “highly automatic” instead of “automatic” here because we feel it is a bit naïve to divide processes categorically into automatic or not automatic. Such a simple dichotomy sets the stage for the development of straw-man hypotheses which are easily rejected. Instead, we believe that many automatic processes lie on a continuum of automaticity with highly automatic processes on one end of the continuum and less automatic processes on the other (see MacLeod & Dunbar, 1988). In some sense, the goal of the present study was to determine on which end of the continuum of automaticity the automatic pilot for reaching movements lies.

participants completed separate blocks of trials in which the target could jump on either 20% of trials (as in previous studies) or on 50% of trials. We chose a 50% jump condition for comparison because on any given trial the likelihood of a target jump occurring is much higher, but is still not predictable. Specifically, when the target jumps on 50% of trials participants knew only that they would have to prepare for the target jump to be more frequent. However, they still could not over-commit their movement strategy to prepare for a static or a jump trial because they could not accurately predict whether or not the target would jump *on any particular trial*. If we made the occurrence of a target jump *highly* predictable (80% jump) participants would have simply been able to set their movement strategy to *always* prepare for a target jump. Thus, by using a 50% jump condition we ensured that participants still had to initiate their movement before they knew whether or not the target would jump on any given trial.

Based on this design, we had two competing hypotheses. First, if the automatic pilot *is* highly automatic then participants should have a great deal of difficulty ignoring the target jump and should therefore make a significant number of unintended corrections on jump trials in the NO-GO condition even when they are explicitly asked to not correct their movement (i.e., participants should not be able to easily disengage the automatic pilot). In addition, the automatic pilot should generate an equal number of corrections in the GO and NO-GO tasks regardless of which set of instructions was carried out first (i.e., no effect of prior experience). Finally, it should be relatively insensitive to changes in the proportion of trials in which the target jumps.

On the other hand, if the automatic pilot *is not* highly automatic then it should be relatively easy for participants to ignore the target jump in the NO-GO task and they should therefore make very few (if any) unintended corrections. Furthermore, if the automatic pilot *is not* highly automatic, then it should be influenced by previous experience. Specifically, if participants perform the NO-GO task first, they should make fewer unintended corrections on jump trials (i.e., fewer errors). But later, when participants perform the GO task on the subsequent testing day, they should make fewer intended corrections on jump trials (i.e., more errors). Finally, if the automatic pilot is not highly automatic, increasing the likelihood that a target will jump on a given trial might be expected to *increase* the number of corrections in the GO task, and *decrease* the number of unintended corrections in the NO-GO task in the 50% jump condition. That is, participants should be able to incorporate the increased likelihood that the target will jump on any given trial into their movement plan in order to *increase* the number of corrections to the target jump in the GO task and to *override* the tendency to correct by disengaging the automatic pilot in the NO-GO task.

Methods

Participants

Twenty experimentally naïve right-handed students (13 female; 7 male; mean ± SD age 23.5 ± 4.06 years; range 18-30 years) from the University of Western Ontario with normal or corrected-to-normal visual acuity participated in the study. Participants were paid $20 for their involvement in the study. The experimental protocol was approved by the Human Research Ethics Board at the University of Western Ontario. All participants gave written informed consent.

Apparatus and procedure

Participants performed the GO and NO-GO tasks in separate testing sessions on different days (range=1-10 days; mean days between sessions, GO first=4.8 days; NO-GO first=5 days). Note that testing order was randomized across participants. The gender distribution within the two testing orders was approximately equal with 6 females and 4 males in the GO first testing order and 7 females and 3 males in the NO-GO first testing order. Within each of the two testing sessions participants were given separate blocks of 100 trials in which the target jumped on either 20% or 50% of trials (order was counterbalanced across the two testing sessions using an ABBA design). Thus participants completed a total of 400 experimental trials across the two testing sessions. In the GO task participants were instructed that if the target jumped to a different location they were to correct their movement and move to the new target location. In contrast, in the NO-GO task participants were instructed that if the target jumped they were *not* to correct their movement (i.e. they were to ignore the target jump), and instead continue to point to the initial (i.e., pre-jump) target location.

For each task, stimuli were presented on a vertically mounted 32-in liquid crystal display (LCD) touch screen monitor (Mass Multimedia Inc.; refresh rate 60Hz). The experiment was completed in a darkened room; however, the light emitted from the monitor allowed participants to have vision of their hand at the end of the movement. Participants sat 40cm away from the screen with their head fixed in a chin-rest aligned with the centre of the screen. At the beginning of each trial a red fixation cross appeared. To initiate the trial, the participant pressed and held down a button on an external button pad (Cedrus RB-530) aligned to the participant’s midline and located 30cm from the surface of the screen. After the start button was pressed, the fixation cross turned black to indicate that the trial had started. Following a randomized 1- to 3-s delay, a small black circular target (5mm in diameter) presented on a grey background appeared 12° above fixation at one of two locations 2.25° to the left or right of the fixation cross. The participant was instructed to release the start key as soon as the target appeared and point towards the target as quickly and accurately as possible.

On static (i.e., no-jump) trials, the target remained in the same position (i.e., at 2.25 ° to the left or right of fixation). On jump trials, however, the target jumped to another position 4.50° to the left or right of the initial target location as soon as the start button was released. For example, on a jump trial, if the target initially appeared 2.25 ° to the left of fixation then it could jump leftward to a position 6.75 ° to the left of fixation or rightward to a position 2.25 ° to the right of fixation. Likewise, if the target first appeared 2.25 ° to the right of fixation it could jump rightward to a position 6.75 ° to the right of fixation or leftward to a position 2.25 ° to the left of fixation. Leftward and rightward target jumps occurred with equal frequency in all testing blocks. Thus participants were not able to predict which direction a target would jump on any given trial.

