Visual Awareness and the On-line Modification of Action

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Abstract An influential theory of visually guided action proposes that (1) conscious perception of target displacement disrupts on-line action and (2) small target perturbations are inconsequential, provided the participant is unaware of them. This study examined these claims in a study of rapid aiming movements to targets. Novel features included on-line verbal reports of target displacement, and the factorial combination of small versus large displacements occurring near peak saccadic velocity or 100 ms later. Although awareness of target displacement had no effect on movement kinematics, even small target displacements near peak saccade velocity affected kinematic measures. These results support both a strong view of visual stream separation in the on-line control of action and richer spatial coding by unconscious processes than has previously been acknowledged.

Résumé Une importante théorie de l'action guidée par la vision suggère que : 1) la perception consciente des déplacements d'une cible interrompt l'action « en ligne »; et que 2) de légères perturbations de la cible sont sans conséquence si le participant n'est pas conscient de ces perturbations. La présente étude examine ces propositions dans le cadre de mouvements consistant à viser rapidement sur des cibles. Comme éléments nouveaux, nous avons inclus des rapports verbaux décrivant à mesure le déplacement de la cible, ainsi que la combinaison factorielle de déplacements légers et marqués se produisant près de la vitesse maximale de saccade ou 100 ms plus tard. Quoique la conscience qu'avaient les participants du déplacement de la cible n'a pas eu d'impact sur les mouvements cinématiques, les déplacements, même légers, avoisinant la vitesse maximale de saccade ont influé sur les mesures cinématiques. Ces résultats confirment une vision forte de la séparation des voies visuelles dans le contrôle en ligne de l'action; ils indiquent ainsi que l'encodage spatial résultant de processus inconscients est plus riche qu'on ne le pensait auparavant.

Research on visually guided action has focused recently on the relations between the on-line control of movement and conscious awareness. According to Milner and Goodale (1995), a determining factor in these relations is that the primate visual system is segregated into two main pathways. The *ventral* stream conducts analyses to support the conscious perception of objects, such that they are seen as relatively invariant with respect to lighting, orientation, and viewpoint. In contrast, the *dorsal* stream is activated more rapidly, is specialized for the guidance of action, does not make its outputs available for direct report, and codes spatial position in an egocentric reference frame.

An early study supporting this view used a task in which participants moved their finger from a central position to a suddenly appearing target in the visual periphery (Goodale, Pélisson & Preblanc, 1986). Participants typically make both an initial saccadic eye movement and an aiming movement in the direction of the target. The first saccade is followed rapidly by a "correction" saccade, allowing the higher-resolution fovea to guide the finger precisely to the target location. The critical manipulation in the Goodale et al. (1986) study was an unexpected displacement in the target location on a random one half at the trials, near the time the initial saccade reached peak velocity. Even though this displacement was large enough to be salient when viewed without eye movements (about 10% of the total movement), participants were unaware of the target jumps. Furthermore, the kinematics of the movement on step trials was indistinguishable from stationary target trials of the same distance (Goodale et al., 1986).

Two claims were central in the interpretation of these results (Goodale & Haffenden, 1998; Goodale et al., 1986). The first was that the kinematics were not disturbed because participants were unaware of the displacement. Had they been aware and acted on this knowledge, it would have intruded on the processes guiding the finger. Support for this position comes from studying target displacements that are larger than

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15% of the movement distance. Participants are both able to see these displacements reliably (Bridgeman, Hendry & Stark, 1975) and movement times are longer (e.g., Carnahan, Goodale, & Marteniuk, 1993; Carnahan & Marteniuk, 1994; Georgopoulos, Kalaska, & Massey, 1981; van Sonderen, van der Gon, & Gielen, 1988). Goodale and Haffenden (1998) concluded that "...if the change in target position is perceived, then subjects fail to make efficient on-line adjustments in their motor output. Efficient on-line adjustments would appear to occur only if the subjects fail to perceive the displacement of the target (p. 165)."

