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Principal Investigator: Ralph Roberts

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We apologize for the long delay of this final report. Our records were confused and we mistakenly believed that a final report had been submitted previously.

The original grant proposal was for 2 to 3 years and covered pilot work and several studies. The scale of this work was necessarily narrowed since the already tight budget was cut in half.[1] However, we completed a good deal of pilot work and developed the eye-movement software required to complete the research. In addition, we carried out several studies that focused on expert-novice differences in the acquisition and organization of skill, with a focus on how increasingly complex strategies utilize incorporate visual look-ahead to calibrate action. The various completed components, beyond the required pilot work, are described below:

1. Software for collecting, calibrating, and scoring eye-movements was refined and updated. We developed some new algorithms for analyzing corneal-reflection eye movement data that detect the location of saccadic eye movements in space and time. We also developed a new user interface for editing and correcting automatically-scored data that provides the user with multiple views of the data. The interface was successful in speeding the time needed to score data and in improving overall accuracy of the final product. Our software is currently being used at several university research sites. We have provided the software free of charge but have not provided any user support.

2. We carried out and analyzed two full-scale studies on how strategically organized action differs in experts and novices. The work examined how experts use foveal and peripheral vision to acquire information about upcoming environmental circumstances in order to plan future action accordingly. We found that differences in the correspondences between motor actions and eye movements reflected the difference between how experts and novices take the future into account when organizing strategic action. The main findings from these studies were published in a book I co-edited (University of Chicago Press) that focused on future-oriented processes from

[1] In addition, the studies in air traffic control were not carried out since we were told that this area of research was not being funded.

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behavioral and neuropsychological perspectives. The relevant references are listed below (references marked with an * are included in this report):

*Roberts, R. J., Jr., & Ondrejko, M. (1994). Perception, action, and skill: Looking ahead to meet the present. In M. M. Haith, J. B. Benson, R. J. Roberts, Jr., & B. F. Pennington (Eds.). The development of future-oriented processes. (pp. 87-117) Chicago: University of Chicago Press.

*Haith, M. H., Benson, J. B., Roberts, R. J., Jr. & Pennington, B. F. (1994). Introduction. In M. M. Haith, J. B. Benson, R. J. Roberts, Jr., & B. F. Pennington (Eds.). The development of future-oriented processes. (pp. 87-117) Chicago: University of Chicago Press.

Haith, M. H., Benson, J. B., Roberts, R. J., Jr. & Pennington, B. F. (1994). .). The development of future-oriented processes. Chicago: University of Chicago Press.

3. The software and that ideas that came out of the funded studies (described above) had a direct impact on my later work into the competitive interactions between working memory, inhibition, and attentional processes. Below was our first piece of work in this area.

*Roberts, R. J., Jr., Hager, L., & Heron, C. (1994). Prefrontal cognitive processes: Working memory and inhibition in the antisaccade task, Journal of Experimental Psychology: General, 123, 374-393.

Introduction

Marshall M. Haith, Janette B. Benson,
Ralph J. Roberts Jr., and Bruce F. Pennington

This book was conceived for a very specific purpose—to generate an interest in how people, especially children, come to organize their behavior around the future and how they develop an understanding of the future. Our motivation was to launch systematic inquiry into this fascinating domain by raising sensitivity to the general issues, asking some important questions, and presenting the most relevant methodologies and research programs available. At the same time, the papers in this book can only be considered an initial foray; emphasis on this topic is so new that one could hardly expect more. That fact alone is curious.

Our society is obsessed with the future. The United States government, for example, is consumed with predicting the military actions of other countries, population trends and economic activity in our own country, the impact of changes in the interest rate, educational and health programs, and so on. Corporations devote a great deal of energy to developing strategic plans, mission and goals statements, and implementation strategies for ensuring competitive positioning. All of these institutional efforts reflect a strong orientation to the future. A consideration of the psychological world of individuals reveals little difference. We are constantly thinking through such issues as what to wear today, whom we should invite for lunch, how best to organize a presentation, and which investment strategy will yield the best return for retirement.

In a recent study, young women were asked how much time they spent thinking about the past, the present, and the future; they reported spending most of their time thinking about the future and the least time thinking about the past (Jason, Schade, Furo, Reichler, & Brickman, 1989). More formal documentation comes from mothers' reports of what they talk about to their offspring, as described by Benson in this volume.

But even for the individual, a preoccupation with the future extends beyond the exclusively personal. Witness the popularity of science fiction and such "future world" attractions as Epcot Center near Orlando, Florida. Of course there are many examples for which personal issues are the driving force, as when some of us appeal to fortune-tellers, astrologists, and biorhythm charts for a hint about what awaits us.

In the light of all of these indications of how much mental time and effort we devote to the future, it is surprising that no systematic conceptual framework exists for talking about psychological representations of the future, nor is there a critical mass of literature for developing such a conception. The situation is even worse when one attempts to approach developmental questions about this domain. Why?

Historians will differ in the story they tell. We have three hypotheses to offer, and they are strongly influenced by the enormous amount of attention that has been paid to memory—the processes and content that deal with the past—in comparison with considerably less concern for the processes and content that deal with the future. The field of memory enjoys a sophisticated taxonomy, a treasure of methods, and no dearth of theories and concepts. Not so for the future.

The first hypothesis concerns psychology's favoritism for the concrete and the specifiable. This claim is not difficult to document through the phases of operationalism and behaviorism in the field. Notwithstanding the enlightenment of current researchers for whom mental constructs are employed with ease, we are all products of our intellectual history. Memory fits these historical dispositions more easily than do future-oriented processes. The past is certain, concrete, and specifiable. It is not difficult for us to think of changes in the brain, be they neural or biochemical, by which experience can be represented. But the future is uncertain, ephemeral, and nonexistent. (It hasn't happened yet!) How do we talk about a nonevent? How can we think about brain processes that represent events that have not yet occurred?

A second hypothesis concerns the discomfort of scientists, in general, in dealing with reverse causality—the dreaded problem of teleology. The future seems to work backward in time, controlling what we do in the present. How can something that will occur later affect what is happening now? We have no good way of dealing with that problem except to invoke explanations, based on nervous system organization, that "make it appear" that the future is controlling current behavior when in fact it is not. Examples include "purposeful" web spinning of spiders to trap insects, the dance of the honey bee to communicate the source of food to members of the hive, and the burial of piñon nuts by the Sierra Nevada nutcracker bird in late fall to stave off hunger in the forthcoming winter. We shrug off these examples in terms of "in the gene" controls or adaptive tropisms. Such explanations are less comfortable when we try to accommodate the behavior of humans who do very diverse and sometimes brand-new things that are oriented toward future purpose. Here we turn to explanations that lean on mental representations of the future that control current behavior, but no one would claim that we have anything close to a satisfactory scheme to account for any kind of future-directed activity that is even mildly complex.

A third hypothesis is that psychologists have not seen future-oriented processes as an integrated set in the same way that past-oriented, or memory, processes have been seen to be interrelated. By using the term "future-oriented processes" we mean to embrace such concepts as intentionality, goal setting, prediction, set, expectation, preparation, anticipation, planning, and feedforward computation. In fact such topics have been researched, even developmentally, but in isolation. For example, Piaget devoted considerable discussion to the development of means-ends relations in early childhood, which involves some notion of a goal. The cognitive revolution opened the horizons of psychologists by demonstrating the value of mental constructs for conceptualizing human thought; many of these constructs are relevant to our topic. And planning in children has received some attention. These examples and the very fact that future orientation is so immanent in behavior and thought, as we argued earlier, imply that psychologists have certainly studied phenomena that involve future-oriented processes. However, no attempt has been made to consider these processes as manageable under the same umbrella, as has been the case for "past-oriented processes," generally treated under the rubric of memory. A good analogy to the current state of affairs is the history of the relation between learning and memory. Memory is clearly related to learning, but research on learning continued apace for many years without deep consideration of memory. The focus of investigators' attention on memory as an interesting process per se had revolutionary effects on the study of human cognition. In the same way that refocusing attention on past-oriented processes (memory) produced immense advances in our knowledge, it may be that turning the spotlight on future-oriented processes will also yield rich dividends.

At the invitation of Robert Emde in 1988, several of the chapter authors organized as an interest area under the Network on Early Transitions that he headed within the Health Science Program of the MacArthur Foundation. We called ourselves the Interest Area on the Development of Future-Oriented Processes and met approximately twice each year to discuss various issues raised by our mandate and to plan research. A key task for us was to examine whether the concepts we have described above do indeed form a meaningful set. Would the beginnings of a conceptual formulation emerge that could satisfactorily integrate these various concepts, and would research in the separate areas under consideration be enriched by this broader perspective? Near the end of the five years that we met, in April 1992, we held a conference in Breckenridge, Colorado, to gather together ourselves and relevant outside people to focus on the topic of the development of future-oriented processes per se. The enthusiasm and encouragement of this group reinforced our sense that we were on a productive path. This book is a product of that conference. The experiment has been too brief to decide whether the domain of "future-oriented processes" will survive as a viable and productive category for study, but the early indications are that it is a worthy endeavor to pursue.

An issue that monopolized much of our discussion was the role of memory in future-oriented processes. An extreme view was that future orientation is just memory replayed. Does one's representation of the future simply represent the past pushed forward? In some cases, the answer is probably yes, but in others it most assuredly is no. Some conceptions of the future can be seen as projections of a repeating past or of past trends, but others seem to be explainable more in terms of construction from analogy and from knowledge.

The future as projection of a repeating past. Examples that fit this portrayal are easy to generate. We hear a dripping faucet, and soon we form an expectation that the next drip will occur at a particular moment. More complex examples among subhuman animals that might fit this category are nicely documented in Gallistel's recent book (1990). Animals come to anticipate feeding times that are tied to the 24-hour diurnal cycle; one could account for this behavior by arguing that animals come to forecast that the past will serve as a guide to the future and form expectations on this basis. This type of future orientation seems to be at play in the chapters by Haith and Reznick. Even though Haith's chapter explores infant expectations in the very early months based on varying rules and cues, basically the baby's expectations for what comes next depend on a repeat of what came before. Reznick, studying older infants, shows that such expectations can become strong enough to result in anticipatory activity that overcomes infants' very strong tendency to respond to the here and now. These may be the very earliest forms of future-oriented processes, tied to fairly concrete recent experience.

One can think of far more sophisticated examples of related processes. For example, predictions (often erroneous) of earthquakes, volcanic eruptions, and solar flares often depend on a cyclicity that has been discovered from past records. Here the boundary of this category gets a bit fuzzy, because "memory" is often not personal but cultural. Even so, this is hardly the whole story.

The future as projection of past trends. The formulations of the future by human adults most certainly go beyond simple replays of past experience. Consider the focus of several scientific disciplines that model a future that is not a replay of the past. Rather, they use trends in the past to project forward. Examples include predictions of future populations in various countries, the spread of AIDS, the effects of tropical deforestation and the decline in biodiversity, and what automobiles will look like in the future. The events in question have never happened before; they are an extrapolation of what is happening now and the trend line leading to the current state of affairs. Predictions of whether the universe will expand forever or collapse for another big bang might also fit this rubric.

The future as construction from analogy. At some age children begin to represent their own future, but it seems highly unlikely that such a representation is based on a trend line. And there can be no question whether it is based on memory. Rather, a child may identify with the same-sex parent or older youngsters and think about the personal self at a comparable later stage of life. Ironically, such analogizing may lead some children to place little faith in any future at all—for example, inner-city children who live in ghettos where violence and death are routine (Kotlowitz, 1991). Here the construction of a future depends on an analogy or a comparison with others. Another example is planning for one's death. Most of us believe our personal death is not an event that has occurred before. Rather, we plan for death based upon what we know has happened to others and what we see around us.

The future as construction from knowledge. One of the most sophisticated organizations of the future seems to involve events that are completely novel and do not depend in any direct way on historical trends. Consider the state of affairs in 1961 when John Kennedy announced that we would put humans on the moon by the end of the decade. Scientists planned and worked toward this goal for years, employing knowledge and experimentation to accomplish a task that had never been attempted before and did not depend in any meaningful way on a projection of historical trends. Other examples include preparation for the emergency program to repair the Hubble telescope, the attempts by biochemists to achieve rational drug design, or for many of us, the plan to test new hypotheses in our laboratories. And we need not limit ourselves to science. Here we are talking about imagination, equally the province of authors, painters, sculptors, and composers—even the sentence-generating child.

These categories prompt speculation both about phylogeny and about development. Whereas the past is certain and concrete, the future is abstract and uncertain—but in degrees, as represented by these categories. It is easy for us to imagine that the lowest-level category is applicable to the cognition and actions of subhuman animals and infants, but few of us would make such a claim for the final category. Perhaps here we have the beginning of a sketch of the stages that children go through in their development of future-oriented processes. Separately, is it uniquely human to imagine what has never happened before? The future at this level is based on knowledge about what can happen—perhaps on how knowledge can be created—not on memory.

At the same time that we can differentiate future-oriented processes (FOPs) from memory, we wonder if the conceptual and empirical advances in this field can provide a springboard for conceptualizing future-oriented processes. For example, is it worthwhile to distinguish short-, intermediate-, and long-term FOPs? Can we distinguish between implicit and explicit FOPs or between central and incidental FOPs? Are some FOPs semantic and others episodic? The answer to at least some of these questions appears to be yes, which suggests that memorial distinctions reflect something meaningful not only about memory but about the general operation of the human mind. Thus the pursuit of these ideas may enrich not only the domain of FOPs but also that of memory and of cognition in general.

What we try to establish here is a foundation and provocation for the study of future-oriented processes. The reader will find amazing diversity, tied together by common problems and concepts. The chapters by Hofsten and by Roberts and Ondrejko illustrate how pervasive is the need for prospective processes even in perceptually driven motor control and how one must represent the future state of things for efficient, dynamic skilled action. Rumbaugh and his coauthors demonstrate that these processes are not the exclusive privilege of the human species. Bidell and Fischer, and also Klahr, carry these ideas forward into problem-solving contexts where children have time for thought rather than having to respond to ever-changing events.

Working memory and the role that the prefrontal area of the brain plays in executive processes are fields of strong interest to current researchers. However, there has been little discussion of how these topics relate to future-oriented processes. In fact the use of the term "memory" in the phrase "working memory" seems to obscure just how future oriented executive processes are. Nevertheless, both Weinberger and his colleagues and Pennington address the role of working memory and the prefrontal area in future-oriented activity in both children and adults.

The remaining chapters consider the development of future orientation in a social and linguistic context. While Bates and her coauthors consider the role of language in communicating and representing the future relative to the present and the past, Trabasso and Stein illustrate how inferences about the future orientation of others are crucial to a child's understanding of their behavior.

Finally, Rogoff and her colleagues, Benson, and Stein and Trabasso move beyond the laboratory to discuss future-oriented processes in the everyday social world of children.

The book closes with an epilogue by Robert Emde, who congratulates us on opening the door while showing us how far there is to travel.

We close this section by expressing our deep gratitude to the MacArthur Foundation for funding our meetings and research, and also to Robert Emde for taking a chance on something new and different. It goes without saying that the trip we undertook could not have begun without the exploratory spirit of both these sources of inspiration.

Finally, we would like to acknowledge the Colorado Lottery for helping us to decide on the order of the editors for this book (with the exception of the first editor). Also, we appreciate several sources of support that aided the preparation of this book: National Institute of Mental Health Research Scientist Award MH00367 and National Institutes of Health research grant HD20026 to Haith, a MacArthur Foundation grant to Benson, National Science Foundation grant BNS86108043 and National Aeronautics and Space Administration grant R91091 to Roberts, and NIMH Research Scientist Development Award MH00419, NIMH research grants MH38870 and MH45916, and National Institutes of Child Health and Human Development center grant HD27802 to Pennington.

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Chapter Four

Perception, Action, and Skill

Looking Ahead to Meet the Future

Ralph J. Roberts Jr. and Michael Ondrejko

In this chapter we explore the perceptual and cognitive processes that are involved in the performance of improvisational action skills. We first discuss an important characteristic of many real-world skills—they are adapted quickly and precisely to a varied and often changing environment. Flexibility and precision can be difficult to achieve jointly, especially under tight time constraints. We argue that future-oriented processes are a key component of successful action. Yet skills that are improvisational cannot be entirely scripted in advance but must be organized on line. We suggest that performers actively seek specific perceptual information to monitor ongoing action and to plan upcoming action. To examine these ideas, we present research that utilizes video games and eye-movement recordings to explore the real-time interactions between perceptual selection and upcoming task actions in performers

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with varying amounts of skill. The findings reveal the characteristics of well-integrated perception-action couplings and suggest important changes in future-oriented processing with the acquisition of expertise.