Within each block, static and jump trials were intermixed in a random sequence. Participants were encouraged to complete their movement towards the target as quickly and accurately as possible within a 300ms time constraint of maximal movement time[4]. A loud 500Hz tone was presented if the movement was not completed within 300ms to indicate that the participant was to move faster on subsequent trials. Note that we did not exclude trials in which the participant did not meet the 300ms MT deadline. We simply used this deadline as a way to encourage participants to move as quickly as possible. However, mean MT for all conditions was

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[4] We used a movement time constraint of 300ms because previous work by Pisella and colleagues (2000) indicated that the largest proportion of "automatic" corrections occurred on trials in which movement times were between 200-300ms.

below 300ms indicating that participants complied with our instructions to move to the target quickly.

Prior to each condition (20%, 50%) in each task (GO, NO-GO) participants completed 40 practice trials which included the correct proportion of jump trials they would encounter in the subsequent block in order to familiarize them with the task and the speed of responses that were required. Participants were explicitly told about the proportion of jump trials to expect in each block. For each trial we recorded the end-point of the participant's pointing movement (using the surface of the touch screen)[5], the reaction time (RT; the time that elapsed between target onset and the release of the start button), and movement time (MT; the time between the release of the start button and contact with the surface of the touch screen).

Data analysis

For each participant, we calculated the mean reach endpoint (in the horizontal 'X' plane), mean RT, and mean MT separately for static and jump trials in each of the tasks (GO, NO-GO) in both the 20% jump and 50% jump conditions. To determine whether or not a movement was corrected on a given jump trial we calculated Z-scores for each jump trial using the mean endpoint and SD from the corresponding static trials for each condition (i.e., 20% static vs. 50%

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[5] Previous research by Cressman et al. (2006) and Cameron et al. (2009a) has demonstrated that participants' reach trajectories may significantly deviate towards the jumped target even when they were able to stop their movement in flight (i.e. the STOP condition). This suggests that the automatic pilot may have still have been 'captured' by the target jump even on trials where participants successfully stopped their movement. Given that we were only recording movement endpoint in this study, we were not able to index trials in which corrections initially deviated toward the target jump but ultimately landed at the initial target location (i.e. in the NO-GO condition). Therefore, these data likely represent a *conservative estimate* of the total number of corrections that occurred in the NO-GO tasks.

static; Pisella et al., 2000; Robert McIntosh, personal communication).[6] Any jump trial with an endpoint that corresponded to a Z-score larger than 1.96 (i.e., *p*=.05 2-tailed) in the direction of the target jump was classified as "corrected." All other jump trials with endpoints that resulted in Z-scores less than 1.96 were classified as "not corrected." Note that no participants ever corrected in the wrong direction on jump trials.

The percentage of movement corrections on jump trials was analyzed using a 3-way mixed-model ANOVA with task (GO, NO-GO) and condition (20% vs. 50% jump) as within-subject factors, and order (GO first, NO-GO first) as a between subject factor. Endpoint data for the static and jump trials, as well as the MT and RT data, were analyzed using 4-way mixed-model ANOVAs including the same variables as in the 3-way analysis (outlined above) with an additional within-subject factor of trial (static, jump). Posthoc comparisons were carried out using a Tukey HSD correction (corrected *p*=.05).

Results

We present the mean endpoint error (in the horizontal 'X' plane), mean MT and mean RT as a function of task (GO vs. NO-GO), condition (20% vs. 50% jump), trial (static vs. jump), and order (GO first vs. NO-GO first) in Table 1.

--Insert Table 1 here--

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[6] One could argue that there is no adequate baseline condition with which to compare jump trials in the NO-GO task because on these trials participants are asked to ignore the target jump and point to the initial target location (which is no longer present on the screen). Presumably this would have increased movement endpoint error and variability in this condition and could lead to jump trials in this condition being incorrectly classified as corrected. To rule out this possibility, we conducted a separate analysis of the movement endpoints for jump trials in the NO-GO tasks that were classified as "not corrected" and compared them to the movement endpoints for the static trials in the same condition. This analysis revealed that the endpoints for the static trials and jump trials classified as not corrected in the NO-GO tasks were identical. This suggests that participants were accurately pointing to the initial target location on trials which were not corrected. Therefore, we can be certain that movements classified as corrected in the NO-GO task were truly corrected and were not misclassified as a consequence of an increase in movement variability.

Endpoint accuracy on static trials.

We first compared the endpoint (‘X’) accuracy in millimeters for the static (no-jump) trials across the different testing conditions. This analysis revealed a significant task x order interaction (F(1,18)=13.10, *p*=.002) such that participants were significantly less accurate for static trials in the NO-GO task when they completed the NO-GO task first (12.55mm) compared to when they completed the GO task first (8.79mm; t(18)=3.04, *p*<.05).[7]

Percentage of movement corrections on jump trials.