One reason for examining this claim more carefully is that the studies of larger displacements confound the size of displacement with awareness by the participant. It is therefore unclear whether movement disruptions occur because of conscious intrusion in the control of action or whether a larger correction is simply needed to reach the more distant target. Furthermore, there are hints in other studies that conscious awareness of a target displacement does not invariably lead to disturbed kinematics. For instance, displacing the target at the onset of the hand movement (rather than near the peak velocity of the eye movement) does not influence movements to targets undergoing short displacements, even though participants should be aware of the displacement (Komilis, Pélisson, & Prablanc, 1993). Also, movements to large target displacements are indistinguishable from movements to stationary targets provided the displacement occurs 100 ms before the hand begins to move (Kerr & Lockwood, 1995).

The second claim was that aiming is fine-tuned during the execution of the action (Goodale et al., 1986). Regardless of whether there has been a small displacement or not, the same postsaccadic information is believed to be used to update the moving finger. In both cases, the early stages of movement are based on coarse spatial information from the visual periphery, whereas the later stages can be modified based on the higher-resolution information gained after the target has been foveated. However, some studies comparing aiming on stationary and displaced target trials have reported that movement times to the displaced targets are slightly, but significantly, longer (Prablanc & Oliver, 1992). One reason they may be longer is that participants are aware of the displacement on some proportion of the trials, as predicted by Goodale et al. (1986). However, it is also possible that displacements are registered by the unconscious processes of the dorsal stream and that the ensuing correction processes are outside of awareness.

The present study examined both of these claims by introducing two important features to the aiming task. First, we elicited a forced-choice measure of the participants' awareness of target displacement on every trial rather than relying on postsession interviews or control conditions in which movements were not made (Goodale et al., 1986). Second, in addition to varying the size of the displacement, we varied the time that elapsed prior to target displacement. Displacements occurring near peak velocity of the initial saccade should be detected less reliably than those occurring 100 ms later (Bridgeman et al., 1975), allowing us to compare movements that were identical in size but differing in participants' awareness of them.

If conscious processes interfere with the on-line control of action, we should find movement kinematics differing on trials on which participants detected the displacement. This would support the view that the two pathways interact during on-line control of action (Goodale & Haffenden, 1998; Goodale & Milner, 1995). Alternatively, if the on-line corrections are unaffected by conscious awareness, then we should find the same kinematics regardless of participants' ability to report on the displacement. This would support the view that the action system is autonomous once set into motion and is immune from influence until the already-initiated action is complete (e.g., Blouin, Bridgeman, Teasdale, Bard, & Fleury, 1995; Bridgeman & Huemer, 1998; Bridgeman et al., 1979).

Method

PARTICIPANTS

Thirteen right-handed university students (10 female) with normal or corrected-to-normal visual acuity participated as volunteers or for extra course credit. Data from one participant was discarded for failure to follow basic instructions.

STIMULI

A small red light emitting diode (LED) served as fixation point for the eyes and "home" location for the hand. Four computer-controlled, standard laser pointers were positioned above a graphics tablet and the point-source projection of each pointer on the tablet surface served as a target stimulus at horizontal distances of 20 cm, 21.4 cm, 30 cm, and 32.1 cm from the fixation point, referred to hereafter as locations A, B, C, and D, respectively.

ELECTROOCULOGRAPHY

Movements of both eyes were monitored using electrooculography (EOG). A pair of Ag-AgCl surface electrodes (KENDALL-LTP, Huntington Beach, CA) were placed around the outer canthi of both eyes and a ground electrode was placed on the forehead. EOG signals were pre-amplified (7HP511 Grass Instruments AC preamplifiers, AstroMed) and sampled at a rate of 500

TABLE 1
Mean Movement Time (MT) for the Initial Saccade and Time of Target Step

Delay (ms)	Initial Target Location	Final Target Location	EOG MT (ms)	Step Time (ms)
0	A	B	81	69
0	A	C	79	66
0	B	D	86	70
0	C	D	103	67
100	A	B	80	167
100	A	C	80	165
100	B	D	85	170
100	C	D	105	166

Hz. The EOG signal was monitored on-line using custom-written software. A signal level just above the baseline EOG signal was set and used as a threshold for on-line triggering of target displacements. Because of software delays, the registration of eye movement onsets had a variable delay. However, detection and subsequent triggering of the target displacements always occurred while the eyes were still en route to the target. As shown in Table 1, target displacements were triggered prior to peak velocity of the saccade in the immediate condition; in the delayed condition, they were triggered after the eyes had completed the saccade.

