

CHAPTER 12

# Attentional limits and freedom in visually guided action

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**AU: 2** **Abstract:** Human vision supports both the conscious perception of objects (e.g., identifying a tea cup) and the control of visually guided action on objects (e.g., reaching for a tea cup). The distinction between these two functions is supported by neuroanatomy, neuropsychology, animal lesion studies, psychophysics and kinematics in healthy humans, as well as in overarching theories of the visual brain. Yet research on visual attention, which concerns limitations in processing information concurrently from multiple objects, has so far not fully exploited this functional distinction. Attention research has focused primarily on the conscious aspects of vision, to the relative neglect of the unconscious control of limb actions and whether we can perceive some objects concurrently while acting on others. Here we review research from our lab leading to the conclusions that (1) the finger is guided visually by an *automatic pilot* that uses different information from that of conscious vision, (2) conscious object identification interferes with concurrent planning of pointing to a second object, though not with the online control needed to complete the pointing action, (3) concurrent perception and action sometimes lead to benefits in motor performance, and (4) the automatic pilot is itself capacity limited in processing information concurrently from multiple locations. These findings help clarify the conditions under which interference-free multitasking is possible and point to new challenges for research on the attentional limits of unconscious visual processing.

**Keywords:** cognitive map; blocking; associative learning; spatial learning

## Introduction

It is time for research on attention to catch up with recent developments in our understanding of how the human brain uses visual information to perform distinctly different functions. Although there is only one stream of light that impinges on our eyes at any moment in time (hereafter referred to as *the image*), the information

contained in that image can be used to serve one of two functions. On the one hand, the image can be used to construct a visual experience of the environment around us, allowing us to recognize a colleague or to discern whether we are viewing scissors or a spoon. Yet the same image can also guide our limb actions so that we interact appropriately with that environment, allowing us to shake our colleague's hand when we greet them and to pick up scissors using a different grasp than we use when picking up a spoon. Research on human vision has demonstrated in numerous ways over the past 25 years that these two functions are

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1 distinct (Goodale and Milner, 2004; Goodale et  
3 al., 2004; Milner and Goodale, 1995; Norman,  
5 2002; Ungerleider and Mishkin, 1982). Specifi-  
7 cally, our visual experience in the absence of overt  
9 action (the conscious experience of objects at a  
11 distance, subserved by the *ventral* visual stream) is  
13 governed by brain regions, neural tracts, and  
15 mechanisms that are distinct from those that guide  
17 our interactions with objects (unconscious  
19 control of visually guided action, subserved by  
21 the *dorsal* stream). It is not our purpose to review  
23 those arguments here, as they have been made  
25 extensively in many reviews. Our purpose is,  
27 instead, to consider some consequences of this  
29 understanding of the visual brain for research on  
31 visual attention.

17 Research on visual attention over the past 150  
19 years can be characterized, at a first approxima-  
21 tion, as the study of channel limitations of the  
23 human brain as it concerns conscious experience  
25 (see Pashler, 1994, 1998; Shapiro et al., 1997 for  
27 reviews). We seem to be aware, and to become  
29 aware, of little more than one discrete event at a  
31 time. If we are expecting imminent visual infor-  
33 mation from one location, we will be delayed in  
35 processing the expected visual information at  
37 another location (e.g., location orienting, as in  
39 Posner, 1980). If we are engaged in identifying  
41 one person, the identification of a second person  
43 must wait (e.g., two object cost, as in Duncan,  
45 1984). Even when we are focused solely on  
47 viewing a single person's face, if we are engaged  
in the process of identifying that person, we will  
be impaired in making judgments of the emo-  
tional expression currently displayed by that  
person (e.g., we are blind to changes that are  
deemed unlikely, as in Austen and Enns, 2003). If,  
during the performance of any of these visual  
tasks, we temporarily allow our thoughts to drift  
among the ideas constantly being offered to our  
awareness by our long-term memories, then our  
ability to identify and localize visual information  
becomes impaired (e.g., mind wandering, as in  
Giambra, 1995).

45 Relative to this intense interest in attentional  
47 limits on conscious aspects of seeing, much less  
effort has been devoted to developing methods

for exploring limits of the visually guided action  
system, and for exploring the conditions under  
which conscious vision and visually guided action  
might interfere with one another, might operate  
independently of one another, or perhaps might  
even mutually enhance one another. Among the  
obstacles encountered in the design of experi-  
ments to probe unconscious visually guided action  
is that it is often difficult to provide input to the  
action system that does not itself have to pass  
through the bottleneck of consciousness before it  
can be used to inform the visually guided action  
system. Take, as a case in point, dual-task studies  
already in the literature that have combined tasks  
of action and perception in an effort to measure  
possible interference when these systems must use  
the same visual image. Some of these studies  
required participants to point to one colored  
shape while simultaneously trying to identify a  
symbol in a separate location (Deubel et al.,  
1998). Other studies required participants to grasp  
a target object while simultaneously monitoring  
for changes in the luminance of a second object  
(Castiello, 1996). Since pointing and grasping are  
thought to be under *dorsal* stream control and  
object identification under *ventral* stream control,  
these could be construed as proper tests of cross-  
stream interference. And since significant task  
interference was observed in both studies, one  
might conclude that efficient multitasking is not  
possible between the visual streams. However, we  
do not consider these results to be strong tests,  
mainly because in order to carry out the limb  
action required in both types of studies, the color  
or the shape of an item has to be processed  
(*ventral* stream function) before the appropriate  
action (*dorsal* stream function) can be initiated.