This analysis revealed a main effect of task (F(1,18)=44.89, *p*<.0001) with a greater percentage of movements corrected in the GO (64%) compared to the NO-GO task (32%), and a main effect of order (F(1,18)=6.06, *p*=.024) with a greater percentage of corrections when people completed the GO task first (55%) compared to when they completed the NO-GO task first (41%) [8]. In addition, there was a trend towards a task x order interaction significant (F(1,18)=3.85, *p*=.065; Figure 1a). This resulted from a decreased number of corrections in the GO task when people completed the NO-GO task first (52%), compared to when they completed the GO task first (76%; *p*<.05; Figure 1a). In contrast, order had no effect on the percentage of movement corrections in the NO-GO task (GO first=35% vs. NO-GO first= 29%, t(18)=0.634, ns). In addition, there was a slight trend towards a task x condition interaction (F(1,18)=3.05, *p*=.09; Figure 1b). This trend was driven by a marginal reduction in the percentage of

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[7] Note that this does not pose a problem for how we classified jump trials as corrected in the NO-GO tasks. The classification of jump trials was done at an individual subject level which takes these differences in accuracy for static trials into account.

[8] In a subsequent analysis we examined whether the order in which the different conditions (i.e., 20% vs. 50% jump) were completed *within a session* had any influence on the percentage of movement corrections. This analysis revealed a significant main effect of task order (GO first vs. NO-GO first; F(1,16)=5.49, *p*=.032), but no main effect of condition order (i.e., 20% jump first vs. 50% jump first; *p*=.63), and no task order x condition order (*p*=.71) or task x condition order (*p*=.22) interaction. Therefore, the order in which the different conditions were completed within a testing session had no significant influence on the percentage of corrections.

movements corrected in the NO-GO task when the target jumped on 50% of trials (27%) compared to 20% of trials (37%; t(18)=1.82, ns, HSD t(18) >2.83). In comparison there was no change in the percentage of movements corrected in the GO task when the target jumped on 20% (63%) compared to 50% of trials (66%; t(18)=0.53, n.s.).

Finally, although participants made many more corrections on jump trials in the GO task compared to the NO-GO task, the number of unintended corrections in the NO-GO task was still much higher than 5% (all means >20%, one sample t-tests, all *p*'s <.05) which is the proportion of static trials that one would expect to be classified as corrected using a 1.96 Z-score cutoff.

--Insert Figure 1 here--

Endpoint accuracy on static and jump trials.

In order to determine whether corrections on jump trials in the GO and NO-GO tasks were of similar magnitude we carried out a 4-way ANOVA on the endpoint errors (relative to the initial target location) with task (GO vs. NO-GO), condition (20% vs. 50% jump), and trial type (static vs. jump) as within-subject factors, and order (GO first vs. NO-GO first) as a between subject factor. This analysis revealed main effects of task (F(1,18)=34.86, *p*<.001), condition (F(1,18)=8.09, *p*=.011), and trial type (F(1,18)=204.22, *p*<.001). Specifically, endpoint errors were larger in the GO (19.82mm) compared to the NO-GO task (14.41mm), were larger in the 50% jump (17.65mm) compared to the 20% condition (16.60mm), and were larger on jump trials (23.74mm) compared to static trials (10.51mm).

There were also significant task x order (F(1,18)=5.04, *p*=.038), trial x order (1,18)=4.94, *p*=.039), task x condition (F(1,18)=8.16, *p*=.01), condition x trial type (F(1,18)=5.85, *p*=.026), and task x trial type (F(1,18)=48.12, *p*<.001), interactions. Importantly posthoc comparisons of difference scores for the task x order, trial x order, task x condition, and condition x trial type interactions were not significant following the Tukey HSD correction. Critically, the task x trial type interaction (Figure 2) revealed that endpoint errors for the static trials in the GO (10.35mm) and NO-GO (10.68mm) tasks were not significantly different from one-another. In contrast, although the endpoints for the jump trials in the GO (29.33mm) and NO-GO (18.14mm) tasks were significantly different from their respective static baseline conditions (*p*'s <.05), the endpoints for jump trials in the GO and NO-GO tasks were also significantly different from one-another (*p*<.05; Figure 2).

--Insert Figure 2 here--

Movement time (MT).

We also analyzed MTs and RTs for all static trials, and for jump trials which were classified as corrected based on the analysis outlined in the previous section. For MT there was a significant main effect of trial (F(1,18)=29.37, *p*<.0001) with jump trials (277ms) having longer MTs than static trials (266ms). In addition, there was also a significant task x trial interaction (F(1,18)=22.69, *p*<.0001; Figure 3). The interaction revealed that MTs for jump trials in the GO condition (284ms) were significantly slower than MTs for jump trials in all other conditions (GO static= 267ms, NO-GO static=266ms, NO-GO jump=269ms; all *p*'s <.05; Figure 3).

--Insert Figure 3 here--

In a subsequent analysis we then compared MTs for jump trials classified as “corrected” or “not corrected” (as outlined in the Methods section) to see if unintended corrections on jump trials in the NO-GO tasks could be explained in terms of differences in MT. We analyzed these data with the same ANOVA used in the previous analysis with classification (corrected vs. not corrected) added as an additional within-subject factor. This analysis revealed a significant main effect of classification (F(1,18)=64.21, *p*<.001) with corrected trials (277ms) having longer MTs than trials that were not corrected (256ms). There was also a significant two-way interaction between task and classification (F(1,18)=35.44, *p*<.001) and a marginal condition x classification interaction (F(1,18)=4.18, *p*=.056).