KINEMATICS

Participants held a computer mouse with their right hand and made aiming movements on a 58.5 x 44.5 cm graphics tablet (SummaSketch II professional MMII 1812). The mouse had a circular, clear, plastic extension containing a cross-hair; the tablet registered the coordinates of the cross-hair. The target was visible for the entire trial, giving participants ongoing visual feedback on their finger location with respect to the target. Position data were sampled at a rate of 118 Hz.

DATA REDUCTION

EOG data were filtered with a second-order dual-pass Butterworth filter using a low-pass cutoff frequency of 15 Hz. Following Carnahan and Marteniuk (1991), the onset of the eye movement was defined as the lowest point in the EOG after which the EOG signal increased.

The raw displacement data in the primary direction of movement (x-axis) were filtered with a second-order dual-pass Butterworth filter using a low-pass cutoff frequency of 6 Hz. Instantaneous velocity and acceleration were determined by differentiating displacement and velocity data, respectively, using a two-point central finite difference algorithm. The first instantaneous velocity equal to or greater than 10 mm/s defined the beginning of the movement. The end of the movement was when the absolute velocity value fell below the 10 mm/s value for greater than eight samples.

TABLE 2
Mean Kinematic Measures as a Function of Movement Size, Delay, and Step

			Step Condition	
Kinematic Measure	Size	Delay (ms)	Stationary	Step
Error (mm)	Small	0	1.60	1.60
		100	2.40	2.30
	Large	0	-0.29	0.02
		100	0.78	-5.40
Movement Time (ms)	Small	0	604	619
		100	600	637
	Large	0	628	724
		100	619	776
Peak Velocity (mm/s)	Small	0	1,069	1,019
		100	1,068	1,034
	Large	0	1,165	978
		100	1,173	941
Deceleration Time (%)	Small	0	58.1	59.4
		100	57.2	59.9
	Large	0	57.6	63.2
		100	56.8	67.1
Deviations (number)	Small	0	0.78	0.75
		100	0.68	0.89
	Large	0	0.76	1.18
		100	0.68	1.13

The velocity and acceleration profiles were used to determine if modifications to the movement trajectory occurred. These were defined as significant deviations in acceleration over and above the primary acceleration and deceleration, and included deviations before and after peak velocity, secondary zero-crossings, and reversals in the direction of movement (see Chua & Elliott, 1993 for details).

PROCEDURE

Participants were seated and their heads supported by a chin rest. On each trial a warning tone signaled participants to fixate their gaze and position their hand on the home LED. As soon as the target appeared in one of the four locations, they were instructed to slide the mouse across the tablet to the target location, as rapidly and accurately as possible, and to hold this position until a second (higher) tone signaled them to return to the home position. Participants were told that the target would sometimes jump to another location (though not the exact percentage of jump trials), that they must point to the final position, and that they would be asked if there was a jump or not immediately after each movement.

Participants were tested on a total of 160 trials, evenly divided between stationary and step targets. Among stationary trials, the target appeared equally often at each of the four locations. Step trials always involved a displacement to the right and so consisted of both a near (A-B) and a far (C-D) small displacement and a near (A-C) and a far (B-D) large displacement. Step trials were also equally divided between jumps that occurred immediately or with a 100-ms delay.

Participants were first given 20 familiarization trials from which data were not analyzed. The test trials followed, divided into four blocks of 40 trials, with a brief rest between blocks. Each trial block consisted of an equal number of stationary and step trials, with all positions equally represented, and the presentation order randomly determined.

Results

ANALYSES

For stationary trials, mean values for each dependent measure were computed for each target location (A, B, C, D) and analyzed with a one-way repeated measures analysis of variance (ANOVA). For step trials, mean values for each dependent measure were computed for each combination of Size (small, large) and Delay (0 ms, 100 ms) and analyzed with a two-factor repeated measures ANOVA. In addition, the two small step trials were often analyzed separately in order to test for effects of Eccentricity (near, far). Finally, step trials were compared with the stationary target conditions, using the final target location as the basis for comparison. These analyses compared Step (stationary, step) and Delay (0 ms, 100 ms) with a two-factor repeated measures ANOVA. Table 2 shows the mean kinematic measures in the study.

The results are organized according to the answers they provide to three questions: (1) How does the size, timing, and eccentricity of target displacement influence movement kinematics? (2) How do these variables influence conscious awareness? and (3) Is there an influence of awareness on movement kinematics?