A second difficulty encountered when designing  
experiments to probe unconscious visually guided  
action separately from conscious vision concerns  
the important distinction between action planning  
(or preparation) versus the online control of that  
action once it is already underway (Henry and  
Rogers, 1960). Action planning is generally  
considered to involve processes that occur prior  
to action initiation, and therefore may be influ-  
enced by the *ventral* stream as well as other

1 consciously accessible brain regions such as the  
 3 *frontal lobe* functions implicated in executive task  
 5 control. It is typically indexed by measuring the  
 7 period from target onset to movement onset  
 9 (response initiation time), and as such, is poten-  
 11 tially influenced by the mental processes of target  
 13 identification, response selection, and movement  
 15 planning (or preprogramming). In contrast, action  
 execution consists of processes involved in bring-  
 ing the action to completion and is usually  
 considered more uniquely a function of the *dorsal*  
 stream system. It is indexed by the time that  
 elapses between action onset and action comple-  
 tion (movement time, MT) and is thus uniquely  
 influenced by processes that occur only once an  
 initiated action is already underway.

AU: 3 An example of research that ignores this  
 distinction comes from recent report by Kunde  
 et al. (2007). These authors paired an auditory  
 tone discrimination task (*ventral* stream) with  
 either a visual size discrimination task (*ventral*  
 stream) or a visually guided grasping task (osten-  
 sibly *dorsal* stream). Their results indicated that  
 response time in both visual tasks was interfered  
 with when these tasks were paired with the  
 auditory task. Although, the dependent measures  
 taken in the grasping task included both response  
 time (preparation) and MT (online control) only  
 the response time data were reported in detail,  
 leaving open the possibility that interference only  
 occurred during the planning phases of the action.  
 Consistent with this possibility was a terse one-line  
 report by the authors that they found no reliable  
 influences of dual-task performance on MT. But  
 this null result was not explored in any greater  
 detail, even though it suggested the possibility that  
 online control of grasping was immune from the  
 task interference measured for action initiation.  
 Our reading of the existing literature on dual-task  
 performance involving ventral and dorsal stream  
 functions therefore suggests that much remains to  
 be done. In particular, there is a need for research  
 involving *dorsal* stream tasks that (1) does not rely  
 on consciously processed input for their initiation,  
 and (2) allow for the separate measurement of  
 action planning (or preparation) from the online  
 control of already initiated actions.

### A model task for studying online control: the finger's automatic pilot

Pressing an elevator button while we are walking  
 toward the door, reaching to grasp someone's hand  
 as we both move toward one another, and striking  
 a tennis ball that has just tipped the top of the net,  
 are all highly sophisticated visual-motor skills that  
 we as healthy humans take for granted. Many  
 complex computations are involved, though they  
 remain hidden from our ability to access them  
 through conscious introspection. This human abil-  
 ity to make rapid, online adjustments in pointing  
 and reaching in response to unexpected changes in  
 the task environment, is often referred to the  
 body's *automatic pilot* (Bard et al., 1999; Brenner  
 and Smeets, 2003; Castiello et al., 1991; Desmurget  
 et al., 1999; Paulignan et al., 1991; Pisella et al.,  
 2000; Prablanc and Martin, 1992). By this,  
 researchers mean that limb movements are mod-  
 ified rapidly and in flight (often called *online*) to  
 changes in the location or shape of a target object,  
 and that these limb modifications occur before or  
 in the absence of individuals being consciously  
 aware of the changing task environment.

A laboratory model for studying the finger's  
 automatic pilot is the *double-step task* pioneered  
 by Goodale et al. (1986). In this task, participants  
 move their finger quickly and accurately from a  
 centrally fixated home position to a suddenly  
 appearing target in the visual periphery. At the  
 onset of the target, participants typically make  
 both an initial saccadic eye movement and a finger  
 pointing movement in its direction. The first  
 saccade is followed rapidly by a corrective  
 saccade, allowing the higher-resolution foveal  
 information to guide the finger precisely to the  
 target location. The actions guiding the eye and  
 the finger to the target location are referred to as  
 the *first step*. The critical manipulation in this task  
 is an unexpected displacement in the target  
 location on a random half of the trials, occurring  
 near the time the initial saccade reaches peak  
 velocity. This displacement of the target is  
 referred to as the *second step* (sometimes also  
 the *jump*). Although this displacement is large  
 enough to be visible when viewed without eye

1 movements (up to 10% of the total movement),  
3 participants seem unaware of the target jumps  
5 when they occur during a saccade. However, the  
7 finger demonstrably takes the jump into account  
in coming to its final resting place, while at the  
same time, the conscious brain seems blissfully  
unaware that a double-step has occurred.