Posthoc analyses indicated that the task x classification interaction resulted from the fact that there was a significant difference in MT between corrected and uncorrected jump trials for the GO task (corrected=284ms vs. uncorrected=248ms; *p*<.05) but not the NO-GO task (corrected=269ms vs. uncorrected=264ms). In addition, MTs for corrected trials in the GO task (284ms) were significantly *longer* than MTs for corrected trials in the NO GO task (269ms; *p*=.05)), and MTs for uncorrected trials in the GO task (248ms) were significantly *faster* than MTs for uncorrected trials in the NO-GO task (264ms; *p*<.05). Finally, the condition x classification interaction was driven by a slight trend towards a larger difference in MT between corrected and uncorrected trials in the 20% jump condition (23ms) compared to the 50% jump condition (18ms; t=1.68, ns; t must be larger than 2.83).

Reaction time (RT).

Analysis of the RTs for static trials and corrected jump trials revealed a significant 3-way task x condition x order interaction (F(1,18)=4.59, *p*=.046). Follow-up 2-way within-subject

ANOVAs revealed that the task x condition interaction was significant for participants who completed the NO-GO task first (F(1,9)=8.74, *p*=.016) but not for the participants who completed the GO task first (F(1,9)=0.51, *p*=.49). However, none of the means for the task x condition interaction in the group who completed the NO-GO task first were significantly different from one-another following the Tukey HSD correction (t(9) must be >3.13).

Discussion

Previous work suggests that the visuomotor system in the PPC possesses an automatic pilot that enables one to make rapid online corrections while reaching to targets that suddenly change position (Goodale et al. 1986; Pelisson et al. 1986; Pisella et al. 2000). Importantly, these corrections can occur even if they are unintended (Day and Lyon 2000; Pisella et al. 2000; Cressman et al. 2006). In the current experiment we were interested in the degree to which the automatic pilot could be considered highly automatic. To investigate this question we examined the influence of a number of different factors on the automatic pilot. Specifically, we examined whether or not the automatic pilot could ignore a target jump when it was not task relevant (i.e., the NO-GO condition), whether or not it was modifiable by prior experience, and whether or not it was sensitive to the proportion of jumping targets,.

Consistent with previous reports, participants made a greater number of movement corrections in response to the target jump in the GO task compared to a condition in which they were asked not to correct their movement (i.e., the NO-GO condition). Importantly, participants made a significant number of unintended corrections in the NO-GO task even though they were explicitly told not to correct their movement (i.e. to ignore the target jump) and point to the original target location (Figure 1). Although endpoint errors for jump trials were significantly larger in the GO task compared to the NO-GO task (Figure 2), the endpoint errors for the NO-GO task were still significantly larger than the static (baseline) condition. This clearly indicates that participants' endpoints were significantly influenced by the target jump in the NO-GO condition.

This finding contrasts somewhat with a recent report by Cameron and colleagues (Cameron et al. 2009a) in which they demonstrated that participants *were* able to ignore the target jump on a majority of trials in an "IGNORE" condition that was quite similar to our NO-GO condition. There are, however, two key differences between the two studies which might explain the discrepancy in results. First, Cameron and colleagues contrasted performance in the GO condition with both a STOP (similar to Pisella et al., 2000) and an IGNORE (i.e., NO-GO) condition. Perhaps the contrast between instructions to STOP (i.e., abort the movement) and instructions to IGNORE (complete the movement but ignore the target jump) was enough to make the participants to behave differently in the IGNORE condition.

Perhaps the more important difference between the Cameron et al. study and ours is that they forced their participants to move *extremely* rapidly; participants in their study had to complete a 27-cm reach in 185-215ms (compared to a 30-cm reach in 300ms in the current study). As noted in the Introduction, Pisella and colleagues (Pisella et al. 2000) demonstrated that the earliest point that movement corrections to target jumps begin to emerge is for MTs of approximately 200ms (i.e., the *maximum time allowed* in the Cameron et al. study). Furthermore, the percentage of movement corrections increases dramatically for MTs between 200-300ms (see Pisella et al., 2000). The lower percentage of movement corrections observed in the IGNORE condition in the Cameron et al. study may simply reflect the fact that there was not a sufficient amount of time for the visuomotor system to incorporate incoming information from sensory feedback loops to correct the ongoing movement and *override* the intention to ignore the target jump that was set at the beginning of the testing block. Specifically, in the Cameron et al. study (as the authors themselves suggest) participants were likely able to use a “task set” to decrease the responsiveness of the automatic pilot to a target jump at the beginning of the IGNORE condition. In addition, because they were moving so rapidly (i.e., a MT goal of 185-215ms) there may not have been enough time for the automatic pilot to override the active suppression and initiate the movement correction at later time (i.e., a later correction time). However, the current study allowed a longer MT deadline of 300ms. This may have been enough time for the automatic pilot to overcome the active suppression and correct the movement during a later point in the reach. Therefore, we are proposing that it may be the case that the automatic pilot can never completely ignore a target jump, only delay its response to the target jump.

Although this hypothesis is speculative it could be directly tested in a future experiment in which participants are asked to complete a NO-GO task in which the maximum MT allowed is either 200ms or 300ms. If the automatic pilot is easily disengaged in the NO-GO task then the MT goal should have no influence on the percentage of corrections. However, if the automatic pilot needs additional time to overcome active suppression, then there should be a greater proportion of movements corrected to the target jump in the NO-GO condition when the MT goal is 300ms compared to 200ms.