MOVEMENT KINEMATICS

Movement error. All analyses of error in final target placement indicated that participants were targeting the final, and not the intial, target location. Mean error with respect to final target location indicated a tendency to overshoot when target displacement was small (1.9 mm) and to undershoot when it was large (-2.7 mm), $F(1, 11) = 23.89$, $p < .001$. Errors were also smaller for the immediate (0.8 mm) than for the delayed displacement (-1.6 mm), and Size interacted with Delay to exaggerate these effects, $F(1, 11) = 6.79$, $p < .03$. This measure gave us confidence that participants were performing the task as instructed.

Comparison of step and stationary trials revealed no differences in movement error for small steps, all Fs < 1. However, for large steps, errors were greater for step (-2.7 mm) than for stationary trials (0.25 mm), $F(1, 11) = 13.35$, $p < .005$, errors were larger for delayed (-2.3 mm) than for immediate displacements (-0.13 mm), $F(1, 11) = 5.02$, $p < .05$, and these effects were even larger when combined, $F(1, 11) = 9.86$, $p < .01$.

Movement time (MT). MT on stationary trials increased with distance to the target, $F(3, 33) = 20.76$, $p < .001$ (A = 542 ms, B = 570 ms, C = 613 ms, D = 674 ms). MT on step trials increased with both Size, $F(1, 11) = 106.51$, $p < .001$ (small = 628 ms, large = 750 ms) and Delay, $F(1, 11) = 6.24$, $p < .05$ (immediate = 672 ms, delayed = 706 ms). This indicates that target distance, displacement, and timing were each influencing the movement in expected ways.

The comparison of step and stationary trials revealed significantly longer MTs for small displacements, $F(1, 11) = 8.64$, $p < .025$ (stationary = 602 ms, step = 628 ms). For large displacement, MT was longer for step (750 ms) than for stationary trials (623 ms), $F(1, 11) = 40.96$, $p < .001$, and a Step x Delay interaction reflected especially long MT when the large step was delayed, $F(1, 11) = 9.57$, $p < .025$. Thus, target displacement influenced MT, even for small steps that occurred during the execution of the first saccade.

Peak velocity. Peak velocity on stationary trials increased monotonically with distance to the target, $F(3, 33) = 20.77$, $p < .001$ (A = 886 mm/s, B = 943 mm/s, C = 1,145 mm/s, D = 1,194 mm/s). Peak velocity on step trials was greater for small than for large steps, $F(1, 11) = 14.94$, $p < .005$ (1,027 mm/s vs. 960 mm/s), and this effect was even larger when the displacement was delayed, $F(1, 11) = 12.314$, $p < .005$. This indicates that the maximum speed of the movement was sensitive to each of the factors we manipulated.

The comparison of step and stationary trials revealed that participants achieved higher peak velocity on stationary trials, even when the step was small. This comparison was significant both for small steps, $F(1, 11) = 48.73$, $p < .001$ (stationary = 1,069 mm/s, step = 1,027 mm/s), and for large steps, $F(1, 11) = 83.08$, $p < .0001$ (stationary = 1,169 mm/s, step = 960 mm/s). The large steps also yielded higher velocity in the immediate than in the delayed condition, $F(1, 11) = 6.98$, $p < .025$ (0 = 1,072 mm/s, 100 = 1,057 mm/s). Thus, it is clear that target displacement influences peak velocity, even for small steps that occur without delay upon the initiation of the first saccade.

Deceleration time. This measure expressed the time after peak velocity as a proportion of total MT, in order to index the time spent in deceleration, where movement corrections usually occur. The analysis of stationary trials revealed no significant effect of distance, $F < 1$. However, the analysis of step trials revealed that more time was devoted to deceleration when steps were large (.642) than when they were small (.596), $F(1, 11) = 27.09$, $p < .001$, and that more time was spent in deceleration when the displacement was delayed (.635) than when it was immediate (.613), $F(1, 11) = 4.94$, $p < .05$. Again, these effects were exaggerated when combined, $F(1, 11) = 10.65$, $p < .01$.