FLEXIBLE PRECISION IN SKILL

Our ability to learn and perform complex action skills is truly remarkable. From crawling and catching balls to driving and improvising jazz, we acquire a wide variety of skills whose extraordinary complexity is often obscured by the seeming effortlessness of performance. Yet successful action must fit many simultaneous constraints defined by the parameters of the world we act in, the physical construction of our bodies, the processing characteristics of our nervous systems, and the goals that mobilize our actions (Bernstein, 1967/1984; Kugler, Kelso, & Turvey, 1980). Skilled action can be viewed as a solution or set of solutions to the problems of meeting these many simultaneous constraints. Although the difficulty of finding such solutions is mostly transparent once we develop expertise, it is far more apparent to the novice. As an example, consider a common predicament the novice snow skier faces when recognizing that the only available path to the bottom of the mountain is an expert-level run:

> You're still waiting for those butterflies in your stomach to stop fluttering. . . . You've been standing here at the lip of this incredible mogul field (2- to 4-foot bumps) . . . for five minutes and already it seems like an eternity. The bumps below you are big, big and mean, choppy and steep . . . not at all inviting. But they must be so to all those other skiers, creatures from another planet maybe, who smoothly slip by you over the lip and disappear down the fall line, snaking through those bumps . . . legs oscillating like rubber pistons, (upper) bodies motionless, poles deftly picking out a line where all you can see is the possibility of linked disasters. . . . You don't belong up here and you know it. (Tejada-Flores, 1986, p. 125)

Skiing down such a steep, bumpy slope without injuring oneself is unquestionably a complex skill. What makes this sort of skill so remarkable is that performers maintain a high degree of precision in the timing and sequencing of action while continually adapting to a varied and often changing environment. In skiing such a slope, an expert makes two to three turns a second, and each turn is composed of several component actions, including knee flexing, lower body turning, weight shifting, arm reaching, and pole positioning. Successful action requires great precision in the timing of these actions as well as the specific way the actions are executed. Small errors can result in quick disaster. But precision is not enough: action must also be continually adapted to environmental particulars. To carve a path down the slope, the skier must adapt to the position and size of the moguls, the varied surface conditions on each mogul, and obstacles such as bare spots and other skiers. Flexibility is a necessity since no two ski runs are identical; each offers a somewhat different set of challenges.

Thus skiing, like many complex action skills, requires that action occur under tight time pressure and be both precise in its execution and adapted to varied environmental particulars. This is an extraordinary accomplishment. In any behaving system, flexibility and precision can easily be at odds with one another and difficult to achieve jointly. Efforts at optimizing one often degrade the other. For example, it is relatively easy nowadays to design robots that carry out actions with single millisecond accuracy when those actions are scripted and not based on varied environmental circumstances. In such cases, action can be programmed in advance and is relatively inflexible. But if the robot needs to adapt its behavior to changing and somewhat unpredictable circumstances, then it is very difficult to achieve quickly organized and precisely timed behavior (cf. Anderson, 1988). It is much easier to be flexible if the system can evaluate the present context and construe a response without regard to timing.

A central question for understanding skilled action, then, concerns how flexibility and precision are achieved jointly in the multitude of action skills learned in a lifetime. One part of the answer relates to the degrees of freedom problem (Bernstein, 1967/1984). Actors can adapt more quickly and effectively if the many degrees of freedom in action are "compressed" so that the controlled parameters are few. Action theorists have discussed how reductions in the degrees of freedom may result from a variety of sources, including functional muscle synergies, properties of neural computations, and the dynamics inherent in the physical construction of our bodies (for recent reviews see Rosenbaum, 1991; Turvey, 1990). In this chapter we focus on the prospective character of skilled action as a means for understanding flexible precision. In particular we are interested in how perception provides information to allow an actor to prepare for a specific future. We suggest that actors must obtain relevant information at particular moments in action and must also know how to use the information to organize upcoming action. Performers' actions, then, need not follow predefined scripts or react to immediate contexts: they can be based on assessments of future conditions construed from an ongoing interaction with the environment.

PROSPECTIVE CONTROL AND THE PERCEPTION-ACTION CYCLE

The insight that some form of prospective control is involved in producing skilled action has been recognized at least since Bryan and Harter (1899), who studied telegraph operators. These researchers concluded that as operators become more skilled, the units of action become increasingly larger hierarchically organized sequences—from letters to words to common phrases. Predictable sequential interdependencies are profitably used so that the future becomes built in, so to speak, in the organization of the units. A half century later, several researchers argued more directly for the importance of prospective control. Lashley (1951) reasoned that skilled behaviors such as speech, piano playing, and typing occur too quickly for one action to serve as a stimulus for the next; sequences of action must be planned in advance. Miller, Galanter, and Pribram (1960) went further to describe a theoretical framework for specifying how plans and goals organize everyday behavior. Even lower-level motor control, Bernstein (1967/1984) argued, involves anticipation, particularly when "during the course of any given segment of a movement, retrospective control becomes practically impossible" (p. 368). These and other researchers (e.g., Piaget & Inhelder, 1969) pointed the way toward several decades of subsequent research and theory aimed at understanding the cognitive constructs that underlie prospective control, such as schemas, plans, scripts, and motor programs, and the associated feed-forward control processes. This work has shown how advance specification of future action makes precision and speed possible, since action need not be reactive to either prior action or environmental events (also see Haith, this volume; Hofsten, this volume).

Despite this progress, it is still somewhat of a mystery how skilled actors can quickly adapt to constantly changing and often somewhat unexpected environmental circumstances. Paralleling the engineer's efforts at programming skilled action in the robot, the work on the prospective control of action focuses on sequential behavior that tends to be scripted in advance (or relatively simple), but not *continuously* adapted to a varied or changing environment. As described earlier, prespecification of the sequencing and timing of action is possible when environmental circumstances are irrelevant or perfectly predictable. Yet this is rarely true—most action skills are more improvisational. Simply put, cognitive theorists have tended to neglect the environment, except as it provides stimuli for a response or after-the-fact feedback. In particular, there has been comparatively little work on the perceptual processes that enable the skilled actor to use environmental information to control action. The notable exception to this trend is the work of James Gibson

(1966, 1979) and those influenced by his views (e.g., Hofsten, 1985; Lee, 1980; Reed, 1982; Turvey & Kugler, 1984; Warren, 1984).

Gibson (1966, 1979) and others (e.g., Turvey & Kugler, 1984) have argued that prospective control is accomplished by the pickup or detection of information that is available in the present optical structure, and that this information unambiguously specifies future states. The best worked out example is the optical flow that accompanies self-motion or the motion of an object as it approaches an observer. Lee (1980) has shown that the inverse of the rate of dilation of an optic image specifies time-to-contact, and can be used in a variety of skilled actions, from slowing a car to stop at an intersection to timing the closing of one's hand to catch a ball. Optical structure is not a stimulus for a response, it is a continuous source of information for guiding ongoing activity.

This analysis not only places perception at the center of action, but also highlights the idea that perception is action based. In addition, it dramatically shifts how we think about the environment, from the long-standing perspective that the environment provides "stimuli" to a realization that there is a wealth of perceptual information available to an observer interacting with the environment. In the context of skilled action, it is our view that the actor must also know *how* to use perceptual information to organize activity and must be *selective* in obtaining the relevant information at the appropriate times.

The ability to utilize available perceptual information to organize upcoming action often depends on an actor's knowledge. For example, the state of a traffic light and its relevance for my actions as a driver approaching an intersection is directly related to my knowledge of traffic lights and their role in controlling traffic. Similarly, my expectation that the police will soon be monitoring my speed might be based on seeing an oncoming motorist flash his or her headlights. I make an inference about the meaning of the flashing lights based on my knowledge of how motorists sometimes communicate with each other. Thus, perceptual information for guiding future action can involve knowledge as well as inference for its effective use.

The optic array typically offers a great deal of information, much more than is relevant for a specific action or action sequence. Thus, perceptual selection may be necessary to obtain appropriate information at the appropriate times. As action unfolds, an actor's goals and subgoals change, as does the information that is most relevant for accomplishing those goals. The most important information may come from different places at different times. As an example, reconsider the expert skier maneuvering down the mogul run. The closest mogul provides information about a turn in progress, adjacent moguls provide information about possible upcoming turns, and skiers, trees, and rocks scattered farther down the mountain provide information about possible future paths. Depending on the skier's current and upcoming goals (e.g., initiating a turn, figuring out which path leads to a particular chairlift, finding a companion in a crowd of skiers), different kinds of information are more or less relevant. We expect that selection is active and knowledge based.

Thus we take the view that contexts of action provide a rich source of perceptual information for determining and calibrating upcoming action. Some information directly specifies upcoming environmental events, other information is useful because a skilled actor can infer the relevance of the information for future action. Perception is also selective in terms of what is most important at any given moment, and what is most important is partially determined by the changing goals and subgoals the actor constructs as action unfolds.

This perspective on the interaction between action, cognition, and perception is similar to the views espoused by Arbib (1980, 1989) and Neisser (1976) when describing the perceptual cycle. In the context of skilled action, the actor's goals for upcoming action direct perceptual selection. Information gathered, in turn, helps organize action planning and modifies the unfolding goals and subgoals for action, which further direct perceptual selection, and so on. Perceptual information is used prospectively; as Arbib (1989, p. 26) notes: "Perception is oriented toward the future as much as the present—not only to interacting with the environment in some instrumental way, but also to updating an *internal model of the world* to be used to guide future action."

Although this approach to the close interconnections between perception and action seems sensible, there are few well-developed methodological approaches readily available for studying such relations. The perception-action cycle is more of a general hypothesis than an empirically established fact. Historically, perception and action have most often been studied separately, and the two have evolved into somewhat different disciplines. In addition, there are practical problems for studying the kind of perception-action cycle described above. In an effort to maintain experimental control, we normally develop tasks that are far less complex than the real-world contexts they are designed to inform us about. Although we eschew stimulus-response theories of learning and performance, most of our experimental paradigms employ a stimulus-response methodology: subjects perform individual trials where a response is made to some stimulus. The interdependent cycling of perception and action may not be evident or even necessary in such simplified settings. Another problem concerns how to measure both perception and action continuously in more realistic, complex settings.

These are problems we have been grappling with in our own research, and in the rest of the chapter we describe an approach we have developed for examining the perception-action cycle. The approach uses specially designed video games as the context of action and the spatiotemporal patterning of eye movements as an indicator of perceptual selection.

CORRESPONDENCES BETWEEN EYE MOVEMENTS AND SKILLED ACTION

Skilled behavior occurs in environments that are often cluttered and dynamic, and the sources of information about various aspects of the environment also vary across place and time. Since we are able to extract detailed visual information only from the fovea, which occupies a relatively small part of the visual field, we move our eyes to reposition the fovea to those areas of the scene that are presumably most informative. Thus in many situations eye movements can be a relatively straightforward indicator of perceptual selection (cf. Loftus, 1983; Stark & Ellis, 1981). In such cases one would expect that the pattern of fixation locations and the timing of saccadic movements should correspond in some regular fashion with the flow of action, and that the form of this correspondence should reveal the ways skilled performers gather visual information to anticipate future states and plan action accordingly.

There is very little research that examines eye movements in the context of ongoing action (although see Bahill & LaRitz, 1984; Shapiro & Raymond, 1989). A notable exception to this trend is the work on reaching and pointing, where researchers have examined correspondences between hand, head, and eye movements (e.g., Biguer, Jeannerod, & Prablanc, 1982; Carnahan & Marteniuk, 1991; Gielen, Van den Heuvel, & Van Gisbergen, 1984). This work indicates that in pointing and reaching tasks, movements of the eye and hand are tightly coupled in time, with the eye beginning slightly before (60–100 ms) or close to the same time as the hand and arriving at the target consistently about 200 ms before the hand arrives (Angel, Alston, & Garland, 1970; Carnahan & Marteniuk, 1991). Early arrival of the eye is viewed as anticipatory, since it allows for late corrective feedback for the hand movement. Several models have been constructed to explain this tight coupling between eye movements and arm movements, yet it is entirely unclear whether the correspondences found in these relatively simple and discrete pointing tasks are representative of what occurs in more complex contexts, where perception and action are continuous and environments are cluttered and nonstatic. A goal for our work was to examine such correspondences in a more complex, less constrained setting as a starting point for exploring the real-time characteristics of the hypothetical perception-action cycle.

SUMMARY AND OVERVIEW OF THE VIDEO GAME STUDY

The perspective on perception and action just reviewed can be summarized as follows, and it acts as a set of guiding assumptions for our work: Skilled action is both flexible and precise in how it is organized in accordance with a varied and changing environment. Action sequences cannot be primarily reactive to environmental particulars because responses would often be too late—some form of prospective control is necessary. Yet action sequences cannot be planned too far in advance, since not all relevant contextual information for planning action can be known in advance. The optic array provides a wealth of information about current and upcoming conditions, and this information can be used for adapting action to an upcoming environment. To use perceptual information effectively, the skilled performer must know what information is relevant at what points in time during the flow of action. Just as action must often be anticipatory, so must perceptual information gathering that subserves that action. Thus action and perception interact in a continual cycle, with the goals of action influencing perceptual selection and the information gained influencing subsequent action planning.

The primary purpose of our research was to examine the perception-action cycle in a reasonably complex task in which behavior was continuous and relatively unconstrained. We examined the spatiotemporal characteristics of eye movements as an index of perceptual selection and the sequence of task actions as an index of the actor's unfolding action goals. Since there is little previous work that examines eye movements in the context of ongoing skilled action, our initial work was necessarily exploratory and descriptive. The research focused on the following questions:

- How is perceptual selection, as evidenced by eye movements, related to ongoing action? In particular, to what degree do the locations of foveal regard and the timing of changes in looking location correspond to what the actor is trying to accomplish?
- If regular correspondences occur, what do they reveal about how visual information is utilized? To what degree does perceptual selection anticipate action? Is there evidence that performers actively look ahead to gather perceptual information to select and calibrate future action?
- Are there differences in perception-action correspondences as a function of expertise? And if so, what do such differences suggest about what is acquired with the acquisition of skill? For example, do novices show a less consistent relation between perception and action? Are they less able than more experienced players to use visual information to plan action appropriately?

To examine these questions, we used a specially designed video game in conjunction with an infrared eye-movement recording system (Roberts, Brown, Wiebke, & Haith, 1991). We used the video game because, although it is a somewhat constrained perception-action context, it shares a number of important similarities with other complex perception-action skills: expertise cannot be acquired quickly and requires both precision in the timing and sequencing of actions and flexibility in the face of a continually changing context.

METHOD

Experimental Setup

The task was presented to subjects in an arcade style video game cabinet (see Figure 4.1). Subjects sat on a stool in front of the cabinet and rested their heads on a chin-forehead support. Subjects' hands rested on a panel that contained three buttons, two for the left hand (middle and index fingers) and one for the right hand (index finger). Subjects viewed a half-silvered mirror tilted 60° from horizontal. The task monitor was a 19-in. (48.3 cm) x-y vector monitor with a 1,024 × 768 resolution that was positioned under the mirror and angled 20° from the horizontal. With this arrangement, the monitor appeared to be directly in front of the subject's face at a distance of 66 cm; 1 cm on the game monitor equaled 0.87° of visual angle. An infrared light and an infrared-sensitive video camera were positioned behind the mirror and aimed at the subject's left eye.

The video output from the camera was fed to an automatic eye tracker that processed the video signal to find the locations of the center of the pupil and the center of the corneal reflection of the infrared light. The difference between these values relates monotonically to looking location (with an accuracy of approximately ½° of visual angle). These data were output to a computer that sampled the data at 60 Hz. The computer also received input from the video game's processor and collected, synchronously with the eye-movement data, a complete digital record of the video game's display and the button presses. (For a more complete description of the hardware and software, see Roberts et al., 1991.)

Video Game Task

The task was based on a commercially available game called Asteroids (see Figure 4.2). The subject controlled the actions of the "ship," a triangle displayed at the screen center (0.7 cm at the base, 1.2 cm high). The two left-hand buttons controlled the ship's orientation by rotating it counterclockwise or clockwise. As long as a turn button was pressed, the ship rotated around its center axis at a rate of 250°/s. The ship always remained at the center of the screen. A "shot" could be released from the nose of the ship when the fire button was pressed. A shot moved

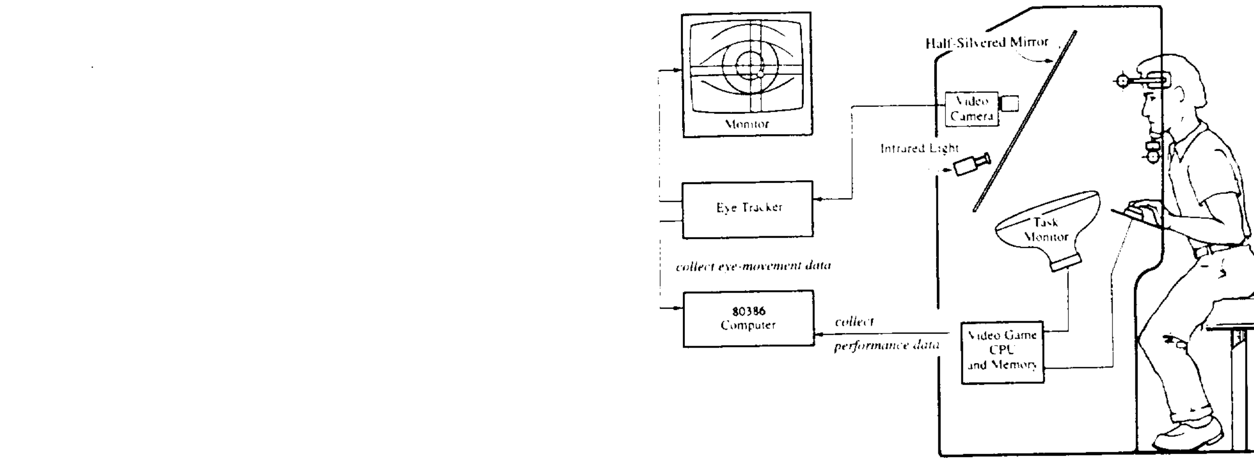

Figure 4.1 A schematic diagram of the data collection system (adapted from Roberts, Brown, Wiebke, & Haith, 1991). The cutaway of the video game booth shows a subject viewing a reflection of the task monitor on a half-silvered screen. Behind the one-way mirror an infrared-sensitive video camera focuses on the subject's left eye, which is illuminated by a near-infrared light. The video signal from the camera is fed to an automatic eye tracker that outputs x-y locations of the centers of the pupil and corneal reflection of the infrared light to an 80386 personal computer. The 80386 PC also collects synchronous performance data from the video game central processing unit.

across the screen in a straight line at 17.7 cm/s and disappeared when it intercepted a target or traversed the length of the screen. Potential targets were moving "asteroids" (jagged circles with a 0.5 cm radius), that also moved in a straight line across the screen at constant velocities. When an asteroid moved off the edge of the screen, it "wrapped around" to immediately reenter on the opposite edge. Each asteroid's velocity and trajectory angle were determined randomly within a range of values. Thousands of combinations were possible.