In addition, our results demonstrate that the automatic pilot can be influenced, at least to some degree, by prior experience. The most direct evidence in support of this hypothesis is the main effect of order, and the task x order interaction that were observed when comparing the percentage of movements classified as corrected in the GO and NO-GO tasks. Specifically, overall there was a 14% drop in the percentage of trials classified as corrected when participants completed the NO-GO task *before* the GO task. In addition, the task x order interaction indicated that, when participants learned to correct for the target jump by completing the GO task first, they made a significantly greater number of corrections compared to when they completed the NO-GO task first in which they learned to ignore the target jump (Figure 1a). Thus, our data are consistent with the notion that even processes which are considered highly automatic can be influenced by training or experience to some degree (see MacLeod and Dunbar 1988).

It is important to point out that task order was randomized across participants and each task (GO or NO-GO) was tested on different days (mean days between testing sessions, GO first =4.8 days; NO-GO first=5 days). Furthermore, prior to each block participants received 40 practice trials with the correct proportion of jump trials in order to learn to carry out the new task. This suggests that the influence of prior experience we observed is not a standard carry-over effect in which subjects simply needed time to overcome the response criterion that was established in the previous task.

While this effect could be considered as task dependent, it would be interesting for future studies to examine the degree to which training can influence automatic motor corrections. For example, would training participants to ignore a target jump in one task make them less able to make online corrections in a subsequent task when they are asked to grasp an object that suddenly changes position at movement onset? The answer to this question would allow researchers to make inferences as to whether similar mechanisms are engaged when making online corrections while reaching compared to grasping. Another interesting line of research for future studies would be to examine whether or not the automatic pilot has a memory for what happened on the previous trial. Specifically, in a situation in which the target jumps on 50% of trials, and the direction of the target jump is predictable (e.g., always a rightward target jump), it would be interesting to examine whether or not ordered sequences of jump trials (e.g. 5 in a row compared to 2 in a row) would result in a participant's reach trajectory being biased toward the location of the target jump earlier in the reach trajectory (see for example Whitwell and Goodale 2009). If the automatic pilot is highly automatic, one would not expect this to be the case.

With respect to the proportion of jump trials, we found no significant differences in the percentage of movements corrected on jump trials when the target jumped on 20% as compared to 50% of the trials. There was, however, a slight trend towards a decrease in the number of unintended corrections (i.e., errors) in the NO-GO task when the target jumped on 50% as compared to 20% of trials. While this trend is suggestive, it may be necessary to further increase the proportion of jump trials to demonstrate any sensitivity of the automatic pilot to this manipulation.

In addition to having an influence on the number of movement corrections, task (i.e., GO vs. NO-GO) also had an influence on MTs. Analysis of the MT data indicated that participants were slower for jump trials in the GO condition (284ms) than in all other conditions (all ≤ 269ms). One issue that arises from this finding is the possibility that, because movements on jump trials in the GO condition were somewhat slower, that they may have been under intentional control. Specifically, as highlighted in the Introduction, previous work by Pisella and colleagues (2000) has demonstrated that instructions can have a differential effect on performance for MTs greater than ~240ms such that there is a significant increase in the percentage of movement corrections on jump trials in the GO compared to STOP task. Thus, one could argue that compliance with instructions might indicate that the movements in these conditions were under intentional (i.e., conscious) control.

We think this assumption is misleading for a number of reasons. First, unintended corrections in the NO-GO task in the current study had an average MT of 269ms. If these movements are assumed to be under the control of the automatic pilot then it seems very unlikely that an increase in MT of a mere 15ms on jump trials in the GO condition (284ms) when subjects are moving rapidly would be sufficient to result in an abrupt switch from automatic to conscious intentional control. Second, in order for one to make this argument it would be necessary to demonstrate an abrupt change in reach trajectory or a second peak in a velocity profile which would be indicative of a new movement planned online. Admittedly, these data are not present in the current study. However, many previous studies have shown that participants can execute reaches to jumping targets at comparable distances with MTs anywhere from 300-600ms without *any* evidence of an abrupt change in reach trajectory or re-acceleration (Pelisson et al. 1986; Prablanc et al. 1986; Prablanc and Martin 1992; Desmurget et al. 1999; Johnson and Haggard 2005; Cressman et al. 2006). This suggests that reaches on jump trials in the GO condition in the current study are under the control of the same visuomotor networks that are also used to guide much faster reaches.

In short, when participants are making rapid reaches, it is unlikely that there is a specific point in time during the reach where there is an abrupt shift from “completely automatic” to “completely conscious” control. In fact, previous work has shown that participants are typically unaware of the target jump (which would be required for conscious control) until long after (e.g., in the order of 200ms) the correction to the target perturbation has been initiated (Castiello et al. 1991). Instead, the increase in MT on jump trials in the GO task in the present study likely reflects the additional time needed for the automatic pilot to use information from sensory feedback loops to correct the movement in flight in order to comply with the instruction to correct which is set at the beginning of the trial (or block). To put it plainly, participants may have taken more time to correct their movements in the GO condition so that they could comply with the instruction to correct.

Finally, the most important point to emphasize is that regardless of what the cause of the increase in MT for jump trials in the GO task might be, the key finding from the present study was the fact that participants were not able to successfully ignore the target jump as they still made a significant number of unintended corrections on jump trials in the NO-GO task. Furthermore, this effect cannot be accounted for by differences in MT as the MTs for “corrected” and “not corrected” jump trials in the NO-GO task were not significantly different from one-another.