Comparison of stationary versus step trials revealed that a greater proportion of time was also spent in deceleration on step trials, both for small displacements, $F(1, 11) = 6.62$, $p < .05$ (stationary = .576, step = .597), and for large ones, $F(1, 11) = 18.31$, $p < .005$ (stationary = .572, step = .651). In the large step condition, there was also an interaction of Size x Delay, $F(1, 11) = 14.16$, $p < .005$, reflecting the synergy of distance and delay on this measure.

Movement deviations. Adjustments to movements did not vary with target location on stationary trials, $F < 1$. On step trials, more deviations were observed when the target displacement was large (1.24) than when it was small (0.82), $F(1, 11) = 38.00$, $p < .001$.

Comparison of step versus stationary trials showed that more deviations were made on step (1.24) than on stationary trials (0.72), $F(1, 11) = 34.15$, $p < .001$. For small displacements, the Step x Delay interaction was marginally significant, $F(1, 11) = 4.57$, $p < .06$, reflecting a difference between stationary and step trials only when the displacement was delayed.

To summarize the kinematic data, participants were slower to respond, did not reach as great a velocity, spent a greater proportion of their time in the decelerative phase of the movement, and made more movement deviations when the targets were displaced. This was true even on small, immediate step trials, indicating that the displacement was being taken into account by the motor commands to modify the movement in response to the displacement.

AWARENESS

Participants made almost no reports of target displacement on stationary step trials. False alarms on these trials were fewer than 2% for each location, and there were no reliable differences among the locations, F < 1. Correct detection of displacement on step trials was also generally very accurate (94% or higher) with two important exceptions. Participants missed detecting most far-small displacements when there was no delay (8.6%) and missed detecting a majority of near-small displacements when there was no delay (38.5%). These differences were reflected in significant effects of Size, $F(1, 11) = 217.86$, $p < .001$, Delay, $F(1, 11) = 272.09$, $p < .001$, and their interaction, $F(1, 11) = 228.99$, $p < .001$. The difference in detection accuracy between near and far small displacements with no delay was also significant, $F(1, 11) = 34.72$, $p < .001$.

AWARENESS AND KINEMATICS

This question was addressed in two ways. The first approach was indirect but informative. We noted in the previous section that on small steps, timing of the displacement was critical to awareness. Nearly all of the delayed steps were detected (94.3%) but relatively few of the immediate steps were detected (23.6%). Yet, the kinematic data indicated that displacement delay in itself had no measureable influence on any movement measure for these small steps (i.e., constant error, MT, peak velocity, time to peak velocity, and movement deviations).

The second approach to this question involved inspection of the data in the condition that permitted the most thorough examination of awareness. This was the near-small step condition where the displacement occurred immediately following peak saccadic velocity (Location A-B). These trials always involved the identical stimulus conditions, but yet were the most evenly divided between those in which displacements were detected (38.5%) and not detected (61.5%). Note also that these reports were not guesses, since the stationary step trial accuracy was very high. Yet, none of the movement analyses involving this condition revealed a kinematic difference that depended on whether the participant detected the displacement. F-values in these comparison were < 1 for all measures (i.e., constant error, MT, peak velocity, time to peak velocity, and movement deviations).

Discussion

Figure 1 illustrates the two main findings of this study using example movement trajectories from typical participants. Panel A depicts typical movement velocity over time on the near-small step trial. One of the curves depicts a trial on which the displacement was detected, the other curve is for a trial on which the participant was unaware of the displacement. These two curves are not distinguishable from one another, illustrating the point made by each one of the kinematic measures: Awareness of target displacement has no measurable effect on movement kinematics.

Panel B depicts typical movement velocity over time on a stationary and a small step trial. In this example, and in all our kinematic measures, target displacement