Direct evidence that the *dorsal* stream is  
involved in the online control of double-step  
pointing comes from studies of patients with  
dorsal stream brain damage, who are able to point  
much more accurately on single-step trials than on  
double-step trials (Pisella et al., 2000), and from  
similar results in studies using transcranial mag-  
netic stimulation to inhibit the same brain region  
on otherwise healthy individuals (Desmurget  
et al., 1999). The dorsal stream, therefore, appears  
critical for rapid online adjustments to actions that  
are already underway, and it can effect these  
changes in as little time as 200 ms.

### ***Decoupling action and awareness***

In our first exploration of double-step pointing,  
we asked whether the claims made by Goodale et  
al. (1986) for a complete dissociation between the  
finger's automatic pilot and conscious awareness  
of target displacements was really justified. In the  
original study, Goodale et al. had only questioned  
their participants about seeing the target jump  
after a series of many pointing trials. Their study  
had also confounded the magnitude of the jump  
with visual awareness (and therefore also the  
extent of online action correction), such that large  
jumps (>10% of the distance from home) were  
both visible to participants and resulted in  
measurable kinematic corrections of the finger,  
whereas small jumps (<10% of distance) were  
both invisible to conscious perception and yielded  
no measurable kinematic differences between  
single- and double-step trials.

The novel features of our study (Fecteau et al.,  
2001) included giving participants full knowledge  
that single- and double-step trials would occur in  
equal proportions and asking them to indicate on  
each trial whether they were able to discriminate  
a jump (double-step) from a stationary (single-  
step) target. This is the strictest possible test of

conscious awareness, since it is based on an  
objective threshold (Merikle and Cheesman,  
1987). If jump sensitivity was greater than could  
be guessed by chance among our participants, it  
would mean that some signal concerning the jump  
was accessible to awareness even though partici-  
pants may not have had the expected subjective  
experience of seeing a jump (i.e., proprioception  
of the limb, extra-retinal signals from the eyes).

The second feature of our study was a factorial  
combination of target jumps that were either  
small or large (space) and timing of the jumps that  
occurred either near maximum saccadic velocity  
or 100 ms later (time). Our intent was to compare  
small jumps that were visible (because their  
timing was delayed) with small jumps that were  
invisible (because they occurred when the eye was  
moving most rapidly away from the home posi-  
tion. If movement correction on jump trials was  
unaffected by awareness, then movement kine-  
matics should be unaffected by jump visibility.  
We measured the activity of the eye using  
electrooculography (EOG), sampled at 500 Hz  
(every 2 ms) and we sampled the movement of the  
limb using a handheld stylus at a rate of 118 Hz  
(every 8.5 ms).

The results were clear. Our examination of the  
kinematic data indicated that every one of the  
stimulus factors had an influence on movement  
parameters. For example, the trajectory of the  
moving limb was influenced in predictable ways  
by whether or not the target jumped (double-  
step), whether the jump was small or large  
(space), and whether the jump was immediate or  
delayed by 100 ms (time). These kinematic results  
point to an automatic pilot in the finger that is  
exquisitely responsive, in an online fashion, to the  
details of the relationship between the visual  
target and the moving limb.

The results for the trial-by-trial measures of  
awareness of the target jump were equally clear.  
In no case did conscious awareness of the jump  
have any influence on the kinematics of finger  
movement. This was true when we compared  
movement on small-immediate jump trials on  
which participants reported seeing the jump with  
the same type of trials on which they reported  
not seeing any jump. It was also true when we

1 compared the clearly visible delayed-small jump  
 3 trials with the invisible immediate small-jump  
 5 trials. In none of the conditions were we able to  
 7 detect an influence on kinematics that was related  
 9 to participants' reports of whether or not they  
 11 detected a jump.

13 We interpreted these results as supporting two  
 15 conclusions. First, the results pointed to a more  
 17 sophisticated form of online control and feedback  
 19 than some researchers had thought necessary for  
 21 this task (Jeannerod, 1988; Keele, 1981). If single-  
 23 and double-step trials were equivalent in that they  
 25 each began with the same ballistic eye movement  
 and initial ballistic pointing action to the general  
 region (coarse coding), followed up by a correc-  
 tive saccade and finer control in the limb action to  
 complete the point based on the final target  
 position (fine coding), then the kinematics of  
 small single- and double-step trials should not  
 differ. The fact that the kinematics differed  
 suggests that there is an important form of control  
 that occurs while the eye and the finger are in  
 flight; a form of visual control that uses visual  
 information that is not necessarily accessible to  
 conscious awareness.