In conclusion, the current study has highlighted the important point that the automatic pilot can be influenced by “top-down” strategies and prior experience, but only to a limited degree. Specifically, participants were able ignore the target jump to some extent given that there was an overall decrease in movement corrections on jump trials in the present study. In addition, there was an effect of testing order (i.e., whether participants completed the GO or the NO-GO task first) on the percentage of movement corrections suggesting that the automatic pilot is influenced by prior experience. However, data from the current study also imply that the tendency to correct one’s reach in response to a sudden change in target position cannot be completely overridden as participants were relatively insensitive to the proportion of jumping targets, and still made a significant number of unintended corrections on jump trials in the NO-GO tasks. In short, this suggests that the automatic pilot cannot be easily disengaged.

Important questions for future research will be to further highlight the degree to which conscious strategies can influence automatic performance. In addition, further work is needed to help reveal the neural architecture that supports the automatic pilot. Specifically, although we know that the PPC plays a role in initiating these online corrections (Desmurget et al. 1999; Pisella et al. 2000; Desmurget et al. 2001; Glover et al. 2005), we know very little regarding which sub-regions of the PPC are critical for this process, and the temporal window(s) in which the PPC activates the automatic pilot. Finally, we know that the PPC is densely interconnected with other brain regions that play key roles in visuomotor control such as the dorsal pre-motor cortex (Petrides and Pandya 1984; Chouinard and Paus 2006) and the cerebellum (Clower et al. 2001; Bastian 2006). However, the role that these structures might play in controlling the automatic pilot is currently unknown.

Acknowledgments:

The authors would like to thank Robert McIntosh for helpful comments on an earlier draft of this manuscript. This work was supported by a Heart and Stroke Foundation of Canada Postdoctoral Award to C.L.S. and a Canadian Institutes of Health Research (CIHR) operating grant to M.A.G.

Table 1: Mean endpoint error in millimeters and movement time (MT) and reaction time (RT) in milliseconds as a function of task (‘GO’, ‘NO-GO’), condition (20% vs. 50% jump), trial (static vs. jump), and testing order (GO first vs. NO-GO first). Please note that the error reported for jump trials reflects the distance from the original target location.

	Completed GO task first							
Trial type	**Static (no jump)**				**Jump (corrected)**			
Condition	**20% Jump GO**	**50% Jump GO**	**20% Jump NO-GO**	**50% Jump NO-GO**	**20% Jump GO**	**50% Jump GO**	**20% Jump NO-GO**	**50% Jump NO-GO**
Endpoint error (SD)	10.75 (2.66)	11.44 (2.27)	8.83 (2.74)	8.76 (2.52)	28.87 (2.93)	34.27 (3.38)	18.63 (3.56)	19.13 (4.76)
MT (SD)	270 (6.36)	268 (7.66)	266 (7.31)	269 (16.64)	288 (12.14)	287 (11.14)	277 (13.27)	268 (19.15)
RT (SD)	294 (44.51)	295 (30.35)	307 (39.26)	320 (52.50)	294 (46.73)	295 (33.18)	309 (38.81)	295 (33.18)
	Completed NO-GO task first							
Trial type	**Static (no jump)**				**Jump (corrected)**			
Condition	**20% Jump GO**	**50% Jump GO**	**20% Jump NO-GO**	**50% Jump NO-GO**	**20% Jump GO**	**50% Jump GO**	**20% Jump NO-GO**	**50% Jump NO-GO**
Endpoint error (SD)	9.31 (1.98)	9.89 (1.22)	13.04 (3.09)	12.06 (2.96)	25.38 (7.84)	28.79 (8.50)	17.99 (5.70)	16.82 (5.83)
MT (SD)	265 (16.77)	263 (21.15)	265 (16.77)	265 (26.71)	279 (15.77)	283 (12.84)	268 (32.61)	265 (26.61)
RT (SD)	276 (26.39)	294 (46.81)	280 (25.56)	276 (27.94)	271 (26.03)	296 (52.66)	276 (44.05)	273 (26.38)

Figure captions.

Figure 1. Mean percentage of movements "corrected" on jump trials as a function of task (GO, NO-GO), condition (50% jump, 20% jump) and order (GO first, NO-GO first). A) Depicts the task x order interaction where participants made fewer corrections on the GO task when they completed the NO-GO task first. B) Depicts the trend towards a task x condition interaction where there was a tendency for participants to make slightly fewer unintended corrections (i.e., errors) in the NO-GO task when the target jumped on 50% of trials compared to only 20% of trials. Error bars depict standard error of the mean.

Figure 2. Mean horizontal ('X') error (in millimeters) for static and jump trials. Depicts the task x trial type interaction where endpoint errors were larger for jump trials in the GO task compared to the NO-GO task. However, endpoint errors for jump trials in the NO-GO task were significantly different from baseline (i.e., the static trials). Error bars depict standard error of the mean.

Figure 3. Mean movement time (in milliseconds) as a function of task (GO, NO-GO) and trial type (static, jump). Depicts the task x order interaction where movement times for jump trials in the GO task were longer than movement times for all other conditions. Error bars depict standard error of the mean.

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Figure 1.