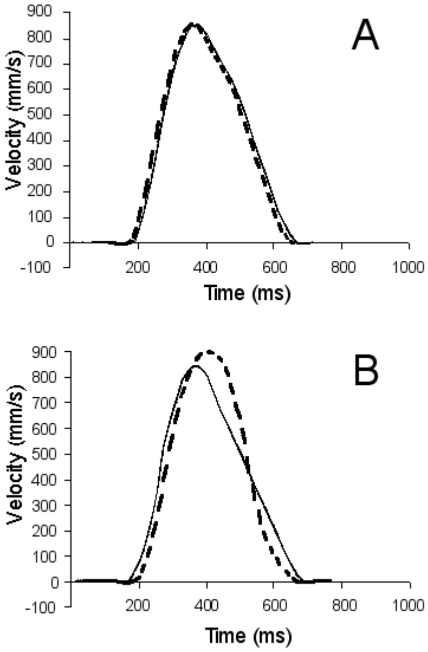

Figure 1. Typical patterns of action toward the target, expressed as velocity of the movement as a function of time. The velocity profile is shown because it depicts movement time, magnitude of peak velocity, time following peak velocity, and any indications of deviation in the movement trajectory. (A) Movement on a near-small step trial in which the participant was either aware (solid) or unaware (dashed) of the displacement. (B) Movement on a near-small step trial (solid) and a stationary trial involving a target at the same distance (dashed).

did have an influence on movement kinematics. This was true not only for large steps, as previous studies had shown (e.g., Carnahan & Marteniuk, 1994; Carnahan et al., 1993; Georgopoulos et al., 1981; van Sonderen et al., 1988), but was also true of small steps, which had yielded mixed findings in past research (Goodale et al., 1986; Prablanc & Oliver, 1992). The important new finding was that these kinematic differences in small step movement could not be attributed to the intrusion of conscious awareness. Small steps affected the movement in the same way, regardless of whether they were detected or not.

These results speak clearly to the two theoretical claims that prompted our study. First, the results showed no interference from awareness, and consequently do not support a strong interaction between ventral and dorsal processing (Goodale & Haffendan, 1998; Milner & Goodale, 1995). At least, they do not do so for movements to small target displacements. Instead, they are more in keeping with the view that the two streams are autonomous during the on-line control of these actions (e.g., Blouin et al., 1995; Bridgeman & Huemer, 1998; Bridgeman et al., 1979). According to this view, the autonomy comes about from the incompatible computations undertaken by the two processing streams for identical visual input. This is not to say that the two streams are never coordinated; indeed, information obtained by the ventral stream may well form the basis for initiating an action (e.g., reach for the *red* cup among other cups). However, once the planning of action is underway with respect to an object, the ventral stream cannot intrude until the action has been completed.

We think there is another possibility worth considering that is a refinement of the interactionist view. Perhaps the longer latency of the ventral stream signals, relative to those of the dorsal stream, renders interaction between the pathways *practically* impossible for small steps. This would come about if the on-line control mechanisms of the dorsal stream had completed their adjustment to the displacement before the ventral stream had completed processing the same information and made it available for report. The participant would be aware of the displacement, but simply not aware early enough to permit an influence on action. Since responses to larger displacements take more time, they would still be vulnerable to intrusion by ventral processes. Evidence from a recent report supports this modified interactionist view. After receiving instructions to halt aiming if the target moves, participants often fail to comply and automatically adjust for the displacement when the aiming movements are short (i.e., 200-300 ms), but not when they are long (Pisella, et al., 2000). Future studies will be required to fully distinguish this possibility from the option of complete autonomy, perhaps by speeding the ventral processes through stream-selective cueing that a target step is about to occur (e.g., using isoluminant hue changes).

It is also worth noting that the delayed displacement conditions resulted in a number of changes in the kinematics of the larger movements, compared to the immediate displacement condition. Specifically, when target displacement was delayed, larger movements required more time to complete, lower peak velocity was achieved, and a greater proportion of movement time was spent in deceleration. This suggests that participants may have tried to modify their movements on-line after the occurrence of a delayed displacement. However, these attempts at modification did not lead to greater accuracy, as movement error was larger under the delayed condition. The reason for this failure to achieve better accuracy despite apparent attempts to modify the movements is unclear. However, the possibility that this is an intrusion effect of conscious awareness is ruled out by the fact that participants correctly reported seeing almost all of the larger target displacements. Some other factor must be responsible.

Finally, the kinematic effects of small target displacements in the present study speak to the question of how richly spatial information is represented by the unconscious processes of the dorsal stream. The previous claim that there is spatial uncertainty of at least 10% in initial estimates of target location (Goodale & Haffenden, 1998) was not supported in this study, as movements were consistently modified in response to displacements that small, even when participants were unable to report that a displacement had occurred. This suggests that future work is needed to determine with greater precision what the inherent spatial uncertainty is for this processing stream.

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