The subject's task was to avoid letting an asteroid intercept the ship and to successfully shoot as many asteroids as possible. To discourage rapid "blind" shooting, we programmed the task so that only one shot could be displayed on the screen at a time—pushing the fire button had no effect until the previous shot either intercepted an asteroid or disappeared from the screen. When a shot intercepted an asteroid, an explosion sequence was displayed and the asteroid disappeared. A replacement asteroid was immediately generated on the edge of the screen, with a new velocity and trajectory. This arrangement ensured that the subject received feedback on the success of each shot and that

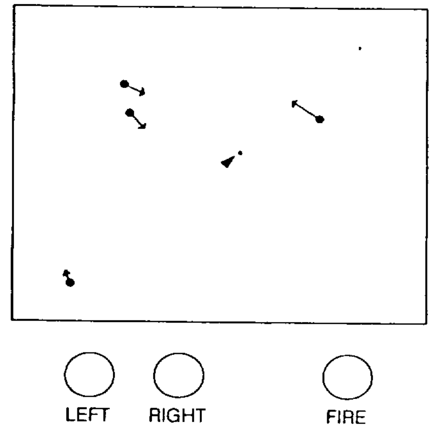

Figure 4.2 A representation of the video game task. The circles represent the asteroids, and the triangle represents the ship. The lines are not displayed on the screen but are shown here to represent the motions of the objects. The circles at the bottom of the figure show the positions of the buttons that control the ship.

the number of potential targets remained constant, regardless of the subject's level of expertise. When an asteroid intercepted the ship, the ship exploded and a new ship was displayed.

We felt that the task, designed with these features, required the key characteristics of perception-action skills that were of interest. First, successful performance (many hits, few asteroid-ship interceptions) required integrating several perception and action components, such as selecting targets, determining intercept times and positions, reorienting the ship for aiming, and timing the release of the shots. Flexibility was required, since the context was continually changing and it was very unlikely that two games would ever be identical. Precision in the timing of action was also required; for example, many targets moved quickly across the screen and had brief intercept windows (30–500 ms) for a given orientation of the ship.

Subjects and Procedure

We tested 13 college-age subjects who were divided into two groups based on their previous experience with video games and their performance on a pretest. The novice group (three males and four females) reported that they had played video games only on a few occasions, whereas the experienced group (five males and one female) said they were avid video game players. Subjects were tested on a pretest that was similar to the experimental task. The pretest consisted of thirty 15-s trials. Subjects in the experienced group obtained an average of 6.6 hits per trial (the range of subject averages was 6.2–7.6), and those in the novice group averaged 2.7 hits (range = 2.0–3.7), $t(11) = 11.2$, $p < .001$. Although the subject partitioning clearly distinguished players of different levels of skill and experience, it is important to note that the experienced players were not true experts on our task, since they had never played our constrained version of the Asteroids game before coming to the lab. Additionally, our novices were not complete beginners, since they had already practiced 30 trials of the game before testing began. With these caveats in mind, we will refer to the groups as experts and novices.

Subjects performed 20 test trials, divided into four blocks. Each block contained randomly ordered trials with 1, 4, 7, 10, and 13 asteroids per trial. These different "clutter" conditions allowed us to sample performance across a range of contexts and to assess how such changes influenced performance. Trials lasted 20 s, which excluded the time the ship was not displayed on the screen after an asteroid-ship interception. At the end of each trial, performance feedback was provided on the screen that showed the number of hits and ship "deaths."

Coding and Dependent Measures

During performance, two 60 Hz streams of data were collected: one contained performance and task-environment information, and the other contained eye-movement information. These data were further processed to obtain the relevant performance variables. Global variables that described summary aspects of task actions for a single trial were straightforward to extract from the performance data. Such variables included the frequency and duration of button presses, the number of hits, the number of shots, the number of asteroid-ship interceptions, and the distances between objects at various points in time (e.g., ship-asteroid distance of hit targets).

Obtaining variables that reflected the relations between eye movements and task actions was more involved. First, the eye-movement data were linearized and transformed into the task-monitor coordinate space (Roberts et al., 1991; Sheena & Borah, 1981). These data consisted of looking locations specified in x–y coordinates of the task monitor for each 1/60 s. These data did not specify what object a subject was looking at, since the objects on the screen, except for the ship, were always moving. In addition, the data did not directly specify the eye's state (fixation, saccade, or smooth pursuit), the timing of the transitions between states, or the relations between eye movements and task actions. The next step in data reduction provided these missing pieces.

The performance data contained the x-y locations of each object and the status of the three buttons (pressed/not pressed) for each 1/60 s. These data allowed us to create a complete replay on a computer screen of a performance trial, in real time, slow motion, or stopped frame. Since the transformed eye-movement data were in the same coordinate space, we developed a program that superimposed a crosshair on the game screen to show the looking location for each frame. Thus we could view a replay of a trial with a moving crosshair showing the player's changing visual regard. The replay program simultaneously displayed, on a separate monitor, a plot of the coordinates of the direction of gaze, highlighting the current frame of data displayed on the task monitor. This replay program provided the core for a computer-assisted coding system (for more detail, see Roberts et al., 1991).

Coders examined replays and the corresponding visual-regard plots of every trial and made judgments about the beginning of saccades (rapid shifts in point of regard), fixations (relatively stationary point of regard), and smooth pursuit or tracking (relatively continuous movement of gaze direction). Coders also indicated, with a cursor on the task screen, the object of visual regard (an asteroid, the ship, the shot, or empty areas) in conjunction with the fixation and tracking codes. Also coded were blinks and other types of noise in the data. All codes were stored with information on the objects of regard (e.g., asteroid distances from ship) and synchronous task performance data (e.g., onset and offset of the button presses). Interrater reliability on the codes was very high: two scorers coded the same 20% of the data set, distributed across all subjects. Coder agreement on the choice of code and the frame to mark the code (+/− 1 frame) was always above 95%. Agreement on the object of regard was always above 90%.

RESULTS

We first describe general characteristics of task performance and then describe activity from a more sequential, time-based perspective. For this latter analysis, we present a framework for segmenting the behavioral stream and a detailed example of typical expert performance. We then present group data for experts and novices that describe the correspondences between eye movements and task actions during each of the behavioral segments.

Performance Overview

The results reported in this section describe global characteristics of task behaviors and eye movements without reference to their moment-to-moment sequencing or interactions. For task behaviors, success at playing the game was expected to reflect expertise. Global measures of eye-movement behavior, such as the percentage of time spent looking at various locations, provided an index for determining how players generally distributed their visual attention. We expected fewer differences in these global indexes of eye movements than in measures that reflected the spatiotemporal interactions between eye movements and task actions. These latter measures, reported in later sections, were expected to better reflect characteristics of the perception-action cycle.

Each subject performed 20 trials, four at each of the five levels of clutter (1, 4, 7, 10, and 13 asteroids). Performance variables were obtained for each trial and then averaged within level of clutter so that there was a single score for each clutter level. We examined performance with mixed analyses of variance with expertise as a between-subjects factor and amount of clutter as a within-subject factor. Since the effects due to clutter were few and not the primary focus of the study, we report these effects only in a few cases.

Task Performance

As would be expected, the experts performed better than the novices. Experts successfully shot more asteroids ($M = 5.9$, $SD = 0.6$) than novices ($M = 2.6$, $SD = 0.8$), $F(1,11) = 61.5$, $p < .001$, although both groups obtained more hits as the amount of clutter increased, $F(4,8) = 56.7$, $p < .001$. A significant interaction between expertise and clutter, $F(4,8) = 8.5$, $p < .01$, indicated that experts were better able than novices to obtain more hits with increasing clutter. Part of the reason experts got more hits was that they fired more shots, $F(1,11) = 26.1$, $p < .001$. On average, experts fired 11.3 shots per 20-s trial while novices fired 7.6. Experts were also more accurate in their shooting: the percentage of shots that successfully intercepted a target was higher for experts ($M = 51$, $SD = 5$) than novices ($M = 33$, $SD = 8$), $F(1,11) = 26.6$, $p < .001$. As would be expected from their superior shooting, experts also had fewer ship-asteroid interceptions per trial ($M = 0.10$, $SD = 0.05$) than did novices ($M = 0.41$ $SD = 0.26$), $F(1,11) = 7.2$, $p < .05$.

The turn buttons allowed subjects to reorient their ship before shooting, and experts tended to use the buttons more frequently than novices (Ms = 17.2 and 14.4; SDs = 1.8 and 2.9, respectively), $F(1,11) = 4.0$, $p = .07$, but they pressed the buttons for somewhat shorter durations (in milliseconds: Ms = 180 versus 235; SDs = 27.1 and 28.0, respectively), $F(1,11) = 11.6$, $p < .01$. Experts and novices did not differ, however, in the average number of turns per shot (overall $M = 1.8$, $SD = 0.6$). Thus, experts turned more frequently because they fired more shots, but both experts and novices made the same number of ship orientation adjustments per shot.

To summarize, experts performed more quickly and more accurately than the novices, although the novices were reasonably successful at obtaining hits and avoiding ship deaths.

Eye Movements

In contrast to task performance, there were very few global differences between experts and novices in where they looked or in how long they looked at various locations. To examine how performers distributed their looking across various possible locations, we collapsed the coded eye movements into the following six categories:

- Fixate on ship: fixation with 2° of visual angle of ship.
- Track target: smooth pursuit of upcoming target.
- Track nontarget: smooth pursuit of nontarget moving asteroid(s).
- Fixate between ship and target: fixate on a blank area of the screen that is near halfway between the ship and the target.
- Fixate between ship and nontarget: fixate on a blank area of the screen between ship and asteroid(s).
- Fixate other: fixate on areas of the screen not covered in the other categories, such as watching the moving shot or the brief animated explosion sequence when an asteroid is hit.

For each trial, we summed the frequencies and durations of fixations and tracking for each category. We present the findings averaged across clutter condition, since there were only a few minor differences related to clutter.

Overall, subjects spent the most time (duration) tracking targets (41%) and fixating on the ship (33%). Interestingly, subjects sometimes looked at a location between the ship and target (9%), perhaps to minimize both objects' distance from central vision. Nontarget asteroids were not looked at as long as the targets (track nontarget = 8%, fixate between nontarget and ship = 3%). The duration of looks at other locations summed to 5%. As shown in Table 4.1, the frequency and average duration of looks at the various locations were almost identical in experts and novices.

The preceding analyses show that experts were indeed better players, in terms of accuracy of shooting, number of shots fired, and avoiding asteroid-ship interceptions. Players were not so different, however, in the general characteristics of their eye movements. Both groups tended to look most often at the ship or the moving target. This global analysis of performance does not inform us, however, about the correspondence between eye movements and task actions.

Segmenting the Flow of Perception and Action

Subjects' actions were not constrained during each trial and consisted of a continuous stream of eye movements and task actions. To examine

TABLE 4.1 Averages for Looking Measures for Experts and Novices

	Looking Locations											
	Fixations								Visual tracking			
	Ship		Between ship and target		Between ship and nontarget		Other		Target		Non-target	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Frequency												
Expert	10.6	2.3	4.8	1.7	1.3	0.6	5.8[a]	0.7	12.7[a]	2.4	3.1	0.5
Notice	10.2	1.5	3.4	0.9	2.1	0.9	3.3	0.8	9.2	1.3	4.6	1.7
Duration (ms)												
Expert	645	91	442[b]	65	365	117	256	46	731	77	377	46
Novice	555	142	343	50	302	54	210	39	671	78	388	62

Note. Numbers represent averages across 20 trials.
[a]Expert/novice difference, $p < .01$.
[b]Expert/novice difference, $p < .05$.

naturally occurring correspondences between eye movements and task actions, we developed a means for segmenting the stream of behavior so that common points of action could be compared within and between subjects. A simple task analysis of the video game suggested three basic components or subgoals of performance. The first component was *selecting a target.* In the multiple-asteroid trials there were 4 to 13 potential targets on the screen. Before releasing a shot, the players needed to determine which asteroid would be the next target. As described below, players routinely made an eye movement to the target before acting on it, in terms of turning the ship toward the target or shooting at it. The next component was *reorienting and aiming.* Before shooting, players typically reoriented the ship, presumably to position the angle of the upcoming shot's trajectory to intercept the selected target. The final component was *timing the interception.* After reorienting the ship, there was typically some time lag before the shot was released. The timing had to be precise, often within tens of milliseconds, to obtain a hit. At some point after the shot was released (or perhaps before), the player would cycle back to the first component—selecting a target.

As described previously, our computer setup allows us to replay performance in slow motion with a crosshair indicating the position of the player's changing visual regard. When viewing such a replay, the observer immediately gets a sense of these sequenced action components, as well as how the shifting of visual regard corresponds to the player's unfolding action goals. We briefly describe an example of such a replay to convey a sense of the flow of action.

Figure 4.3 presents a sequence of still-frame samples of a 1,900 ms

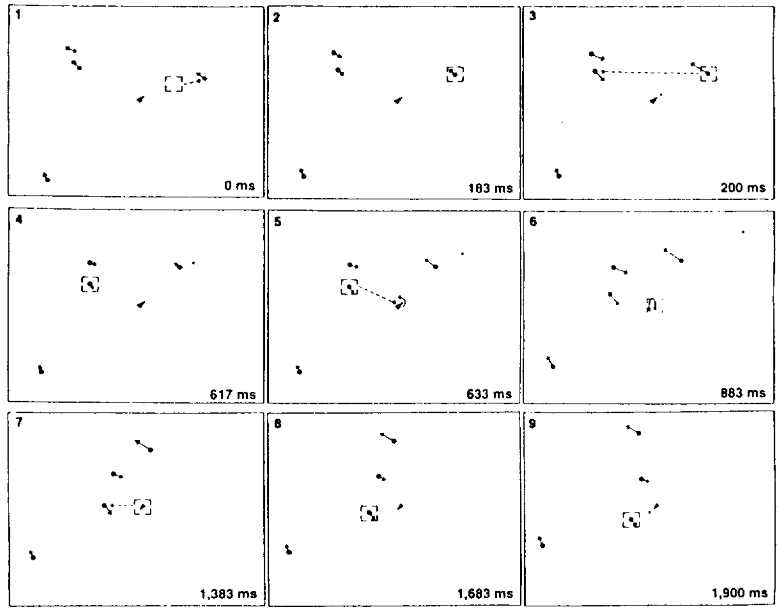

Figure 4.3 A sequence of still-frame samples of a 1,900 ms excerpt of an expert performance. Each panel represents a snapshot in time when some aspect of performance changed: the person either used one of the buttons or made an eye movement to a new object of regard. Shown are the positions of the asteroids (dots) and the shot (small dot), the orientation of the ship (triangle), and the position of foveal regard (box). The lines and arrows on each of the objects indicate the position of the object in the *next* panel. Panel number and elapsed time (beginning from the first panel) are shown in the upper left and lower right corners, respectively. See the text for a description of the sequence of events.

excerpt of expert performance. The excerpt represents nothing remarkable or unusual; it is typical of good performance. Each panel represents a snapshot in time when some aspect of performance changed; the person either used one of the buttons or made an eye movement to a new object of regard. Shown are the positions of the asteroids (dots) and the shot (small dot), the orientation of the ship (triangle), and the position of foveal regard (dotted box). The lines and arrows on each of the objects indicate the position of the object in the *next* panel. Panel number and time elapsed (beginning from the first panel) are shown in the upper left and bottom right corners, respectively.

The panels show the player shooting twice. In panel 1, the player had already reoriented the ship and was fixating on the blank area between the ship and the target. In panel 2, 183 ms later, the player made an eye movement to the target and tracked its movement. Shortly thereafter (17 ms, panel 3), the player fired the shot (as indicated by the dot above the ship). Notice that the shot was fired *before* the target reached its intercept point, although the shot was still too late for an interception. Less than half a second later (417 ms, panel 4) the player made an eye movement to another asteroid on the other side of the screen, which became the next target. Two points are worth noting. First, the player did not foveally examine several asteroids before selecting the next target. The selection must have been made peripherally, since the player had not viewed the new target foveally. Second, the selection occurred quickly—the eye movement to the new target began after the shot passed the intercept line of the old target but before the shot traversed the rest of the screen. Given that it takes some time to program an eye movement, the selection had to occur even earlier. In this case it most likely occurred before the shot reached the intercept line. Shortly after the eye movement to the new target (16 ms, panel 5), the player pressed the left turn button, which started the ship's rotation toward the new target. Notice that during the initiation of the turn, the subject was foveating on the target, not the ship. But 250 ms later (panel 6), the player made a saccade to the ship while the turn was in progress. The turn continued for another 500 ms (panel 7), and 300 ms after the turn was completed, the player made a saccade back to the moving target (panel 8). As decribed below, this pattern was very common—players determined turning direction without the benefit of foveal examination of the ship, but they almost always shifted to examining the ship during the turn and for several hundred milliseconds after the turn was completed before saccading back to the target. The pattern suggests that looking at the ship is not necessary for deciding which direction to turn it but is important for determining when to stop the turn and for encoding the ship's new orientation. Returning to the example, the player released the shot 217 ms after returning to tracking the target (panel 9).