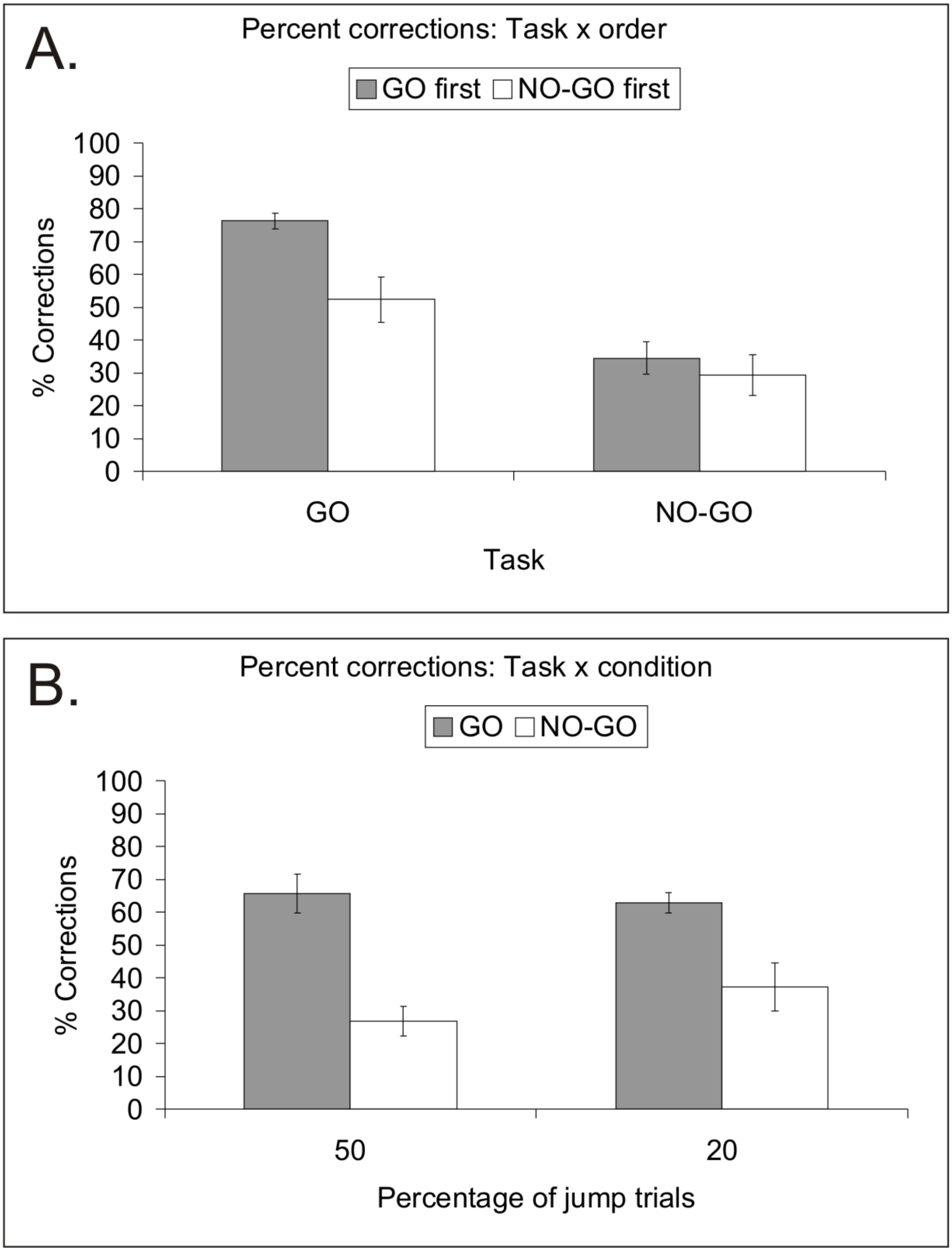

A.
Percent corrections: Task x order
GO first
NO-GO first
100
90
80
70
60
50
40
30
20
10
0
% Corrections
GO
NO-GO
Task
B.
Percent corrections: Task x condition
GO
NO-GO
100
90
80
70
60
50
40
30
20
10
0
% Corrections
50
20
Percentage of jump trials

Figure 2.