27 Our second conclusion was that there was  
 29 perhaps an even sharper degree of visual stream  
 31 separation in the online control of action than  
 33 some researchers had proposed (Goodale et al.,  
 35 1986). In particular, we argued that these data rule  
 37 out the possibility that kinematic features of the  
 movement are being influenced by conscious  
 awareness of where the target appears to be.  
 When a kinematic correction occurs, it does so in  
 the same way regardless of whether or not the  
 change in the environment that caused the correc-  
 tion has also been seen by the conscious brain.

### 39 *Can the finger reveal its secrets?*

41 In another study of the automatic pilot (Chua and  
 43 Enns, 2005), we asked whether spatial movements  
 45 of the finger, either through our direct visual  
 47 perception of them or perhaps through our inner  
 proprioception of them, could inform the con-  
 scious brain when they were being guided by  
 information that was not otherwise accessible to a  
 participant. An important arena in which the

action systems (i.e., eye, hand) and conscious  
 awareness are guided by different aspects of the  
 same visual scene occurs with regard to percep-  
 tion of an object's location in space.

When it comes to conscious awareness of  
 whether an object is stationary or has moved, the  
 conscious judgment is based on perceived con-  
 tinuity between views of the same scene. For  
 example, if the target object of the saccade is  
 displaced a large distance while the eye is in  
 motion, its displacement is readily detected  
 (Bridgeman et al., 1975; Fecteau et al., 2001).  
 Also, if the target object is extinguished briefly  
 (blanked) during the saccade and then redis-  
 played after the saccade is complete, even small  
 image displacements can be detected (Deubel and  
 Schneider, 1994; Deubel et al., 1996). Taken  
 together, these results suggest that when objects  
 are deemed continuously present during a sac-  
 cade, they are judged to be stationary (within  
 some bound of spatial tolerance that is estimated  
 as large as 50% of saccade distance by some, e.g.,  
 Deubel et al., 1998) and when they are deemed to  
 be discontinuous during the saccade, they are  
 judged to have moved.

Chua and Enns (2005) asked whether these  
 rules also apply when participants were engaged in  
 finger pointing. We thought that finger pointing,  
 unlike eye movements, might reveal to participants  
 that a target was actually displaced during the arm  
 motion. This is because, unlike the profound  
 insensitivity we have for our own eye movements,  
 we are fully conscious that we are pointing with  
 our finger. We can see them move and can even  
 monitor movements through proprioception. Our  
 question was whether this information could be  
 made available for conscious report.

To test this possibility, we conducted what we  
 think must be the simplest possible *change  
 blindness* experiment (Rensink, 2002). As in the  
 previous experiment, each trial began with the  
 participant's eyes and finger resting at the home  
 position on a display table. The sudden appear-  
 ance of two objects on the right side of the panel  
 was a signal for the participant to point as rapidly  
 as possible to the lower of the two objects (the  
 lower one was always the pointing target; the  
 upper object served only as a reference point and

1 was itself never a target). We monitored both the  
 3 eye movement (using electrooculography) and the  
 5 hand movement made to the target (using an  
 7 Optotrak motion analysis system) at 500 Hz.  
 9 During the first eye movement away from the  
 11 home position, one of the two objects was spatially  
 13 displaced by 2 cm (a “jump”) and, independently  
 15 either one, both, or neither of the two objects was  
 17 extinguished for 100 ms (a “blank”) before being  
 19 redisplayed. At the end of the pointing action,  
 21 participants were forced to choose which object  
 23 had *jumped* during the trial. This allowed us to  
 25 associate a measure of visual awareness of object  
 27 stability with kinematic measures of hand position  
 29 on every trial.

17 The results were very dramatic in showing that  
 19 the movement of the finger was governed by  
 21 completely different visual information than  
 23 the perception of object stability. Although the  
 25 finger’s position was ruled very reliably by the final  
 27 position of the target (i.e., pointing accurately  
 29 regardless of whether the target was stationary or  
 31 jumped), the perceptual judgment of which object  
 33 had remained stationary was governed entirely by  
 35 which object had remained continuously visible  
 37 (i.e., if an object was not blanked, it was judged to  
 39 be stationary). Conversely, if an object had  
 41 blanked briefly while the eyes and finger were in  
 43 flight, that is, the object blanked while staying in  
 45 the same place or while jumping, then it appeared  
 47 as though the blanked object had moved.