This example scenario exemplifies the kind of correspondence we found between eye movements and task actions. Performers moved their eyes to gather visual information that was important for organizing upcoming action. The following analyses cover the entire data set and were aimed at examining the generality of the patterns just described and exploring the similarities and differences between the two expertise groups. For these later analyses, we were interested in comparing the patterns of correspondences as well as the relative consistency in the couplings between eye movements and task actions.

In the following analyses the shot was the unit of analysis. Each shot defined an *episode* that covered the period extending from the firing of the previous shot to the firing of the current shot. In several of these analyses we excluded the one-asteroid trials. Medians were calculated for all time and distance variables within each trial and were then averaged for each clutter condition. Times are reported in milliseconds. In instances where we were interested in the degree of variability in the timing between eye-movement onsets and task events, we calculated standard deviations for each trial and then averaged the deviations within each clutter condition. Most of the analyses consist of mixed ANOVAs, with expertise group as a between-subjects factor and degree of clutter as a within-subject factor, although we report clutter effects in only a few cases. The findings are presented in order of the three subgoals of action: selecting a target, reorienting the ship, and timing the interception.

Target Selection

The coding system differentiated between looking at targets and looking at nontargets. This was a relatively simple, highly reliable judgment because subjects tended to foveally examine only one or two potential targets in an episode. All subjects tended to visually track at least one asteroid in over 90% of the episodes (experts: $M = 96\%$, $SD = 4$; novices: $M = 93\%$, $SD = 2$, n.s.). In these episodes, where the target was identified, we calculated the number of asteroids that were considered foveally (tracking an asteroid) or close to the fovea (fixating between an asteroid and the ship). Both groups of subjects rarely looked at more than two potential targets, although experts looked at significantly fewer ($M = 1.2$, $SD = 0.06$) than novices ($M = 1.6$, $SD = 0.34$), $F(1,11) = 5.1$, $p < .05$. Remarkably, the number of potential targets looked at did not increase with increasing clutter (4 to 13 asteroids), $p > .3$. One could argue that performers looked at so few asteroids because they were pursuing the same target across several episodes. In fact, however, both groups chose the last episode's missed target on only 15% of the episodes. When these episodes were removed from the analyses, the pattern of results did not change.

The preceding analyses suggest that players limited their foveal examination to only a few asteroids before deciding which one would be the actual target. It appeared that deciding which asteroid to choose was based on visual information obtained outside the fovea. We examined the first eye movement to the target in cases where the target was not the same as in the previous episode. The average visual angle between the point of regard immediately before the eye movement and the target was 7.6° ($SD = 0.9°$), well outside the foveal region. This distance did not differ as a function of expertise.

The first saccade to the new target also occurred relatively quickly after the previous shot was fired, and experts were faster than novices (experts: $M = 714$, $SD = 148$; novices: $M = 1247$, $SD = 397$), $F(1,11) = 9.5$, $p < .05$). The time between the previous shot and the first look to the target was also more variable in novices than in experts (mean trial standard deviations, novices: $M = 1445$, $SD = 445$, experts: $M = 683$, $SD = 94$, $F(1,11) = 16.5$, $p < .005$.

It did not appear that the choice of target was random or haphazard for either group of subjects, and our impressions from observing many replays was that the choices were in fact good ones—players seemed to choose targets that were most likely to intercept or come close to the ship. Such targets not only were more dangerous but were often easiest to hit. A comparative analysis of all the asteroids on the screen immediately before the first look to the target showed that players looked at the asteroid closest to the ship in 50% of the episodes ($SD = 8\%$). Players also seemed to take direction of movement into account: when the asteroid closest to the ship was moving toward the ship, it was chosen 64% of the time ($SD = 8\%$), but when it was moving away it was chosen only 17% of the time ($SD = 9\%$). These selection percentages did not differ between the two groups.

To summarize, players did not foveally examine several possible targets among the many moving asteroids. Instead, they visually identified one or two possibilities soon after shooting at the previous target. The target selection was most often made from information gained in the periphery and seemed to reflect good choices. Compared with the novices, the experts foveally considered fewer alternatives, shifted visual regard to the target more quickly, and were less variable in the timing between the previous shot press and initial saccade to the new target.

Reorienting and Aiming

The first look to the new target occurred before shooting at the target and was the first straightforward behavioral indication that the player had started preparing for the next hoped-for interception. The time between the first look and the eventual shot was often used for repositioning the ship and presumably for obtaining visual information about the target's trajectory, velocity, and position for timing the release of the shot (see below). The median time lag between the first look to the target and the shot was shorter for experts ($M = 989$ ms, $SD = 178$) than for novices ($M = 1560$ ms, $SD = 579$), $F(1,11) = 5.3$, $p < .05$, and it decreased with increasing amounts of clutter, $F(3,9) = 4.3$, $p < .05$. Experts were also less variable in the time lag between the first look and the shot; the averaged within-trial standard deviations of this lag were 539 ms ($SD = 28$) and 821 ms ($SD = 62$) for experts and novices, respectively, $F(1,11) = 59.4$, $p < .001$.

As would be expected, experts were more effective at turning the ship to increase the likelihood of an interception. A straightforward measure of turning effectiveness is whether a possible intercept existed before the first turn and after the last. Intercepts did not exist for a given orientation when the target would not cross the intercept line, such as when the asteroid had already passed the ship. The percentage of such "impossible" targets before the first turn was high and did not differ between the groups (experts: $M = 54$, $SD = 6$; novices: $M = 56$, $SD = 8$), $p > .5$. After the last turn, the percentage of impossible targets was low, and experts had a significantly lower percentage ($M = 3$, $SD = 2$) than novices ($M = 10$, $SD = 3$), $F(1,11) = 13.7$, $p < .005$.

Turning the ship appropriately for an interception required taking into account characteristics of the target, such as its trajectory, velocity, and distance from the ship; thus, visually tracking the target provided important information for determining an appropriate ship orientation. Foveating on the ship, however, was also important for preparing for an eventual interception, since looking at the ship provided information on the direction it was pointing, which was especially important when turning. The timing of when to stop turning needed to be precise, since pressing the turn button for even a short duration had a large effect: a 200 ms press changed the ship's orientation by 50°. Thus both ship and target provided important information for calibrating action, and these locations could often not be examined foveally at the same time. Players shifted their gaze, on average, 1.7 times during an episode ($SD = 0.87$). Shifting of visual regard between ship and target would presumably increase when both locations could not be placed at or near the foveal region, that is, when the distance between the objects increased. To examine whether this was indeed the case, we divided episodes into two groups using a median split of target-asteroid distances early in the episode (the median distance was 7.3° of visual angle, which did not differ between groups, $p > .3$). Those episodes with targets farther from the ship averaged 2.0 shifts ($SD = 0.9$), while those with closer targets averaged 1.0 shifts ($SD = 0.7$), $F(1,11) = 87.6$, $p < .001$. This effect did not interact with expertise.

When subjects did turn the ship before shooting, they tended to make an eye movement to the ship sometime during the turn, although this tendency varied somewhat depending on the context, such as the degree of clutter, the distance from the target, and the extent of the turn. Subjects looked at the ship on 76% of the turns ($SD = 9$). This percentage did not differ as a function of expertise, $p > .2$, but it did decrease linearly with increasing clutter, from 89% of the turns ($SD = 9$) with 1 asteroid, to 68% of the turns ($SD = 14$) with 13 asteroids, $F(1,11) = 23.3$, $p < .005$. Shifting of visual regard between ship and target would presumably increase when both locations could not be placed at or near the foveal region, that is, when the distance between the objects increased. A comparison of the turns at which subjects did and did not look at the ship showed that turns including an eye movement to the ship involved targets that were significantly farther from the ship (*Ms* = 8.2° versus 6.1°, *SDs* = 0.5 and 0.7), $F(1,11) = 160.4$, $p < .001$. Turns that incorporated an eye movement to the ship were also significantly larger (*Ms* = 74° versus 57°, *SDs* = 13 and 14), $F(1,11) = 33.3$, $p < .001$. Thus, subjects most often looked at the ship sometime during a turn, and looking was more likely with fewer asteroids on the screen, when the ship and the target were farther apart, and when the player was making larger turns.

When subjects did look at the ship during a turn, the saccade to the ship occurred close to the start of the turn, while the eye movement away from the ship usually occurred well after the turn was completed. On average, saccades started 92 ms ($SD = 87$) before the turn began; in 44% of these cases the fixation began after the turn had started. This timing suggests that subjects usually decided which direction to turn the ship when not foveally examining the ship's orientation. There were no differences in this timing across groups. Eye movements away from the ship began after the completion of the turn in 92% ($SD = 3$) of the cases. The lag between the end of the turn and the look away from the ship was remarkably long in both groups, although the lag was shorter for experts than for novices (*Ms* = 422 versus 565 ms, *SDs* = 128 and 99), $F(1,11) = 5.1$, $p < .05$. The long lag suggests that subjects almost always watched the end of the turn and continued to foveate on the ship to encode the new orientation before shifting visual regard back to the target.

Experts were less variable in the timings between looking and turning. The average trial standard deviation for the timing between the saccade to the ship and the start of the turn was greater in novices ($M = 528$ ms, $SD = 110$) than in experts ($M = 395$ ms, $SD = 71$), $F(1,11) = p$ $< .05$. Similarly, the average trial standard deviation for the timing between the end of the turn and the look away from the ship was greater in novices ($M = 535$ ms, $SD = 96$) than in experts ($M = 397$ ms, $SD = 100$), $F(1,11) = 6.2$, $p < .05$.

To summarize, between the first look to the target and the eventual shot, players most often reoriented the ship. Both the ship and the target provided important information for determining the final orientation, and players shifted visual regard between the two locations. Changes in looking location seemed to occur when updated information was needed most: shifts from target to ship were most likely when the target and ship were far apart and farther out of alignment. Saccades to the ship occurred near the beginning of the turn, but saccades away occurred well after the completion of the turn, suggesting that foveal information was not needed for initiating the turn but was used for monitoring changes in orientation and updating information on the postrotated position. Overall, experts were faster and less variable in the timings between shifting visual regard and task actions.

Timing the Interception

After the last turn players needed to determine the best time to release the shot. As in the example scenario described earlier, shots usually needed to be fired before the target reached the intercept line, since it took time for the shot to reach the intercept (the shot traveled at 1.4° of visual angle per 100 ms). In many cases firing when the target was at the intercept would be too late, since the target would have passed the intercept point by the time the shot arrived. The best time to release the shot varied as a function of the target's velocity and trajectory (which determined the time for the target to reach the intercept) and the distance between the intercept and the ship (which determined the time for the shot to reach the intercept).

The time lag between the last turn and the fire button press varied from 0 to 4702 ms. Experts generally pressed the fire button earlier ($M = 551$, $SD = 122$) than did novices ($M = 827$, $SD = 158$), $F(1,11) = 12$, $p < .005$, and were also significantly less variable in this timing ($M = 363$, $SD = 51$) than were novices ($M = 512$, $SD = 115$), $F(1,11) = 7.8$, $p < .05$. Determining the right moment to release the shot required precise trajectory and velocity information about the target, and performers' visual regard immediately before shooting suggests that the moving target provided the most relevant immediate data for timing the interception. Both groups of players tended to visually track the target immediately before pressing the fire button, although experts did so significantly more often than novices (Ms = 86% versus 71%, SDs = 5 and 6), $F(1,11) = 14.2$, $p < .005$. There was also evidence for a functional relation between looking at the target before shooting and the likelihood of a successful hit. When tracking the target before shooting, players were almost twice as likely to hit the target ($M = 0.40$, $SD = 0.14$) as when looking elsewhere on the screen before shooting ($M = 0.22$, $SD = 0.11$), $F(1,11) = 50.6$, $p < .001$, and this relation did not differ between groups.

We also examined the timing characteristics of missed shots. For each target, we calculated the best time to release the shot given the ship's orientation before shooting. Misses by experts were closer to a hit (M = 531 ms off, $SD = 90$) than were the misses of novices (M = 760 ms off, $SD = 153$), $F(1,11) = 10.6$, $p < .05$. Missed shots by novices tended to be late rather than early. The average percentage of late misses was 68% (SD = 7) for novices, but 47% (SD = 9) for experts, $F(1,11) = 19.3$, $p < .005$. Experts were also less variable in the timing of their misses (mean of trial standard deviations = 594 ms, SD = 110) than novices (M = 767 ms, SD = 84), $F(1,11) = 9.2$, $p < .05$.

To summarize, determining the best time to fire the shot required information about the target's trajectory and velocity, and subjects tended to track targets visually before shooting. Tracking the target was related to increased probability of a hit, and experts tracked the target more often than novices. Novices also tended to fire too late, so that when the shot reached the intercept, the target had already passed. Experts' misses were almost equally divided between being late and early. As in other aspects of performance, experts were less variable in the timings between actions.

DISCUSSION

The findings suggest that the patterning of eye movements during performance was well integrated with ongoing action. The timing of shifts in visual regard in relation to the subjects' actions and events on the game screen was well coordinated, even in the less skilled players. The probabilities of shifting visual regard at particular points in the sequence of action and the relatively low variability in the timings between looking and acting reflected relatively stable looking-acting correspondences. These coordinations were not, however, as tightly synchronized as is typically found in reaching and pointing studies (e.g., Biguer et al., 1982; Carnahan & Marteniuk, 1991). In less constrained settings, such as the one examined here, eye movement and other action systems may be more flexibly coordinated by adapting to variations in context and the goals of action.

Obtaining visual information via eye movements also seemed remarkably efficient. For example, players did not foveate on more than one or two potential targets, even when there were many possibilities. Players used peripheral information to make the selection and usually made a saccade to the new target less than a second after the previous target was shot. In many such cases, the peripheral selection must have occurred before the previous shot reached its target.

Another example of the efficiency of visual selection was shifting between looking at the target and looking at the ship when setting up for the next shot. There was an implicit competition between looking at the two locations. The target provided critical time-varying information for organizing action to obtain an intercept, but the ship usually needed to be turned, and the player needed to precisely gauge the ship's new orientation to accurately time the release of the shot. Most of the time players tracked the target, but when a turn began they usually shifted to looking at the ship, especially in cases where foveal information was particularly needed (when the ship was farther from target and when the new orientation was significantly different from the old one). Deciding which direction to turn the ship did not require detailed foveal information on the ship's orientation, so players usually shifted visual regard to the ship about the beginning of the turn; they did not waste time looking at the ship before the turn. Alternatively, players needed to determine the ship's new orientation accurately to obtain a hit; a miscalculation of just a few degrees could misplace the intended intercept point by several centimeters. Yet if players returned to tracking the target before releasing the shot (which they usually did), they could determine the ship's orientation only from peripheral vision or from memory. Our guess is that memory was important, since peripheral vision often would not provide detailed enough spatial information to determine the orientation within several degrees. These ideas are consistent with player performance: players almost always continued to foveate on the ship for several hundred milliseconds after the turn was completed before making a saccade back to the target. In the context of the game, several hundred milliseconds was a long time to stare at the only stationary object on the screen, but that amount of time would be required if one wanted to encode the ship's new orientation into memory.

These examples illustrate the fact that perceptual selection was efficient and well organized for regulating action. Knowing something about what the subject was doing was very instructive in determining where the subject would be looking and when shifts in foveal regard were likely to take place. In the context of the perception-action cycle discussed in the chapter opening, the findings suggest that visual information gathering was used to regulate ongoing action and, most significantly for the present purposes, to *prepare for upcoming action*. Almost every shift in looking location can be viewed as future oriented: one selects a new target to determine a new ship orientation, one looks at the start of the turn to determine when to stop the turn, one looks at the ship after the turn to acquire information that will be used later to time the shot release, one tracks the target to determine when to release the shot, and one continues to track the target after the shot is released to see if it will hit the target.

Perceptual information was used in preparing for future action, but action was also based on anticipated future states, determined from current visual information and from task knowledge. For example, the ideal time to release the shot most often was before the target reached the intercept point. In such cases the shot would be released based on some estimate of when the target would reach the intercept, which would be the same time it should take the shot to reach the intercept. The time for the target to reach the intercept involved examining the velocity, trajectory, and current position of the asteroid. Determining the time it would take to take the shot to reach the intercept entailed combining the perceived distance between the ship and the intercept with one's knowledge of the shot speed. Anticipating future states was also involved in determining the new orientation of the ship when setting up for a new target. There was usually a time lag of several hundred milliseconds between the end of the last turn and the firing of the shot. Players positioned the ship in an orientation that provided enough time to encode the ship's final orientation, saccade back to the target, and track the target. Thus players needed to determine how far ahead to turn the ship based on the target's velocity, trajectory, and current position as well as some determination of the amount of lead time required for "setting up" for the interception.

The ability to use visual information to anticipate upcoming events and plan action accordingly was undoubtedly important in allowing action to be both flexible and precise. Players adapted to the particulars of each episode by quickly and efficiently repositioning their foveae to obtain the relevant information for organizing action. Precision was possible when players organized their actions appropriately to an accurate appraisal of the near future. Yet players did not always perform effectively, and the novices were clearly less effective than the experts. Our findings suggest several hypotheses about what is acquired with increasing levels of expertise.

Experts and novices did not differ in many of the general characteristics of eye movements; they were also quite similar in how task actions corresponded to eye movements. (Although as described in the methods section, these groups were not as disparate in skill level as would be expected with genuine experts and novices.) For example, despite some group differences, novices were surprisingly good at using peripheral vision to select the next best target and at efficiently moving visual regard to and from the ship during turning. Given that our task was fairly novel for those who were not video game players, these findings suggest that the novices employed well-developed perceptual skills that could quickly be adapted to the particulars of the game.