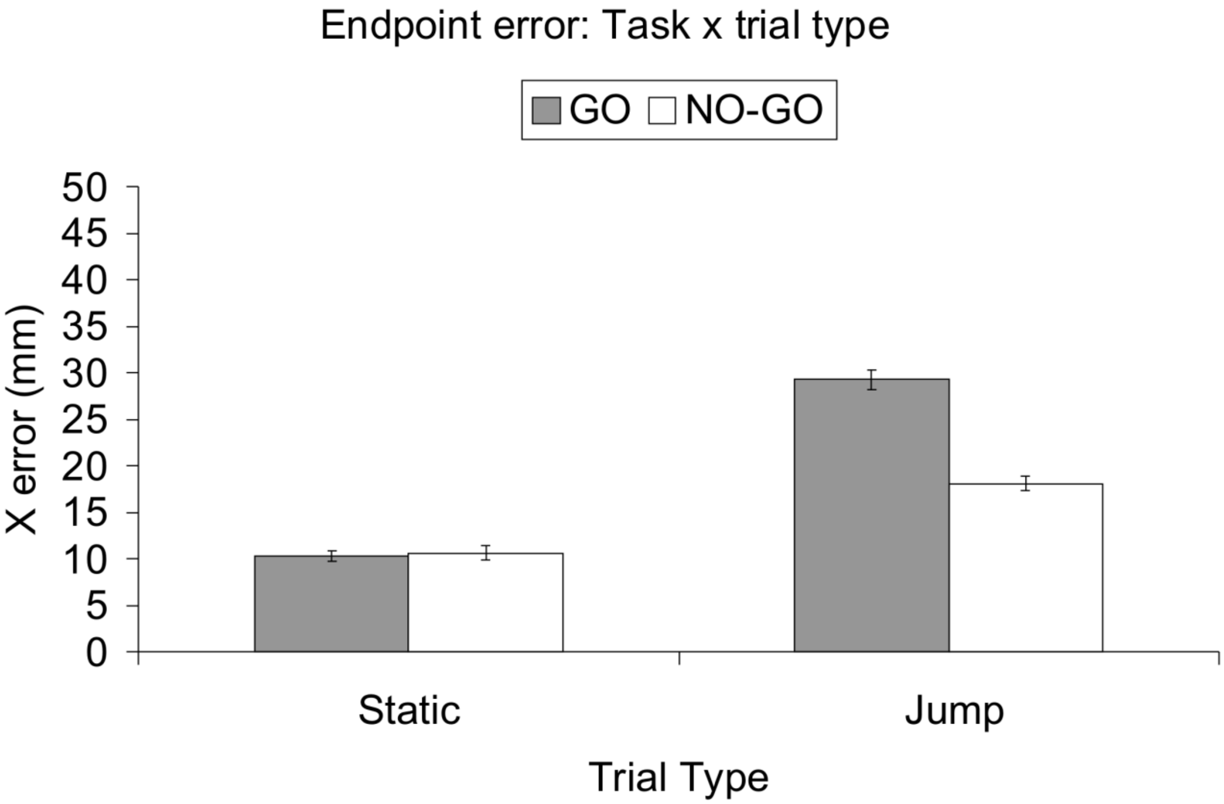
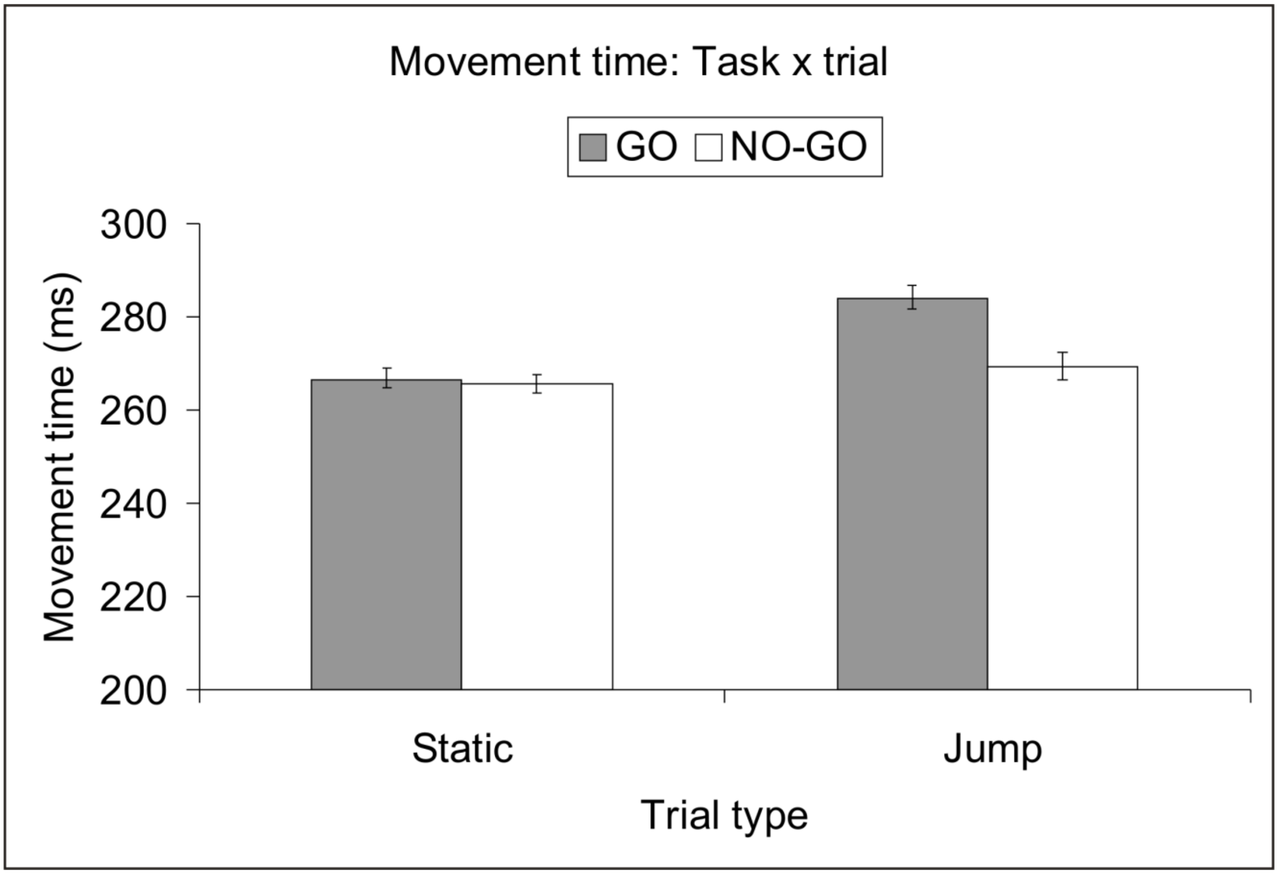

Endpoint error: Task x trial type
GO
NO-GO
X error (mm)
50
45
40
35
30
25
20
15
10
5
0
Static
Jump
Trial Type

Figure 3.


Movement time: Task x trial
GO
NO-GO
300
280
260
240
220
200
Movement time (ms)
Static
Jump
Trial type