33 We conducted an even more stringent test of  
 35 this dissociation by repeating the experiment, but  
 37 this time asking participants to *stop* (to withdraw  
 39 their fingers from the table entirely) whenever  
 41 they detected that the target they were moving  
 43 toward had jumped. These results showed that the  
 45 finger tracked the target position just as reliably as  
 47 before, with very few finger withdrawals occurring  
 prior to completion of the point. However, when  
 the finger was withdrawn on the roughly 50% of  
 trials on which participants thought that the target  
 had jumped, the withdrawal was based on  
 whether target visibility had been interrupted  
 (blanked) briefly during the saccade to the target,  
 rather than on whether the target had actually  
 jumped. This meant that finger withdrawals  
 occurred equally for jumping targets and for

completely stationary targets; the only criterion  
 for withdrawal was that these targets had blanked  
 during the flight of the eye and finger.

### ***Unconscious does not mean inflexible***

Establishing the existence of an unconscious  
 influence on visually guided behavior does not in  
 itself imply that the influence is occurring online,  
 that is, during the recruitment and implementa-  
 tion of the appropriate motor routines to com-  
 plete a task. An unconscious influence could, in  
 principle, come about by the initiation of a  
 response that had already been consciously  
 prepared at an earlier time. For example, as a  
 consequence of the instructions provided by the  
 experimenter at the beginning of some tasks, an  
 action plan may be established, or prepro-  
 grammed. If this plan is in place prior to the  
 onset of a trial, events processed subliminally  
 during the trial may be sufficient to initiate the  
 preprogrammed response. Indeed, this is what  
 many researchers believe underlies many uncon-  
 scious perceptual priming effects. Thus, to firmly  
 establish that ongoing visually guided actions can  
 be controlled by subliminal visual events in a  
 dynamic way, it is necessary to show that the  
 priming itself occurs while the motor actions are  
 ongoing. Moreover, once online subliminal con-  
 trol has been established, it opens up the  
 possibility of exploring the intelligence (i.e., the  
 adaptability or flexibility to changing circum-  
 stances) of the unconscious action system.

These were the challenges we set upon in  
 Cressman et al. (2007). In this study, we asked  
 whether the shape of an unseen object could  
 influence an action after a different action had  
 already been initiated. Figure 1 illustrates the  
 spatial layout of the stimuli and the trial sequence.  
 Participants initiated pointing to a center target  
 location, which triggered the appearance of a  
 stimulus shape (left arrow, right arrow, or  
 composite pattern of superimposed left and right  
 arrows) in that location. If the central shape was  
 the composite pattern (75% of the time), they  
 were to continue pointing to the central pattern,  
 but if the central shape was a left- or right-  
 pointing arrow (25% of the time), they were to

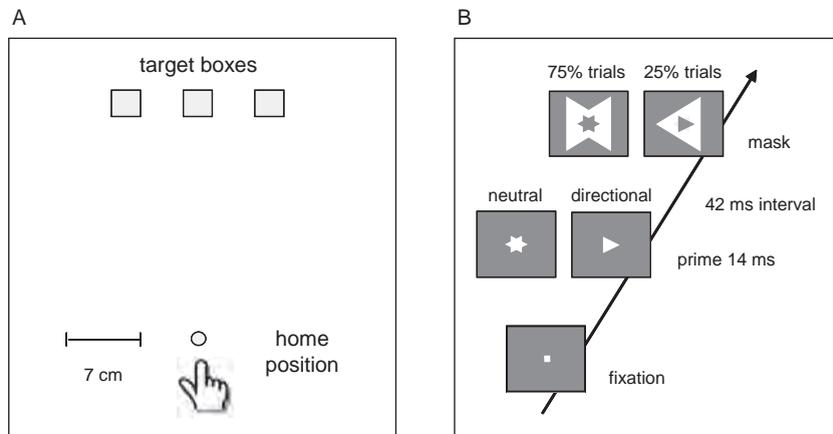


Fig. 1. The spatial layout of the experiment (A) and the sequence of trial events (B) as given in Cressman et al. (2007).

point instead to a left or a right target location as rapidly as possible.

Unbeknownst to participants, upon pointing initiation, the large visible shapes that appeared in the central pointing location were preceded by smaller and briefly flashed prime shapes that were made invisible by the large mask shapes that followed. We reasoned that if the masked prime shapes could influence the online control of a goal-directed action, we would observe deviations in movement trajectories that corresponded to the identity of the unseen primes. Furthermore, there should be a difference in the pointing trajectories observed for congruent (small and large shapes point in the same direction) and incongruent (small and large shapes point in different directions) shape sequences. On the other hand, if the invisible prime shapes are only able to influence the initiation of an already-prepared action and not online control, then deviations in the pointing trajectories should only be measured in response to the direction indicated by the visible mask, and congruent versus incongruent prime-mask sequences should not exert any influence on pointing trajectories.

After the pointing task, we ensured that the small shapes in our procedure were inaccessible to participants' consciousness by measuring their visibility when presented immediately before the large shapes. When participants were fully informed of the presence of the small shapes and encouraged to guess their identity, their accuracy

was quite low. However, pointing was influenced by the small unseen shapes, replicating numerous previous studies indicating *masked priming* despite a lack of consciousness of the stimuli governing the priming. Additionally, the kinematic measures of pointing indicated that invisible shapes can not only alter the speed with which a goal-directed action can be initiated, as in many other previous studies (Ansorge et al., 2002; Breitmeyer et al., 2004; Neumann and Klotz, 1994; Schmidt, 2002), but that invisible shapes also influence the control of an ongoing action.