Although general perceptual processes did not appear to differ across the groups, there were aspects of performance that were consistently different. Experts were faster than novices in almost every respect: they took less time to find a new target, to orient the ship, to move visually between ship and target, and to time the interception. Experts' actions were also better tuned to the task environment: their shots were more accurately timed, and their turning was more effective in setting up for the next target. Novices' actions were often too late. In shooting, novices tended to release the shot when the target had already moved too close to the intercept. We also noticed that subjects often pushed the turn button too long and consequently turned the ship too far. This would occur if players did not take into account their own reaction time in determining when to stop pressing the button. Perhaps the most salient expert/novice difference was the within-subject variability in the timing between eye movements and task actions. Almost every measure of the variability in the time lag between an action and the initiation of an associated eye movement was significantly higher in novices.

Taken as a whole, the pattern of expert/novice differences in behavior suggests several important differences in cognitive and perceptual processing. First, novices have greater difficulty using current perceptual information to determine future states, such as where a particular target will be at some future time. This difficulty often results in action that is based relatively more in the present time frame—that is more reactive to current conditions. In such cases action will be late. Second, novices are also less knowledgeable about the properties of their "tools" for action, such as the rotation rate of the turn button and the velocity of the shot. Increased uncertainty about how to use current information for planning upcoming action and about the properties of one's tools for action would contribute to increased variability in performance. Such variability may be an essential part of eventually determining appropriate mappings between action, perception, and context (Freedland & Bertenthal, 1994; Siegler, 1989). With practice, however, uncertainty and variability are reduced and perception-action components become increasingly "automatic." Automatized components should reduce the degrees of freedom that require explicit control and increase overall speed.

Our findings, when examined along with related research, suggest a more speculative set of hypotheses about future-oriented processing and the acquisition of complex perception-action skills. Novices are not as adept as experts at using current contextual information to determine future states and organize upcoming action appropriately, and consequently they appear less future oriented. Yet less experienced performers might actually commit *more* cognitive resources to future-oriented processes, such as in planning action or determining what will happen next. As one develops expertise, the future gets built in to increasingly automated perception-action modules (cf. Bryan & Harter, 1899). During skill acquisition, the performer learns the implications of specific perceptual information for upcoming action and develops perception-action modules that embody those regularities. As the modules become well developed, performers can quickly adapt to new situations, since they have a repertoire of well worked out components that can be rapidly chosen and implemented. Thus experts do not need to plan far into the future (cf. Simon, 1981) and may spend fewer resources on "scenario spinning" (Calvin, 1990) than novices. Returning to the example discussed at the outset, when novices learn to ski moguls, instructors often teach them to plan four or five turns ahead. Yet the goal of the training is to ski like experts, who can adapt very quickly to the particulars of the slope and rarely look more than two turns ahead (Tejada-Flores, 1986). Thus we are suggesting that expert action is better adapted to the future, but that experts may allocate fewer resources to future-oriented processes than novices do. Novices are not as successful at taking the future into account and, at least at particular points in learning, will devote a great deal of effort to trying to predict future states and plan accordingly.

Two other studies of video game performance (using different tasks) support this view. In one study, Logie, Baddeley, Mane, and Donchin (1989) examined the role of working memory in the performances of more or less skilled players. Working memory is seen as a limited resource for holding transient information on line and performing simple computations, and it is viewed as essential for future-oriented behavior in general and short-term planning in particular (Baddeley, 1986; Goldman-Rakic, 1987; Pennington, this volume; Roberts, Hager, & Heron, in press). Logie et al. (1989) found that the performance of less skilled players was disrupted more by secondary working-memory tasks than the performance of more skilled players. It is worth noting that not all interference tasks showed this pattern; for example, a motor-timing task was more interfering for more experienced players than for less experienced ones. The findings suggest that working memory, which may be essential for future-oriented processes, is more heavily utilized at lower levels of skill. In another study, Haier et al. (1992) found that more skilled players showed less overall cerebral activity (measured by PET) while playing a video game than did novices. Taken together, these studies give some support for the somewhat paradoxical idea that as they acquire skill performers commit fewer resources to future-oriented processing but are nevertheless better able to adapt to the future.

From a neuropsychological perspective, the prefrontal cortex, which is viewed as essential for working memory and future-oriented processes (Goldman-Rakic, 1987; Weinberger, Berman, Gold, & Goldberg, this volume), may initially be more involved during learning than at higher skill levels. Acquiring a new skill, such as playing a video game, is a problem-solving exercise that requires learning new relations and integrating perceptual, motor, and strategic components. This sort of deliberate problem solving in novel contexts has traditionally been associated with frontal functions (for reviews, see Fuster, 1989; Shallice, 1988).

With increasing automatization, however, other motor areas, such as the basal ganglia or the cerebellum, may assume increasing control over larger units of automated behavior. Further research will be required to elaborate the changes in processing that occur during the learning of complex perception-action skills.

CONCLUSION

The relatively unconstrained flow of skilled activity in the work reported here reveals a remarkably intricate interweaving between the past, the present, and the future. Performers are continually gathering visual information for determining the outcomes of past acts, for monitoring the progress of ongoing acts, for determining what will happen next, and for planning and calibrating upcoming action. At the same time, the performer is producing a stream of activity that is based on the continual flow of perceptual information. All of this occurs quickly and, at least in the expert, relatively effortlessly. This chapter provides a descriptive window into how perceptual selection, via eye movements, is used to adapt flexibly and precisely to a changing and indeterminate context.

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Prefrontal Cognitive Processes: Working Memory and Inhibition in the Antisaccade Task

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Recent research suggests 2 principal processes are assessed in many neuropsychological tests of prefrontal functioning: the ability to keep transient information on-line (working memory) and the ability to inhibit prepotent, but incorrect, responses. The current studies examined the hypothesis that taxing working memory beyond some threshold can result in decreased inhibition, resembling the errors committed by patients with prefrontal dysfunctions. Across 3 studies, 70 nonpatient subjects were tested on the antisaccade (AS) task (D. Guitton, H. A. Buchtel, & R. M. Douglas, 1985)—a task sensitive to inhibitory deficits. Subjects were required to look in the opposite direction of a flashed cue, inhibiting the reflexive tendency to saccade to the cue. Subjects performed concurrent tasks that varied working-memory load. The results indicated that conditions with the highest working-memory load produced inhibitory errors comparable to patients with prefrontal dysfunctions. The findings are discussed in terms of the interaction between working memory and the inhibition of prepotent responses.

For at least 20 years the prefrontal cortex has been thought to be important for a variety of cognitive functions, including planning, impulse control, and attention. The prefrontal cortex also is thought to provide integrative functions for higher cognition, integrations that occur across space and time as well as across component cognitive and perceptual processes (for reviews see Fuster, 1989; Levin, Eisenberg, & Benton, 1991). Recent research with human and infra-human subjects has suggested two principal prefrontal functions: a) the preservation of transient information across short time intervals for organizing upcoming action, often referred to as *working memory,* and b) the inhibition of prepotent but inappropriate responses. Although there is increasing consensus on the centrality of these processes, little is known about whether and how such processes *interact* in the generation of behavior.

The present work is motivated by recent theories and computational models that attempt to provide unified accounts of prefrontal functioning (Cohen & Servan-Schreiber, 1992; Dehaene & Changeux, 1991; Diamond, 1990; Fuster, 1989; Goldman-Rakic, 1987; Kimberg & Farah, 1993; Levine & Prueitt, 1989; Norman & Shallice, 1986). Such models suggest two important ideas that are explored here. First, working memory and the ability to inhibit prepotent responses are intimately related, and a deficient working memory system can increase the difficulty of resisting prepotent actions. Second, there is more of a continuum between normal and abnormal functioning than is often portrayed in the literature, so that many everyday action errors result from a similar process that produces the behavioral "breakdowns" seen in patients with known frontal dysfunctions. To explore these ideas empirically, we examined nonpatient subjects on a task that is sensitive to prefrontal dysfunction—the antisaccade task—in conditions that made varying demands on working memory. The studies allowed us to examine how working memory relates to successful inhibition and whether normal subjects resemble frontally impaired patients under specific high-load conditions. Before describing these studies, we first provide more detail on the framework for characterizing prefrontal cognitive processes from which we are working.

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Commonalties Across Tasks that Assess Prefrontal Functioning

The most common analytic technique to assess prefrontal functioning has been to study prefrontal dysfunctioning—breakdowns that occur when some part of the prefrontal cortex is disabled, such as by lesion, disease, or accident. The functions of the prefrontal cortex are inferred from the processes that seem to be changed or missing in the dysfunctioning group as compared with some control. Although there are some difficulties with this analytic strategy (Farah, 1994; Shallice, 1988), it has proved highly successful in documenting a range of behavioral changes associated with frontal insults (for reviews, see Fuster, 1989; Shallice, 1988). In addition, the conclusions about structure–function relations have generally been corroborated and extended by approaches that assess on-line neural processing, such as single-cell recording, evoked potentials, and positron-emission tomography (PET) scanning (for a review, see Fuster, 1989).

Both kinds of studies use a variety of tasks that appear sensitive to prefrontal functioning, including the Wisconsin Card Sort Task (Milner, 1963), the antisaccade task (Guitton, Buchtel, & Douglas, 1985), the Tower of Hanoi Task (Shallice, 1982), the continuous performance task (Cohen & Servan-Schreiber, 1992), the Stroop Task (Perret, 1974), and prospective-memory tasks (Shimamura, Janowsky, & Squire, 1991). Studies with nonhuman primates have used delayed-response tasks, the A-Not-B task, and visual-search tasks (Diamond & Goldman-Rakic, 1989; Funahashi, Bruce, & Goldman-Rakic, 1990; Fuster, 1991). These and other prefrontally sensitive tasks vary in many of their surface-level characteristics and the relevant behavioral indicators of performance. Such differences have contributed to the wide range of hypothesized prefrontal functions, which are often grouped together into the global category of "executive functions."

Despite the differences across prefrontally sensitive tasks, a remarkable variety of them fit a common structure: They place a subject in a context in which a prepotent response tendency is directly opposed to the activity or activities that lead to correct responding. The prepotent tendency is either built-in or is acquired during an experimental session. To perform correctly, a subject must maintain some information over a short time interval, refrain from performing the habitual or prepotent action, and carry out an alternative action. "Prefrontal" subjects readily fall victim to the prepotent tendency.

Thus, as shown in Table 1, a consistent feature of the prefrontal task is that it puts a prepotent tendency in competition with an alternative response. For example, in the Wisconsin Card Sort Task, subjects sort cards containing figures that vary in form, color, and number. The subject is reinforced consecutively for sorting by one category and is then given feedback indicating that the category is no longer correct. The prepotent tendency is to continue sorting by the previously correct category; the alternative response requires using the feedback to determine a new sorting category. In the antisaccade task, the subject is asked to look in the opposite direction of a peripherally flashed cue. There is a strong reflexive-like pull to look at peripherally flashed stimuli, yet correct responding requires looking in the opposite direction. In the Stroop Task, the subject must name the ink color of color words. The words are color names that are different from the ink colors (e.g., the word *red* is printed in green). The prepotent tendency is to read the word—a highly automatic skill for readers, yet the correct response is to ignore the written word and identify the color of the ink. In the A-Not-B task, a monkey or human infant searches for food (or a toy) in one of two covered wells. After the subject repeatedly finds the food in one location, it is visibly hidden in a new location. The prepotent tendency is to search where the food was found previously, the alternate response is to look in the new location. The delayed alternation task also involves searching for food in one of two covered wells, but in this case the food is always located in the well opposite of where the subject searched on the last trial. The prepotent response is to look where the food was searched for previously; the alternative response is to look in the other well.

Working Memory and Response Inhibition

This prepotent–alternative response analysis may help identify common processing dynamics across a wide range of prefrontal neuropsychological tests. It suggests two minimum requirements for successful responding. First, the subject must keep in mind information that is required to make a correct response and must use that information to guide action appropriately. In many cases, the information changes from trial to trial and must be maintained across a temporal gap (e.g., A-Not-B, Delayed Alternation). In other cases, the subject must maintain a rule or self-instruction that specifies how to act and then must apply the rule to the current circumstances on a particular trial (e.g., Stroop, antisaccade, Wisconsin Card Sort). Keeping transient information in mind and performing explicit computations to guide upcoming action is seen in the cognitive psychological literature as involving working memory (Baddeley, 1986; Carpenter & Just, 1989).

Working memory is assumed to involve both the temporary storage of task-relevant information and a "scratch pad" for on-line computations and their results (Baddeley, 1986; Case, Kurland, & Goldberg, 1982; Daneman &

Table 1
Prepotent Responses, Alternative Responses, and Working Memory Demands for Several Prefrontal Tasks

Task	Prepotent response	Alternative response	Working-memory demand
Wisconsin Card Sort	Sort by previously successful category	Sort by new category	Use feedback to determine possible correct category
Antisaccade	Saccade to flashed cue	Saccade in opposite direction of cue	Keep task instruction active, apply to current context
Stroop	Read the word	Say the ink color	Keep task instruction active, apply to current context
A-Not-B	Search where previously found	Search where hidden	Keep last seen location in mind over a delay
Delayed alternation	Search where previously searched	Search in location opposite to where previously searched	Keep last location reached in mind, apply "opposite" rule

Carpenter, 1980; Pennington, in press). It is assumed to have a limited capacity that is constrained by both the amount of information that can be held simultaneously and the length of time that information can be kept on-line. Unlike longer-term semantic, episodic, and procedural memory, working memory is both transient and of limited capacity, thus resembling the concept of short-term memory. However, the computational and prospective aspects of working memory distinguish it from traditional conceptualizations of short-term memory. Most significantly, working memory is used not only for holding information on line but also for using that information along with contextual specifics to generate upcoming action.

The other requirement of many prefrontal tasks is to avoid or inhibit carrying out a prepotent response. In some cases, the prepotency is high, such as in the Stroop or antisaccade tasks, and even control subjects have difficulty completely inhibiting the prepotency. In other tasks, such as the Delayed alternation or Wisconsin Card Sort, the prepotency is not as strong.

Although there is a growing consensus that prefrontal tasks assess some form of working memory and response inhibition, the relevant underlying processes still are not well understood. One important question concerns the relation between working memory and inhibition (cf. Diamond, 1990; Harnishfeger & Bjorklund, 1993; Hasher & Zacks, 1988). Each might involve separate processes that do not strongly interact. Prefrontal tasks may require that both processes operate effectively for success, although some tasks may pull more for one or the other process. Another possibility is that the ability to inhibit a prepotent response is dependent on, or at least intimately related to, working-memory processes. When working-memory processes are appropriately activated and maintained, then inhibition of other possible actions occurs by default. Stronger incorrect prepotencies require greater working-memory activations to avoid falling prey to the prepotency.

This latter hypothesis is consistent with several current models of performance on prefrontally sensitive tasks. For example, Cohen and Servan-Schreiber (1992) developed connectionist models of schizophrenic and normal performance on the Stroop and the continuous performance tasks. In these models, increasing the activation of units that represented information required for correct responding (working memory) inhibited units that represented prepotent stimulus–response associations, which decreased the probability of incorrect responding. Other connectionist models, by Dehaene and Changeux (1991) and Levine and Prueitt (1989) of the Wisconsin Card Sort task, although different in many respects, simulate an interaction between prepotency strength and the ability to use feedback to determine new sorting categories. Similarly, production-system models developed by Kimberg and Farah (1993) of several prefrontal tasks contain a response-competition dynamic, such that weakening of working-memory associations leads to increased prepotent responding.

From this perspective, task performance and the ability to successfully inhibit are a function of the strength of the prepotency, the current functioning of working-memory processes, and the working-memory demand of the task. Task difficulty can be increased either by increasing prepotency or by increasing working-memory demand (Cohen & Servan-Schreiber, 1992). For example, the antisaccade task involves a highly prepotent action (reflexive-like glance to a peripheral flash) and a relatively low working-memory demand (remember to look to the opposite side of the flash). Because of the strong prepotency, even a slight deficiency in working memory can result in reflexive responding. In contrast, the Wisconsin Card Sort involves a relatively low response prepotency (sort on the previously correct category) but a relatively high working-memory demand (use the feedback to infer which categories might be correct). Difficulties in determining the new category increase the likelihood of a default response, the previously correct category.

The hypothesis that increasing working-memory demand for the alternative response will decrease inhibition is implied in the models of prefrontal functioning but has rarely been examined empirically.[1] Most of the studies that have used prefrontal neuropsychological tasks have examined differences across populations of subjects but have not varied the processing demands of the tasks. One purpose of the present studies was to test the hypothesis that as working-memory load increases, the ability to inhibit prepotent responses decreases.

Computational models suggest various ways that working memory may become chronically dysfunctional in populations with known or suspected prefrontal abnormalities. For example, Cohen and Servan-Schreiber (1992) simulated reduced dopaminergic tone in the prefrontal cortex—a suspected dysfunction in schizophrenia—by lowering a gain parameter of the activation function of working memory units. Kimberg and Farah (1993) weakened the associations among items in working memory. Dehaene and Changeux (1991) and Levine and Prueitt (1989) modified parameters that decreased the system's ability to use feedback to determine alternative responses. All such models have been designed to simulate some type of abnormal prefrontal processing. But less severe and more transient dysfunctioning may also occur, not because of cortical insult or neurochemical abnormality, but because working-memory resources are temporarily overloaded or engaged in other tasks. Such cases of everyday dysfunctioning may share important similarities with more severe forms of frontal dysfunctioning.