The main evidence for this conclusion came from a detailed look at the pointing trajectories for the different shape sequences. These showed that initial deviations of the finger, away from the center target, were consistently in the direction indicated by the first small shape, regardless of the direction of the subsequent larger visible shape. Thus, *congruent* shape sequences gave the pointing action a head start in the correct direction, with these modifications occurring within 277 ms of movement onset. By way of comparison, *incongruent* shape sequences resulted in initial trajectory deviations toward the wrong target, with the consequence that additional MT was required for participants to complete the action. Pointing trajectories were not directed to the correct target until approximately 330 ms into the movement, a delay that was roughly equivalent to difference in the onset of the first and second

1 shapes (56 ms). This suggests that pointing rele-  
 3 vant visual information was being incorporated  
 into control of the pointing almost as soon as it  
 was available.

5 We concluded that the automatic pilot is indeed  
 7 flexible enough to respond to the differences in  
 shape between left- and right-pointing arrows and  
 that it can respond to changes in this information  
 9 even while an already programmed action is  
 underway. This is consistent with other recent  
 11 findings of unconscious action responding to  
 visual size (Binsted et al., 2007). The question  
 13 we turn to next is whether the visually guided  
 control of actions such as this can be accomplished  
 15 simultaneously with tasks of conscious perception,  
 or whether the usual interference that we have  
 17 come to expect when two visual tasks are  
 combined will occur.

#### 21 **Attention sharing between visual identification and the automatic pilot**

23 The tasks we chose to combine in a dual-task  
 25 setting involved participants monitoring a rapid-  
 fire sequence of digits for the presence of a central  
 27 letter target (*ventral* task) while simultaneously  
 pointing to a second letter target that appeared  
 29 with variable temporal lag in the visual periphery  
 (*dorsal* task) (Liu et al., 2008). Additionally, in a  
 31 single-task condition, participants ignored the  
 central target while pointing to the peripheral  
 33 target. This is a version of the well-established  
 method for obtaining an *attentional blink* (AB),  
 35 which refers to a reduction in accuracy for the  
 second of two targets presented in rapid succes-  
 37 sion (Shapiro et al., 1997). We chose to use this  
 methodology because it allowed us to make a  
 39 direct comparison between the conscious percep-  
 tions of the second target (through participant  
 41 reports of target identity) with their ability to  
 point rapidly and accurately to it (a visual-motor  
 43 function governed by the *dorsal* stream).

45 A second key feature of our method was that  
 we included both single- and double-step pointing  
 trials. Measuring pointing in only the single-step  
 47 condition would leave our results vulnerable to  
 the interpretation that pointing could be based

solely on the initial feed-forward activation of a  
 response. Double-step pointing trials ensure that  
 error-correcting feedback is also involved in the  
 action that is measured (Desmurget et al., 1999).

A third key feature of the methodology in Liu et  
 al. (2008) was that we measured both action  
 planning (response initiation time) and action  
 execution (MT and accuracy). This is important  
 because, as we mentioned earlier, planning is  
 generally considered to involve processes that  
 occur prior to action initiation, whereas execution  
 consists of processes involved in online control.  
 Studies measuring the real-time kinematics of limb  
 movement have shown that total MT is comprised  
 of two distinct phases, an initial, ballistic phase  
 based on previously programmed movement  
 characteristics (e.g., movement direction, ampli-  
 tude), and a later feedback-sensitive phase in  
 which the movement is refined (Desmurget et al.,  
 1999; Elliott et al., 2001).

Measurements of initiation time (IT) and MT in  
 Liu et al. (2008) were made using a touch screen  
 display, rather than with a three-dimensional limb  
 tracker as in previous studies. This meant we were  
 unable to measure the fine-grained details of  
 movement trajectories, but these were not required  
 to answer our main question, which was whether  
 planning, execution, or both of these components  
 of visually guided pointing to a target were  
 influenced by a concurrent perception task. Guided  
 by the dual vision systems framework (Goodale  
 and Milner, 2004; Norman, 2002), we predicted  
 that the task of letter identification (*ventral* stream)  
 would interfere with IT (movement planning), but  
 not with MT or pointing accuracy (both measures  
 of online action execution).