Everyday Action Errors

At least since the era of James (1890) and Freud (1901/1966), theorists have viewed the errors we commit in the

[1] Some important exceptions are studies that have varied the length of time information must be maintained in working memory. In studies that have used search tasks with monkeys (Funahashi, Bruce, & Goldman-Rakic, 1993; Fuster, 1973; Goldman-Rakic, 1987) and human infants (Diamond, 1991; Diamond & Goldman-Rakic, 1989), longer delays typically increase the probability of making the prepotent responses.

course of everyday action as providing insight about general cognitive processes. Errors that occur in particular contexts, such as when a system is overloaded, can reveal processes that are invisible under normal circumstances. Recently, some neuropsychologists have commented on the similarity between certain types of everyday action errors and the kinds of difficulties experienced by frontal patients (e.g., Luria, 1966; Shallice, 1988). The most relevant kinds of errors are referred to as *capture errors* (Norman, 1981) or *strong habit intrusions* (Reason, 1979). James (1909/1962) described an often-cited example:

> "Persons in going to their bedroom to dress for dinner have been known to take off one garment after another and finally to get into bed, merely because that was the habitual issue of the first few movements when performed at a later hour." (p. 155)

Additional examples include following an incorrect but habitual route in one's automobile when the intended route deviates from the more traveled one, continuing to dial an old telephone number long after the number has changed, and looking for cookies in the place they were always kept after they have been moved to a new storage location. Such errors are most likely to occur when one is otherwise occupied, such as when listening to the radio or thinking about some other topic.

The working-memory hypothesis suggests that avoiding such errors requires maintaining one's goals and plans online, especially when a strong prepotent or habitual tendency is present. The stronger the prepotency and the more working-memory is otherwise engaged, the greater the probability of error. This view is similar to that of Norman and Shallice (1986), who hypothesized a supervisory attentional system that modulates actions of a lower-level contention scheduling system consisting of automatic-like, condition–action productions. This conception of everyday action errors is also consistent with computational models of prefrontal functioning described earlier and suggests a continuum between more severe forms of working-memory dysfunction in patient populations and the moment-to-moment variations seen in everyday functioning.

We examined this hypothesis in the present study by testing nonpatient subjects on the antisaccade task, a task that has been shown to be sensitive to prefrontal dysfunctioning and that is viewed as requiring a strong inhibitory component. We expected that as the working-memory load of the task increased, the proportion of strong habit or capture errors would also increase, perhaps to the point at which the performance of normal subjects would begin to resemble that of frontal patient populations. Such a finding would support the idea that temporarily overloading working memory can result in functionally similar outcomes as more permanent prefrontal dysfunctions due to lesion or neurochemical abnormalities.

The Antisaccade Task and Overview of the Present Study

The antisaccade task was originally developed by Hallett (1978; Hallett & Adams, 1980) to examine the mechanisms responsible for generating automatic and goal-directed saccades. The task was later adapted by Guitton, Buchtel, and Douglas (1982, 1985) to study deficits in inhibitory control in patients with prefrontal lesions and subsequently has been used by others to examine deficits of other populations with suspected prefrontal dysfunctions (e.g., Aman, Roberts, & Pennington, 1994; Fletcher & Sharpe, 1986; Fukushima et al., 1988; Merrill, Paige, Abrams, Jacoby, & Clifford, 1991; Pierrot-Deseilligny, Rivaud, Gaymard, & Agid, 1991; Rothlind, Posner, & Schaughency, 1991). The antisaccade task has a number of desirable characteristics for studying prefrontal cognitive functions. First, it captures a key characteristic of frontal deficits, as summarized by Fuster (1989): "The patient with even minor prefrontal damage tends to show a paucity of deliberate actions . . . The frontal patient, like the frontal animal, tends to perseverate—to repeat old patterns of behavior even in circumstances that demand change" (p. 131). The antisaccade task presents discrete and repeatable instances in which a built-in prepotent tendency must not be acted on in order to produce an appropriate response. In many other tasks the prepotency must be established during testing (e.g., in the Wisconsin Card Sort Task) and therefore may vary in strength and not be as reliably present as often as in the antisaccade task. Another benefit of the task is its relative simplicity and its ability to be used with a wide variety of subjects, including children (Aman et al., 1994). Despite the simplicity in the basic instructions for the task, it is still difficult to perform correctly in a consistent manner, as even control adult subjects do not perform at ceiling.

Guitton et al. (1985) tested patients with discrete unilateral excisions of frontal lobe tissue (for relieving intractable epilepsy) as well as patients with temporal lobe removals and nonpatient controls on the antisaccade and prosaccade tasks. In the antisaccade task a fixation point was displayed for a brief indeterminate time period and was subsequently extinguished when a cue was displayed 12° to its left or its right. Subjects were to look an equal distance to the opposite side of the cue where a target would appear 300–600 ms after the cue's onset. The target, an open square that was missing one of its sides, was displayed for 150 ms before it was masked. Subjects indicated which side of the square was missing by pointing their thumbs in different directions. This procedure was also followed for the prosaccade task, except that the subjects were instructed to make a saccade to the cue, where the target was subsequently displayed. Performance on the prosaccade task did not differ across the groups, suggesting that frontal lesions did not affect the ability to program or execute visually guided saccades. In contrast, there were striking differences in the antisaccade task between the frontal group and the temporal and nonpatient controls (who did not differ from each other). First, the frontal patients made more than twice as many incorrect saccades to the cue (referred to as *reflexive saccades*) than did the other groups (56% vs. 20%). Second, the frontal group's initial antisaccades and corrected antisaccades (after reflexive ones) more often appeared to be reactive to the target onset than in the control groups. The controls were better able to make an anticipatory saccade to the target location before its onset; the frontal group had difficulty initiating a saccade to an empty location. Difficulty in the antisaccade task has been demonstrated in other frontal-lesioned groups (Pierrot-Deseilligny et al., 1991) and in other syndromes with known or suspected prefrontal dysfunctioning, such as schizophrenia (Fukushima et al., 1988; Fukushima, Fukushima, Morita, & Yamashita, 1990), Alzheimer's disease (Fletcher & Sharpe, 1986), and attention deficit hyperactivity disorder (Aman et al., 1994).

The purpose of the present research was to examine the relation between working-memory load and the ability to inhibit prepotent saccades in the antisaccade task. In particular, we tested the hypothesis that as working-memory resources are increasingly taxed, reflexive responding will increase, so that the patterns of errors in nonpatient subjects will begin to resemble the performance of frontal patients. This expectation was based on the interactive framework, presented earlier, that posits the probability of performing various actions is a function of the strength of the prepotency, the available working-memory resources for determining and generating the alternative response, and the working-memory demands of the task. In the presence of a high prepotency, such as in the antisaccade task, a temporary increase in working-memory demand may have a functionally similar effect as a more permanent dysfunction in working-memory processing—a difficulty generating the alternative response, which will result in being "captured" by the default prepotency.

Experiment 1

A well-developed technique for examining the working-memory demand of a task is to add a secondary task whose demand on working memory has already been established. When processes across the tasks share working-memory resources, the decrement in performance in the primary task, secondary task, or both, should be greater than when the tasks share fewer common resources. This strategy has proven effective in a variety of task domains (e.g., Hitch & Baddeley, 1976; Logie, Baddeley, Mane, Donchin, & Sheptak, 1989; Wickens, Kramer, Vanasse, & Donchin, 1983). We adopted this basic methodology here as a means of increasing the overall working-memory demand of the saccade tasks. Put differently, we expected that introducing a secondary working-memory task would decrease the working-memory resources available for the primary saccade tasks.

In the first study, we tested college students on the antisaccade and prosaccade tasks. Each task was performed under two conditions, without a concurrent task and with a concurrent task that involved simple addition problems. The addition problems required a memory component (keeping a changing sum in mind) and a computational component (adding the current sum to a new number). Although we did not expect the concurrent math task to affect performance on the prosaccade task, we did expect it to have a deleterious effect on performance in the antisaccade task. We also tested subjects on an individual-difference measure of working-memory capacity, the sentence span task (Daneman and Carpenter, 1980) to assess whether differences in this task correlated with individual differences in the antisaccade task.

Method

Subjects

Subjects were 21 college students at the University of Denver (8 men, 13 women) who were given course credit for their participation. The subjects ranged in age from 19 years to 28 years (M = 22.1 years; SD = 2.3 years). All subjects participating in the study had normal or corrected-to-normal vision and spoke English as their primary language. Because of problems with the eye movement data collection system, the data from 14 additional subjects could not be used. The data from a subject who misunderstood the instructions also were not used.

Tasks and Apparatus

The subjects were given two eye movement tasks—the prosaccade and antisaccade tasks—in each of two conditions, without a concurrent task and with a mental arithmetic task. The mental arithmetic task was also administered alone. Subjects were also tested on an individual-difference measure of working memory, the sentence span task (Daneman & Carpenter, 1980).

Eye movement tasks. For the prosaccade and antisaccade tasks, stimuli were displayed on a 14-in. (36-cm) VGA color monitor controlled by an IBM compatible 80386 PC. The tasks were programmed using the Micro Experimental Laboratory software package (Schneider, 1988). The program controlled the stimulus presentation and recorded keypress timing and accuracy for target identification. Eye movement data were collected using a corneal reflection eye tracking system. An infrared-sensitive video camera was mounted under the task monitor and focused on the subject's left eye. The eye was illuminated by a near infrared light. The video signal from the camera was fed into an Iscan RK-426 eye tracker that output the x–y positions of the pupil and corneal reflection of the infrared light to a separate 80286 PC at 60 Hz. This computer also collected synchronous data from the task-presenting PC that specified what stimuli were displayed on the task monitor at each 1/60 of a second. For more information on the eye movement hardware and software, see Roberts, Brown, Wiebke, and Haith (1991) and Roberts and Wiebke (1994).

Each trial of the prosaccade (PS) task began with a fixation point at the center of the screen (see Figure 1). At intervals that varied randomly between 1,500 and 3,500 ms the fixation point was extinguished, and a cue consisting of a white square was presented 11.5° to the left or right of the fixation point. Cues of three different sizes were used: small (0.4° square), medium (2.0° square), and large (3.4° square). The different-sized cues allowed us to examine whether cue size affected saccadic direction or response time. The cue was extinguished 400 ms after its onset, and a target was displayed at the cue's location. The target was a 2.0° box containing an arrow pointing left, right, or up. The arrow was displayed for 150 ms before a pattern masked it. The mask was displayed for 1,500 ms or until the subject responded with a keypress. Cue side, cue size, and arrow direction were counterbalanced across 90 experimental trials that were presented in individually determined random orders. There were 12 practice trials.

Subjects were instructed to look at the fixation point until the cue was presented, at which point they were to make an eye

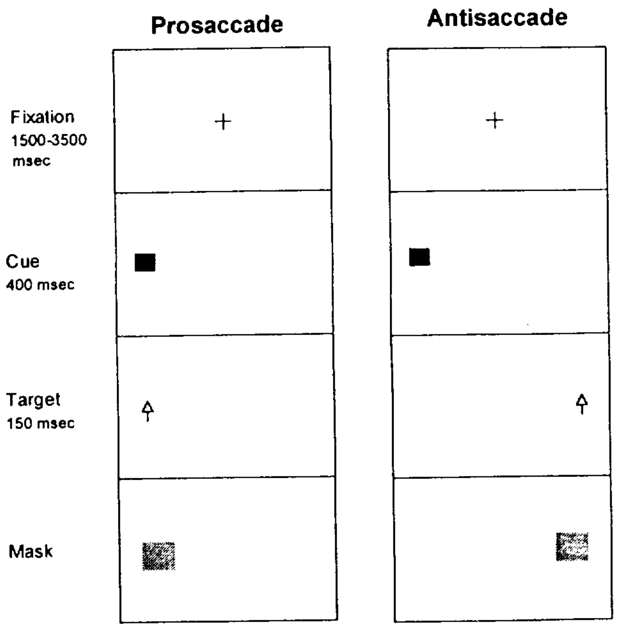

Figure 1. Sequence of events for the prosaccade and antisaccade tasks. Each frame represents what was displayed on the computer monitor for the period of time shown on the left of the figure.

movement to the cue to determine the direction of the target arrow. They indicated their response by pushing one of the corresponding arrow keys (left, up, right) on a computer keyboard.

The occurrence, timing, direction, and amplitude of saccades were scored by an automatic scoring system developed by Roberts and Wiebke (1994; Roberts et al., 1991). The system uses a hierarchical set of algorithms to disambiguate saccadic movements from background noise. Briefly, when the difference between two successive moving averages crosses a threshold, the program assumes a saccade has occurred within a specific time window. Each pair of successive looking locations is then compared within the window to make a best guess about the exact moment the saccade was initiated. The program's performance is highly reliable with skilled human scorers (Roberts & Wiebke, 1994). In addition, a skilled observer reviewed all of the program's judgments and corrected the few that seemed inaccurate.

The dependent measures of interest were the direction of the eye movement, the latency of the initiation of the saccade to the cue, and the correctness of target identification.

The antisaccade (AS) task was identical to the PS task, except the target was always presented on the side opposite the cue (see Figure 1). Subjects were instructed to look in the direction opposite the cue to see the target. It was stressed that an eye movement to the cue was considered incorrect and would diminish the speed and accuracy of target identification. Eye movements were scored in the same fashion as described for the PS task. The dependent measures were the proportion of incorrect initial saccades to the cue (called *reflexive*), the latency of the first eye movement (reflexive or antisaccade), the timing of corrective saccades after reflexive ones, and the correctness of target identification.

The AS and PS tasks were each performed under two conditions, with and without a concurrent task. In the no-load condition, the tasks were administered as just described. In the arithmetic condition, the experimenter orally presented random sequences of numbers ranging from 1 to 9 as the subjects performed the eye movement tasks. Subjects were required to add the first two numbers in the sequence and verbalize the answer. The third number was immediately presented, and the subject was instructed to add the previous sum to the new number and verbalize the answer. This continued through the fifth number in the sequence, after which a new sequence was started. The experimenter said "new" to inform the subject when a new sequence began. Before subjects performed the PS or AS task in the arithmetic condition, they performed 10 sets of the arithmetic problems alone as a baseline (after 2 practice sets). In all conditions, subjects were instructed to answer problems as quickly as they could with a high degree of accuracy. The experimenter presented a new problem immediately after an answer was given. When performing the eye movement tasks, subjects were also instructed to try to do as well as they could on both tasks. The goal of this procedure was to have subjects maintain high accuracy on arithmetic problems at a relatively constant pace. The procedure appeared to be effective: The proportion of correct answers was high in both the baseline ($M = 0.95$, $SD = 0.05$) and eye movement ($M = 0.94$, $SD = 0.05$) tasks, and there were no differences between performances in the AS or PS tasks, $t(20) < 1$, $p > .3$. The average time per problem was slightly shorter in the baseline tasks ($M = 2.4$ s, $SD = 0.6$ s) than in the eye movement tasks ($M = 2.9$ s, $SD = 0.8$ s), $t(20) = 6.9$, $p < .01$, and there were no differences in time per problem across the two eye movement tasks, $t(20) = 1.0$, $p > .2$.

Sentence span task. A version of the sentence span task developed by Daneman and Carpenter (1980) was used as a separate individual-difference measure of working-memory capacity. Subjects read single sentences aloud at their own pace and were instructed to remember the last word of each sentence. After a set of sentences had been read, each subject was asked to recall all of the last words for all sentences in the set. Sentences were selected from a total of 65 unrelated sentences, each of which was displayed individually on an 8-in. × 5-in. (20-cm × 13-cm) card. Sentences were 13–16 words long, and each ended with a noun. The sentences were presented one at a time, in set sizes ranging from 2 to 6 sentences. Subjects performed three sets at each set size in increasing order, starting at a set size of 2, until they failed to accurately recall all the words in all three sets of a particular set size. There were two practice trials (with a set size of 2) before testing. The dependent measure of interest was the largest set size for which the subject correctly remembered two out of the three sets.

Procedure

Subjects were tested individually on 2 separate days with a mean delay of 6.8 days ($SD = 6$) between testing sessions. Subjects were assigned randomly to one of two task orders with the constraint that there were equal numbers in each order. Because some subjects' data could not be analyzed because of equipment problems, there were unequal numbers in the two orders. Twelve subjects received the PS tasks in the first session and the AS tasks in the second, and 9 subjects received the tasks in the reverse order. In each session, subjects first performed the eye movement task without the concurrent arithmetic problems, then the baseline arithmetic problems, and finally the eye movement task with the arithmetic problems. Pilot work indicated that this ordering maximized subjects' ability to perform well on the concurrent-load version of the eye movement task. At the end of the second session, all subjects were tested on the sentence span task.

The eye movement tasks were administered in a dark room relatively free of distractions. Subjects' heads were steadied with a forehead rest and were positioned 42 cm from the computer monitor. Before the eye movement tasks, calibration data were collected as the subject looked at particular locations on the screen. We used the calibration data to linearize the eye movement data and to map looking locations onto the coordinate space of the task monitor (for details, see Roberts et al., 1991; Roberts & Wiebke, 1994).

Results

Eye Movements

Saccade direction. The dependent variable of primary interest was saccade direction. A reflexive saccade to the cue was the correct response on the PS tasks but was the incorrect response on the AS tasks. As shown in Figure 2(a), subjects made reflexive saccades close to 100% of the time in the PS tasks; we therefore did not analyze these accuracy data further.

We hypothesized that reflexive responding in the AS task would increase when subjects performed the concurrent addition problems. To examine this hypothesis as well as other potential influences on performance, we analyzed the proportion of reflexive saccades in the AS tasks in a mixed analysis of variance (ANOVA) with order (AS or PS tasks performed first) as a between-subjects variable and concurrent load (arithmetic or none), cue size (large, medium, or small), and cue side (left or right) as within-subject variables. As expected, subjects made more reflexive saccades when solving the simple addition problems ($M = 51\%$, $SD = 22\%$) than when not performing a concurrent task ($M = 31\%$, $SD = 22\%$), $F(1, 19) = 26.5$, $p < .001$, also see Figure 2(a).