The results clearly showed that, compared to  
 when the central letter was ignored, successful  
 central letter identification interfered with identi-  
 fying a second letter in a peripheral location,  
 replicating the standard attentional blink for the  
 conscious perception of two targets presented in  
 rapid succession (Shapiro et al., 1997). Results  
 also showed that central letter identification  
 interfered with the initiation of the pointing  
 response to this peripheral letter (by slowing  
 down IT). This is the expected result, one that  
 is consistent with the hypothesis that conscious

1 action planning shares cognitive resources with  
 3 conscious letter identification (Goodale and  
 5 Milner, 2004). The truly novel finding was that  
 7 there was no evidence of interference from central  
 9 letter identification in either the speed or accuracy  
 11 of the pointing action to the peripheral letter.  
 13 That is, MT and pointing accuracy were sensitive  
 to the distance the finger had travel and to  
 whether online feedback was required or not  
 (double- vs. single-step pointing), but there was  
 no hint of any difference in these pointing  
 measures as a function of whether a central letter  
 was being identified at the same time.

15 One unexpected finding of this study was the  
 17 emergence of significant dual-task *facilitation* in  
 19 MT when the pointing target was presented in  
 21 temporal proximity to the central letter target.  
 23 This result is surprising from the perspective of  
 25 typical dual-task costs in performance, although  
 27 we note that it concurs with other research  
 29 showing dual-task benefits in visually guided  
 31 action. For example, researchers have reported  
 33 benefits in bimanual over manual pointing  
 35 (Diedrichsen et al., 2004) and in manual peg  
 placement by Parkinson’s patients when combined  
 with a tapping task (Brown and Jahanshahi, 1998).  
 Finding MT facilitation in the Liu et al. (2008)  
 study concurs with these researchers who remind  
 us that focused, singular attention on an automatic  
 task can interfere with fluent performance (e.g., in  
 sports, performance arts). Attention to a second  
 task can ensure that such overfocusing does not  
 occur, leading to better performance (Arend et al.,  
 2006).

### 37 **Capacity limits of the automatic pilot?**

39 In the study of attentional limitations on conscious  
 41 perception, it is conventional to refer to a task as  
 43 *automatic* when it can be accomplished without  
 45 interference from concurrent tasks, when it can be  
 47 done with little or no cognitive effort, and/or when  
 it is not influenced by increases in the sensory  
 information available during performance of the  
 task. Tasks of conscious perception can sometimes  
 meet these criteria for automaticity, either because  
 they involved innately privileged processing (e.g.,

biological relevance or a high degree of stimulus  
 saliency) or because an individual has devoted a  
 great deal of learning and practice to their  
 performance (e.g., some aspects of driving, over-  
 learned visual search involving a consistent map-  
 ping of targets and distractors).

From this perspective, the Liu et al. (2008)  
 result, showing no interference between central  
 letter identification and online control of visually  
 guided pointing, makes it tempting to surmise that  
 the finger’s automatic pilot is also capacity  
 unlimited. However, we think caution is in order  
 when extrapolating from studies of conscious  
 perception to questions about unconscious visual  
 processing. To begin exploring these possibilities  
 for the automatic pilot, we designed a study to  
 explicitly test for capacity limitations in visually  
 guided pointing. Specifically, we measured the  
 finger’s ability to modify movements in a double-  
 step pointing task under dual-target conditions.  
 This laboratory task is directly relevant to the  
 many actions we make every day involving  
 multiple targets and multiple movement compo-  
 nents. Any time we key in telephone numbers or  
 place sugar cubes into a cup of tea, multiple  
 targets are involved in the movement sequence.  
 The question of whether the visuomotor system,  
 like the conscious perception system, suffers  
 interference under multiple target conditions was  
 the focus of a study by Cameron et al. (2007).

Before summarizing Cameron et al. (2007), it is  
 important to note that there have been previous  
 studies of sequential action. For example, partici-  
 pants in some studies tap two or more targets in  
 rapid sequence. When the kinematics of a single  
 tap was compared to those for a tap to the same  
 first location in a series of taps, movement times  
 were typically longer in the multiple target  
 condition (i.e., there is a “one-target advantage”).  
 This in itself would appear to implicate a capacity  
 limit for dorsal stream visual processing. How-  
 ever, there is reason to be cautious in this  
 interpretation because all studies showing the  
 one-target advantage have emphasized speed of  
 response and very low accuracy criteria, with no  
 requirement to correct the action online in  
 response to changing display characteristics (see  
 review by Adam et al., 2000). As such, the actions

1 measured may have been memorized and thus  
3 have little connection to the online dorsal stream  
processes of interest in the present discussion.

5 Participants in Cameron et al. (2007) made fast  
7 sequential aiming movements to either one (single  
9 target) or two targets in succession (targets in  
11 different locations), with a goal of reaching the  
13 first target within 200 ms of target onset. The main  
15 measure of interest was the extent to which the  
17 finger deviated in its movement trajectory in  
response to a double-step in either or both targets  
(a target jump). The prediction was that if the  
online control processes of the dorsal stream are  
capacity limited, then there should be less respon-  
siveness of the automatic pilot to the double-step  
in the two-target than in the single-target condi-  
tions.