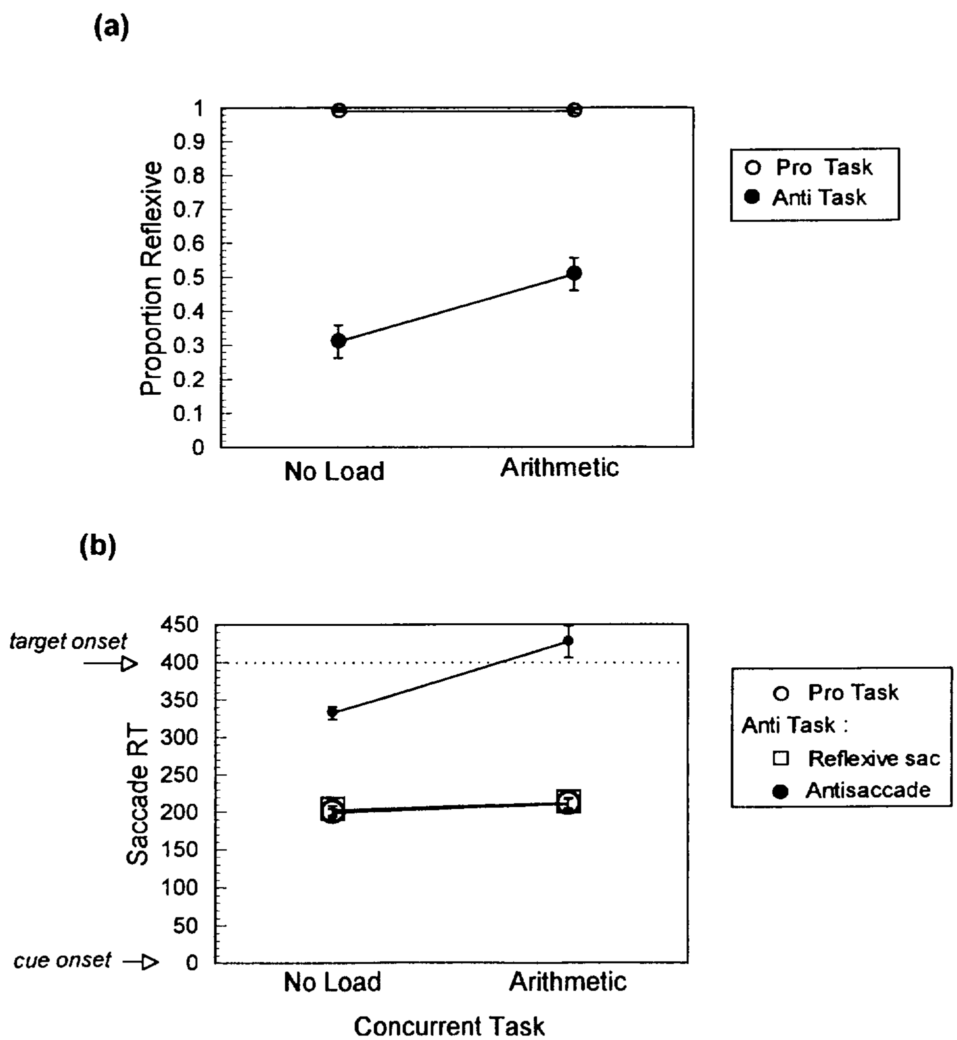

Figure 2. Panel (a): Proportion of reflexive saccades in the prosaccade (Pro) and antisaccade (Anti) tasks as a function of concurrent-load condition in Experiment 1. Panel (b): Saccade response times (RT; in msec) for reflexive saccades in the prosaccade task and reflexive and anti-saccades in the antisaccade task as a function of concurrent load in Experiment 1.

We also found main effects for cue size and task order: Performance improved slightly (fewer reflexive saccades) as cue size increased, (proportion reflexive for small, medium, and large cues: *M*s = 44%, 41%, 37%; *SD*s = 19%, 22%, 33%; respectively), $F(2, 38) = 10.0$, $p < .001$. The improvement fit a linear trend, $F(1, 19) = 17.1$, $p < .005$. Thus, increasing the cue size moderately increased the subjects' ability to make an antisaccade away from the cue. The proportion of reflexive saccades in the AS tasks also was lower when the AS tasks were performed before the PS tasks ($M = 31\%$, $SD = 14\%$) than when they were performed after the PS tasks ($M = 48\%$, $SD = 22\%$), $F(1, 19) = 4.2$, $p = .05$. Presumably, the prior experience of making 180 reflexive saccades in the PS tasks further strengthened the prepotent tendency to make a saccade to a peripherally flashed cue in the AS tasks. Interestingly, this carryover effect spanned the several days between the two testing sessions. The only other significant effect was an interaction between the side of the cue and the presence or absence of the concurrent load, $F(1, 19) = 6.0$, $p < .05$. Post hoc contrasts indicated that the proportions of reflexive saccades did not differ between left and right cues when there was no concurrent load (left: $M = 30\%$, $SD = 24\%$; right: $M = 32\%$, $SD = 22\%$), $F(1, 20) = 0.3$, *ns*, but did differ in the arithmetic concurrent-load condition, with more reflexive responding when the cue was on the left side (left: $M = 55\%$, $SD = 22\%$; right: $M = 46\%$, $SD = 26\%$), $F(1, 20) = 3.07$, $p < .07$.

Saccade response time. Saccades toward a peripherally flashed cue are presumably generated by a relatively automatic process (cf. Funahashi, Bruce, & Goldman-Rakic, 1993; Guitton et al., 1985; Pierrot-Deseilligny et al., 1991); thus, we expected the latencies for reflexive saccades to be fast and to not be significantly affected by task or concurrent load. In contrast, antisaccades should result from a more deliberate and effortful process involving working memory and should therefore be relatively slow overall and further slowed by the presence of the concurrent working-memory load. To examine these expectations, we calculated saccadic reaction time (RT) from the onset of the cue to the initiation of the eye movement. Median RTs were computed separately for reflexive saccades (on the PS tasks and AS tasks) and antisaccades (AS tasks only).

We first analyzed the reflexive RTs in a mixed ANOVA with task order (PS task or AS task first) as a between-subjects variable and task (PS task or AS task) and concurrent load (arithmetic or none) as within-subject variables.[2] As shown in Figure 2(b), RTs for reflexive saccades remained at about 200 ms regardless of task or concurrent load (overall $M = 198$ ms, $SD = 30$ ms), all $ps > .18$. The only significant effect was an interaction between task and order, $F(1, 19) = 5.8$, $p < .05$. Although no post hoc contrasts were individually significant, the interaction reflected relatively faster RTs in the PS task when it came before the AS task ($M = 193$ ms, $SD = 20$ ms) than when it came after the AS task ($M = 209$ ms, $SD = 29$ ms) in comparison to the RTs in the AS task, where there were smaller differences across the two orders (PS task first: $M = 197$ ms, $SD = 26$ ms; AS task first: $M = 193$ ms; $SD = 27$ ms).

We separately examined all RTs on the AS tasks as a function of type of response (reflexive or antisaccade), concurrent load (no-load or arithmetic), and task order. As shown in Figure 2(b), there was a large main effect for type of response, $F(1, 19) = 340.1$, $p < .001$, with much slower RTs for antisaccades ($M = 333$ ms, $SD = 28$ ms) than for incorrect reflexive saccades ($M = 196$ ms, $SD = 41$ ms). There was also a main effect for concurrent load, $F(1, 19) = 14.5$, $p < .005$, with slower responding with the arithmetic concurrent load than without the load. A significant interaction between response type and concurrent load, $F(1, 19) = 15.1$, $p < .005$, indicated that the additional requirement of performing the arithmetic problems slowed antisaccades (arithmetic: $M = 425$ ms, $SD = 100$ ms; no-load: $M = 333$ ms, $SD = 41$ ms), $F(2, 19) = 8.1$, $p < .005$, but did not have a significant impact on reflexive saccades (arithmetic: $M = 197$ ms, $SD = 34$ ms; no-load: $M = 194$ ms, $SD = 29$ ms), $F(2, 19) < 1$, *ns* (see Figure 2). Thus, performing the addition problems slowed antisaccades but did not affect the timing of reflexive saccades.

Guitton et al. (1985) found that the antisaccades of frontal patients, as compared with those of controls, had longer latencies and that many more antisaccades occurred only after the onset of the target (referred to as *visually triggered saccades*). In contrast, Guitton's control subjects more often began the saccade toward the target before it came on the screen (there were 400 ms between the cue and target onsets). A conservative estimate of saccadic RT is 200 ms, so saccades occurring 200 ms after the onset of the target could be considered visually triggered. Guitton et al. (1985), however, found visually triggered antisaccades occurring at 100 ms after target onset and argued that the faster-than-usual RTs resulted from an already programmed saccadic movement that lacked an internal trigger (also see Fischer & Weber, 1993). This proposition was supported by the finding that the profile of antisaccade RTs was similar at various cue–target stimulus onset asynchronies (SOAs). In the present case, subjects in the arithmetic condition made more visually triggered antisaccades than they did in the no-load condition. With the 200-ms criterion, subjects made visually triggered saccades 11% ($SD = 8\%$) of the time in the arithmetic condition and 2% ($SD = 3\%$) of the time in the no-load condition, $F(1, 19) = 18.0$, $p < .001$. With the 100-ms criterion, subjects made 40% ($SD = 21\%$) visually triggered saccades in the arithmetic condition and 13% ($SD = 8\%$) in the no-load condition, $F(1, 19) = 29.4$, $p < .001$.

After subjects made an incorrect reflexive saccade in the AS tasks, they typically made a corrective antisaccade.

[2] Because there were varying proportions of reflexive and antisaccades on the AS tasks, we did not analyze for all possible within-subject effects, because the cell sizes for RTs were too small (less than 5 subjects) in the full design. Thus, we focused our analyses on the primary variables of interest (task and concurrent load), which maintained cell sizes > 10.

Frontal patients' corrective saccades are typically slower and more often visually triggered by the target than are the corrective saccades of controls (Guitton et al., 1982, 1985). In the present case, subjects were slightly slower at making corrective saccades (as measured from the cue onset) in the arithmetic condition (M = 475 ms, SD = 50 ms) than in the no-load condition (M = 450 ms, SD = 46 ms), $F(1, 19) = 6.9$, $p < .05$. The percentage of visually triggered corrective saccades did not differ between the conditions using the 200-ms criterion (M = 10%, SD = 10%; M = 6%, SD = 10%; for arithmetic and no-load, respectively), $F(1, 19) = 2.7$, $p = .11$. Using the 100-ms criterion, corrective saccades in the arithmetic condition were more often visually triggered (M = 48%, SD = 20%) than in the no-load condition (M = 33%, SD = 19%), $F(1, 19) = 14.6$, $p < .005$.

To summarize the eye movement findings, the extra demand of performing simple addition problems increased the likelihood of making reflexive saccades and increased the latencies of antisaccades in the AS task. In contrast, the additional demand did not affect the timing of reflexive saccades in either the AS or PS tasks.

Target Identification

The target consisted of an arrow facing in one of three directions, and subjects pressed one of three buttons to indicate which target was displayed before the mask. Accuracy of target identification generally mirrored the eye movement findings, which is to be expected given that the direction and timing of eye movements often determined the length of time a subject had to view the target. Proportions of correct keypresses were analyzed in a mixed ANOVA with task order as a between-subjects variable and task (PS and AS), concurrent load, cue size, and cue side as within-subject variables. As shown in Table 2, subjects correctly identified more targets in the PS task (93%) than in the AS task (68.7%), $F(1, 19) = 116.6$, $p < .001$, and performed better without the arithmetic concurrent load (87.7%) than with the additional load (73.9%), $F(1, 19) = 54.2$, $p < .001$. A significant interaction between task and load condition, $F(1, 19) = 25.8$, $p < .001$, indicated a larger decrement in performance due to the arithmetic load in the AS task (20.4%) than in the PS task (7.2%), although both decrements were statistically reliable, $ps < .01$. As found with eye movements, performance was slightly better with the larger-sized cues (large: M = 83.3, SD = 10.2; medium: M = 81.8, SD = 9.8; small: M = 77.4, SD = 9.8), $F(2, 38) = 20.2$, $p < .001$. Post hoc contrasts revealed a significant difference between the small and medium sizes ($p < .05$), but not between medium and large sizes (*ns*). Size also interacted with task, $F(2, 38) = 8.6$, $p < .005$, reflecting greater differences due to size in the AS versus the PS task. There were no other significant effects.

Table 2
Target Identification as a Function of Task and Concurrent-Load Condition in Experiment 1

	Task			
	Prosaccade		Antisaccade	
Concurrent load	No-load	Arithmetic	No-load	Arithmetic
Percent correct[a]				
M	96.6	89.4	78.9	58.5
SD	4.2	7.7	11.8	17.3

[a] Significant effects for task, concurrent load, and Task × Concurrent Load, $p < .001$.

To summarize, difficulty in correctly identifying targets generally paralleled the eye movement findings: Accuracy worsened with the additional load of the math problems, and the decrement was more severe in the AS task than in the PS task.

Individual Differences and Working Memory

The Daneman and Carpenter (1983) working-memory sentence task provided an independent measure of working-memory capacity. We correlated performance on this task with the proportion of reflexive responses, the median latency for antisaccades, and the number of correct target identifications on the AS task with and without the concurrent arithmetic load, as well as with the degree of individual decrement on these measures in the arithmetic version as compared with the no-load version. None of the correlations was statistically reliable, $ps > .5$. The lack of reliable relations cannot be attributed to a restricted range in any of the variables. For example, percentage reflexive responding on the AS task without the arithmetic concurrent load ranged from 9% to 92% (SD = 22%), and working-memory scores on the sentences task ranged from 5 to 12 (SD = 2.1). Another potential assessment of individual differences in working memory was the rate of performance on the baseline arithmetic problems before the concurrent arithmetic conditions of the PS and AS tasks. We averaged the time taken to answer the arithmetic problems correctly on both assessments. This measure also did not correlate with any measures from the AS task.

Discussion

Taken as a whole, the findings support the hypothesis that increasing the working-memory demand of the AS task increases the difficulty of inhibiting the prepotent tendency to glance at a peripherally flashed cue when attempting to generate a saccade to the opposite direction. In several respects, the pattern of performance decrements associated with adding the concurrent task resembles the deficits shown by frontal patients and other patient populations with suspected prefrontal dysfunctioning. "Frontal" subjects do not differ from controls in the timing or accuracy of prosaccades, but they make many more incorrect reflexive saccades in the AS task. In addition, frontal subjects consistently take longer to initiate antisaccades and corrective saccades, with higher proportions of these eye movements appearing to be visually triggered by the onset of the target (e.g., Guitton et al., 1985; Pierrot-Deseilligny et al., 1991). This pattern of differences was the same pattern found between the no-load and arithmetic-load concurrent conditions in the present study.

The findings support the idea that reflexive saccades are generated by a relatively automatic process. Reflexive saccades, whether as correct responses in the PS task or incorrect responses in the AS task, occurred about 190 ms after the onset of the cue. Adding the concurrent load in either task did not alter this timing. In contrast, antisaccades took about 150 ms longer to initiate and were further slowed by the arithmetic concurrent load. These findings support the idea that the generation of the antisaccade involves working memory and that increasing the load on working memory decreases the resources available to generate the antisaccade, allowing the reflexive saccade to more often "win" the competition.

The size and the side of the cue also affected performance. We expected that larger-sized cues might increase the prepotency of looking at the cue. Instead, larger-sized cues were slightly easier to look away from in the AS tasks, which presumably resulted in somewhat improved target identifications. A possible explanation for this result is that larger cues are noticed more easily and quickly, allowing deliberate processes of working memory more opportunity to program an antisaccade. Cues on the left side caused slightly more reflexive saccades than did cues on the right, although this difference occurred only in the arithmetic concurrent-load version of the AS task. This effect may be due to the concurrent arithmetic task recruiting disproportionate processing in the left and right cerebral hemispheres. The subtle extent of the effect, however, requires replication before further hypothesizing is warranted.

Individual differences on the Daneman and Carpenter (1980) sentence span task did not correlate with performance on the AS tasks. There are several possible reasons for the lack of a relation. First, variability between individuals in a normal population on the antisaccade task may not be due primarily to differences in working-memory capacity (as they might in a frontally impaired group). Another possibility is that the two tasks tap different types or characteristics of working memory. It still seems to be the case, however, that externally increasing the working-memory load has an overall detrimental effect on AS performance (arithmetic condition). In the next two experiments we further explored these hypotheses by varying the hypothesized working-memory load of concurrent tasks and by examining another individual difference measure of working memory.

Experiment 2

Our explanation for why the arithmetic concurrent load had a large adverse effect on performance in the AS task is that performing addition problems taxed limited working-memory resources that are required for inhibiting the reflexive response and generating an antisaccade. It is possible, however, that many concurrent tasks would have a detrimental impact on performance regardless of their demand on working-memory resources. Performing any other task may divert attention or share other limited resources that affect the difficulty of generating antisaccades. In the present case, listening to the experimenter present numbers, vocalizing a response, or both, may have worsened performance—not the hypothesized working-memory component of adding numbers and keeping in mind the current sum. To examine this hypothesis we tested subjects in another concurrent-load condition, the shadowing condition. In the shadowing condition, the subjects listened to numbers presented at approximately the same rate as in the arithmetic condition and were required to vocalize the number they had just heard. The input and output requirements of the task were identical to those of the arithmetic condition, but the shadowing task lacks the additional requirement to add the number and keep in mind the previous sum while a new number is presented. Thus, the shadowing condition allowed us to examine whether it was the working memory demand associated with the arithmetic task, and not the requirement to perform two tasks simultaneously, that interfered with performance on the AS task in Experiment 1. We expected that the ability to inhibit reflexive saccades and initiate antisaccades would be significantly better in the shadowing condition than they had been in the arithmetic condition. To examine this hypothesis, we tested subjects on the AS task without a concurrent load, with the arithmetic load, and with a shadowing load. In addition, we added another individual difference measure of working memory, the counting span task, to examine whether performance on this task related to performance on the AS tasks.