19 The participants were also tested under both  
21 the standard “go” instructions (i.e., point rapidly  
23 and accurately to the target(s) when they appear)  
25 and the “stop” instructions (i.e., the same  
27 instructions as in the “go” condition, with the  
caveat to withdraw the finger immediately from  
the table if a target jump is detected). As in  
previous studies, the stop instructions are useful  
in assessing whether the results are influenced in  
any way by the conscious intent to modify the  
action in response to a consciously perceived event.

29 The results of Cameron et al. (2007) revealed  
31 that the finger’s automatic pilot suffers interfer-  
33 ence from multiple targets in much the same way  
35 that conscious perception is reduced when more  
than one object must be attended in rapid  
succession. Although the actions of the finger  
took the double-step of a single target into  
account, these corrections were much less in  
evidence (both in frequency and in magnitude)  
when the same double-step target was the first  
of two targets to be pointed to in quick  
succession. Moreover, detailed kinematic analyses  
indicated that this interference came about  
specifically because the preparation of the second  
target action interfered with the online control  
of pointing to the first target. Similarly, exami-  
nation of pointing accuracy to the first target  
revealed that it was specifically impaired on  
double-step trials when a second target was  
present. Simply having to take that target into  
account, even

before it moved to a second possible location,  
reduced the automatic pilot’s ability to correct an  
action in response to a change in the first target’s  
location.

Our confidence that we were actually measur-  
ing the dorsal stream’s online abilities grew when  
the results also showed that the “stop” instruc-  
tions led to the same conclusions as the “go”  
instructions. In short, participants following  
“stop” instructions were unable to alter the  
actions of their finger in response to consciously  
perceived events (i.e., jumps) before their finger  
touched down and the results we have already  
described had taken place. Their finger with-  
drawals occurred after the first touchdown,  
implicating conscious rather than unconscious  
control. We have now also replicated this finding  
in the context of an experiment in which the  
double-step occurs entirely during the intra-  
saccadic period (i.e., while the eye is in transit  
between two fixations) (Cameron et al., in press).  
That experiment revealed that the online control  
of actions could be based on target jumps that  
began and ended entirely within the span of what  
is normally referred to as *saccadic suppression*.  
This implies that while the ventral stream of visual  
processing may indeed be suppressed during a  
saccade, the dorsal stream governing the online  
control of action is not. This finding further  
boosts our confidence that we are studying the  
unconscious control system of the dorsal stream,  
because participants are typically unaware of  
visual events that occur while a saccade is being  
made.

#### **Future research on attentional interactions involving seeing and acting**

Lurking beneath the surface of our normally  
smooth visual-motor interactions with the environ-  
ment is the fact that there are two independent  
streams of visual processing that make use of the  
same pattern of light. One of these streams  
enables us to consciously identify objects and to  
apprehend their layout in space; the other serves  
to unconsciously facilitate our motor interactions  
with these objects. Although most previous

1 research on the attentional limitations of vision  
 3 have focused on the conscious stream to date, the  
 5 purpose of this chapter has been to emphasize  
 7 that we should be focusing equal effort in our  
 understanding on the attentional capabilities —  
 both limits and freedoms — of the unconscious  
 action stream.

9 But doing so confronts us with new challenges.  
 One of these challenges is that care must be taken  
 to measure visual functions that are uniquely  
 governed by the unconscious action system. As we  
 pointed out, studies in the past that have been  
 aimed at this question have often inadvertently  
 posed tasks that involved conscious attentional  
 processing prior to the unconscious processes that  
 were the focus of the study. Another problem of  
 past research in this area is that adequate care has  
 not been taken to distinguish between the  
 planning (or preparation) of visually guided  
 action and the online control of those actions.

21 In our own beginning efforts to overcome these  
 challenges with the research we highlighted here,  
 we have come to the conclusions that (1) the  
 finger is guided visually by an *automatic pilot* that  
 uses different information from that of conscious  
 vision (Chua and Enns, 2005; Cressman et al.,  
 2007; Fecteau et al., 2001); (2) conscious object  
 identification interferes with concurrent planning  
 of pointing to a second object, though not with the  
 online control needed to complete the pointing  
 action (Liu et al., 2007); (3) concurrent perception  
 and action sometimes lead to benefits in motor  
 performance because the action task is not over-  
 managed by conscious processes (Liu et al., 2007);  
 and (4) the automatic pilot is itself capacity  
 limited in processing information concurrently  
 from multiple locations (Cameron et al., 2007, in  
 press). The challenge for future research will be to  
 find methods for exploring the attentional cap-  
 abilities of unconscious visual processes that take  
 us beyond what can be learned from studying the  
 action of the visually guided finger (i.e., the  
 automatic pilot), its responsiveness to changes in  
 spatial position (i.e., the double-step paradigm),  
 and the participant's intent to either execute or  
 halt an action (i.e., the go-stop paradigm) in  
 response to simple visual targets (i.e., luminance  
 defined discs in an otherwise empty display).

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