Method

Subjects

Subjects were 23 college students (6 men, 17 women) who were given course credit for their participation. The subjects ranged in age from 19 years to 27 years ($M = 20.6$ years; $SD = 10$ months). All subjects participating in the study had normal or corrected-to-normal vision and spoke English as their primary language. Four additional subjects were tested but were not included in the data analyses: 1 subject's eye movement data contained too much noise to be reliably scored, 1 subject failed to complete a second testing session, and 2 subjects performed several tasks incorrectly.

Tasks

Subjects performed the AS task in three concurrent-load conditions: no-load, arithmetic, and shadowing. The hardware and software used to present the tasks and to collect, calibrate, and score eye movements were the same as those used in Experiment 1. Subjects performed two individual difference tests of working memory: Daneman and Carpenter's (1980) sentence span task, which was used in Experiment 1, and a counting span task (Case et al., 1982).

Eye movement tasks. The AS task was the same as that described in Experiment 1, except that each condition contained 60 experimental trials rather than 90 and used only medium-sized cues. Procedures for the arithmetic condition and the no-load condition were the same as those described in Experiment 1. As in the first experiment, subjects performed well on the addition problems when they were administered alone (M = 95% correct, SD = 5%) and during the AS task (M = 94% correct, SD = 4%), $t(22) = 0.6$, *ns*. The average time per problem was slightly slower when performed during the AS task (M = 2.8 s, SD = 0.4 s) than when performed alone (M = 2.4 s, SD = 0.5 s), $t(22) = 4.9$, $p < .01$.

In the shadowing concurrent-load condition, randomly chosen digits (1–9) were presented on an audiotape at the rate of 1 every 2 s, which was faster than the average time taken per digit in the arithmetic problems in Experiment 1 (1 per 2.9 s). Subjects were instructed to repeat each digit out loud during the brief interval. Subjects practiced repeating the digits for 1 min before the experimental trials began.

Sentence span task. This task was the same as described in Experiment 1.

Counting span task. This task was based on the task used by Case et al. (1982). Subjects were instructed to count yellow dots shown on 8-½-in. × 11-in. (22-cm × 28-cm) white cards on which both blue and yellow dots appeared. The dots were arranged in scrambled irregular patterns. Subjects were instructed to count the yellow dots, ignore the blue dots, and remember the number of yellow dots on each card. When subjects were shown a blank card, they were instructed to recall the number of yellow dots on the previous cards. Cards came in set sizes from two to six cards, and there were three different sets for each size. There were two practice sets, each containing two cards. Subjects performed the sets in increasing order, from a set size of two to six. When a subject failed all three sets at a particular level, the testing was discontinued. The dependent measure was the largest set size in which the subject correctly remembered at least two of the three sets.

Procedure

Subjects were tested individually on 2 separate days with a mean delay of 6.9 days between testing sessions (SD = 3.7 days). All subjects performed the no-load AS task on the first day of testing, followed by either the arithmetic or shadowing concurrent-load versions. (Pilot work indicated that giving the no-load condition first aided performance on the concurrent-load versions of the task.) Half of the subjects received the arithmetic condition on the first day and the shadowing condition on the second day, and half received the tasks in the reverse order. Because of the 4 subjects whose data were not analyzed, the number of subjects in each order was not equal: 10 subjects received the arithmetic version first, and 13 subjects received the shadowing version first. Subjects performed one of the working-memory individual difference tasks at the end of each testing session.

The testing conditions and general procedures were the same as in the first experiment.

Results and Discussion

Eye Movements

Saccade direction. We expected that repeating single digits (shadowing condition) would put less demand on working memory than would adding digits to a running total (arithmetic condition). Consequently, subjects were expected to make fewer reflexive saccades to the cue in the shadowing version of the AS task than in the arithmetic version of the task. To examine this hypothesis, we submitted the proportion of reflexive saccades to a mixed ANOVA with task order (arithmetic or shadowing version first) as a between-subjects variable and concurrent load (no-load, shadowing, arithmetic) and cue side (left, right) as within-subject variables. As seen in Figure 3(a), there was a significant main effect for concurrent load, $F(2, 42) = 17.9$, $p < .001$. Post hoc contrasts indicated that there was significantly more reflexive responding in the arithmetic condition (M = 52%, SD = 20%) than there was in the shadowing condition (M = 37%, SD = 24%) and that there was more reflexive responding in the shadowing condition than in the no-load condition (M = 25%, SD = 14%), all $ps < .005$. The only other significant effect was a Cue Side × Concurrent Load interaction, $F(2, 42) = 7.7$, $p < .005$. Post hoc contrasts indicated no differences between left and right cues in the no-load or shadowing conditions, $ps > .3$, but indicated a marginally significant decrement in performance for left-side cues (M = 59%, SD = 23%) relative to right-side cues (M = 46%, SD = 24%), $p < .06$ in the arithmetic condition.

Saccade response time. Although we did not expect the timing of reflexive saccades to be sensitive to the concurrent-load manipulation, we did expect antisaccades to show longer latencies as the working-memory load of the concurrent task increased. To examine this expectation we submitted median saccade response times (from the cue onset) to a mixed ANOVA with task order as a between-subjects variable and response type (anti- or reflexive saccade) and concurrent load as within-subject variables. As shown in Figure 3(b), the pattern of saccade latencies supported our expectations. A large main effect for response type, $F(1, 21) = 279.7$, $p < .001$, was due to the considerably shorter latencies for reflexive saccades (M = 180 ms, SD = 19 ms) than for antisaccades (M = 352 ms, SD = 60.4 ms). There was also a main effect for concurrent load, $F(2, 42) = 21.4$, $p < .001$, which resulted from differences in the antisaccade RTs across load type. Antisaccade latencies in the arithmetic condition (M = 430 ms, SD = 90 ms) were significantly longer than in the shadowing condition (M = 318, SD = 65), $F(2, 21) = 18.3$, $p < .001$. RTs in the shadowing condition did not differ from those in the no-load condition, $F(2, 21) < 2.0$, $p > .18$. There were no differences in the latencies of reflexive saccades across the three load conditions, $ps > .3$.

The antisaccade could be initiated before or after the target was presented. The proportion of antisaccades that could be considered visually triggered from the target onset reflected the same pattern of findings just described, with the arithmetic load causing more visually triggered antisaccades than the other two conditions. With the criterion of 200 ms or more after target onset, 13% (SD = 14%) of the antisaccades in the arithmetic condition were visually triggered, whereas 1% (SD = 3%) and 2% (SD = 3%) were visually triggered in the no-load and shadowing conditions, respectively, $F(2, 42) = 11.0$, $p < .005$. With the 100-ms criterion, 36% (SD = 19%) of the antisaccades in the arithmetic condition were visually triggered, as compared with 8% (SD = 10%) for the no-load condition and 10%

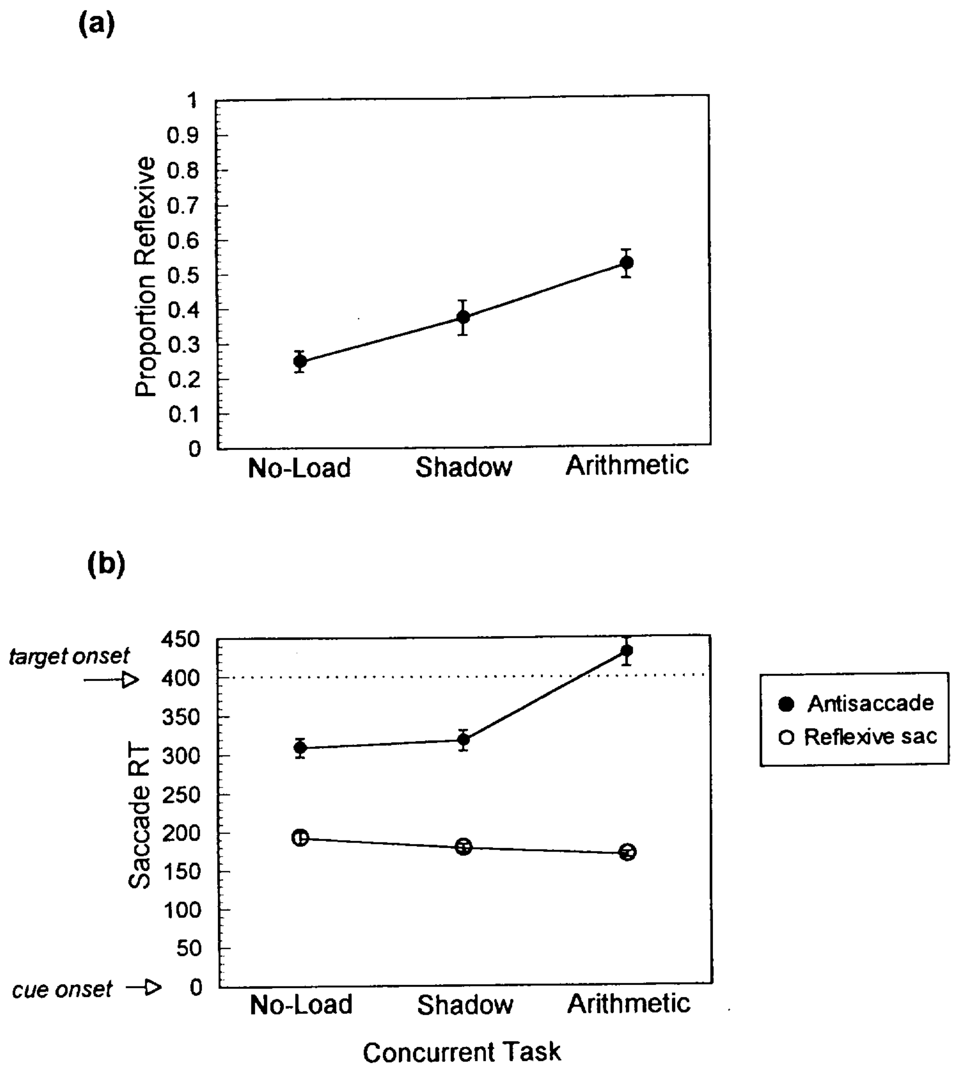

Figure 3. Panel (a): Proportion of reflexive saccades for each of the concurrent-load conditions during the antisaccade task in Experiment 2. Panel (b): Saccade response times (RT; in msec) for reflexive and antisaccades in each of the concurrent-load conditions in the antisaccade task in Experiment 2.

(SD = 13%) for the shadowing condition, $F(2, 42) = 39.9$, $p < .001$.

The latency to make a corrective saccade to the target (after a reflexive one) also differed as a function of concurrent-load condition, $F(2, 44) = 8.6$, $p < .005$. Post hoc contrasts indicated that the arithmetic condition produced longer latencies (M = 432 ms, SD = 58 ms) than either the shadowing condition (M = 389 ms, SD = 63 ms) or the no-load condition (M = 395 ms, SD = 57 ms), $p < .005$. The latter two conditions were not significantly different from each other. The proportion of visually triggered corrective saccades did not differ across load condition with the 200-ms criterion (overall M = 4%, SD = 3%), $F(2, 42) = 0.5$, $p > .6$. With the 100-ms criterion, subjects made more visually triggered corrective saccades in the arithmetic condition (M = 30%, SD = 20%) than in the no-load (M = 18%, SD = 18%) or shadowing (M = 19%, SD = 20) conditions, $F(2, 42) = 3.5$, $p < .05$.

Target Identification

Consistent with the eye movement findings, correct target identification was most difficult in the arithmetic condition (see Table 3). The proportion of correct judgments was analyzed in a mixed ANOVA with task order as a between-subjects variable and concurrent load and cue side as within-subject variables. A significant concurrent-load effect, $F(2, 42) = 31.6$, $p < .001$, was due to less accurate identification in the arithmetic condition (M = 68%) than in the shadowing condition (M = 87%) or no-load (M = 88%) condition, $p < .001$, which were not significantly different

Table 3
Target Identification as a Function of Concurrent-Load Condition in Experiments 2 and 3

Percentage correct	Concurrent load			
	No-load	Repeat	Shadow	Arithmetic
Experiment 2[a]				
M	87.8	—	86.6	68.0
SD	12.8	—	13.1	17.7
Experiment 3[b]				
M	81.9	82.5	85.8	—
SD	15.4	11.7	13.9	—

Note. Dashes indicate no data.
[a] The arithmetic condition significantly differs from the other two conditions, $p < .001$. [b] There is no significant difference between the conditions.

from each other, $p > .4$. There were no other main effects or interactions.

Individual Differences and Working Memory

The two independent measures of working-memory capacity (sentence span and counting span tasks) and the time taken to answer the baseline arithmetic problems were correlated with the response measures on each of the three versions of the AS task. These measures were the proportion of reflexive saccades, the median response latencies for antisaccades, the number of correct target identifications, and the degree of decrement in these measures in the arithmetic version as compared with the no-load version. The vast majority of correlations were not statistically reliable at the .05 level. The only significant correlations were between the counting span task and the antisaccade latencies on two versions of the AS task, (no-load version: $r = -.44$, $p < .05$; arithmetic version: $r = -.42, p < .05$). There were also marginally significant relations between correctness of target identification and performance on the counting span task for the three conditions, *r*s from .36–.41, *p*s $\leq .08$. Although these correlations were in the correct direction, suggesting that higher scores on the counting span working-memory measure related to better performance on the AS tasks, the low significance levels given the large number of correlations prompts caution in interpretation.

Summary

To summarize, the pattern of performance on the no-load and arithmetic conditions of the AS tasks replicated the findings of Experiment 1: Adding the arithmetic load to the AS task doubled the incidence of reflexive saccades, slowed the latencies of antisaccades by an average of 120 ms, and decreased the accuracy of target identification by more than 20%. Also replicated was a laterality effect for reflexive saccades in the arithmetic condition, with more reflexive saccades when the cue was on the left versus the right side. The shadowing load had less of a negative impact on performance: Percentage of reflexive saccades increased as compared with the no-load version but was significantly less than in the arithmetic version. Shadowing and no-load conditions did not differ in antisaccade latencies or in target identification.

In both the arithmetic and shadowing versions, the subjects listened to the presentation of single digits and verbalized a number after each presentation. The primary difference between the conditions was that the arithmetic version had the additional requirements of mental addition and keeping in mind the current sum as each new number was presented. This additional load appeared to interfere with the processes involved in inhibiting reflexive saccades and initiating antisaccades.

We conducted a third experiment to assess the degree of interference on the AS task of another concurrent load condition, one hypothesized to have even less of a working-memory demand than the shadowing task. Another purpose of the third study was to further examine the possible relation between counting span and measures from the AS tasks.

Experiment 3

In this last study we further examined how variability in the presumed working-memory load of a concurrent task affects performance on the AS task. Most concurrent tasks probably put some demand on working memory, although the extent of that demand must vary widely. Although we expect that the shadowing task involves less demand on working memory than the arithmetic task does, it still requires attending to and encoding each new digit and holding the current number in mind before vocalization. In this third study we examined the impact of another concurrent task, one that involves listening to a tone and vocalizing a single nonchanging digit. As in the shadowing task, the subjects were required to listen to a stimulus and respond vocally. However, the working-memory load was reduced because the subjects did not need to attend to the content of the stimulus (tone), store the identity of the stimulus, or respond according to the content of the stimulus. The tone acted only as a timing cue for when the subject was to verbalize the same, nonchanging digit. We compared this "repeat" condition with the no-load and shadowing conditions. We also tested subjects on the sentence span and counting span tasks to reexamine the marginal correlations found with AS task performance in Experiment 2.

Method

Subjects

Subjects were 26 college students (4 men, 22 women) who were given class credit for their participation; the data from 1 additional subject could not be scored. Subjects ranged in age from 18 to 27 years ($M = 21.4$ years; $SD = 2.4$ years). All subjects had normal or corrected-to-normal vision, and all spoke English as their primary language.

Tasks

Subjects performed the AS task in three concurrent-load conditions: no-load, repeat, and shadowing. The hardware and software used to present the tasks and to collect, calibrate, and score eye movement data were the same as those used in Experiments 1 and 2. Subjects performed two individual difference tests of working memory: the sentence span task (Daneman & Carpenter, 1980) and the counting span task (Case et al., 1982).

Eye movement tasks. The AS task was the same as the one in Experiment 2, except that each condition contained 36 trials. (Analyses from the previous two experiments indicated that 36 trials were sufficient to obtain stable accuracy and RT data.) Procedures for the shadowing and no-load conditions were the same as those followed in the previous experiments. In the repeat condition, subjects repeated a number once every 2 s. Subjects repeated the same number throughout the condition. A number between 1 and 49 was chosen at random for each subject. Subjects paced themselves by repeating the number after hearing a beep from an electronic metronome. A 1-min practice session was given before the dual task during which the subjects repeated the same number after hearing a beep.

Sentence span task. This task was the same as the one described in Experiment 1.

Counting span task. This task was the same as the one described in Experiment 2, with the exception that the highest set size was changed from 6 to 9.

Procedure

Subjects completed all tasks in one session. For the three AS tasks, all subjects received the no-load version first followed by either the shadowing version (14 subjects) or the repeat version (12 subjects). The order of the sentence and counting span tasks was counterbalanced, with one given before, and the other after, the AS tasks. The testing conditions and general procedures were the same as in the prior two experiments.

Results and Discussion

Eye Movements

The findings clearly indicated that the repeat and shadowing concurrent tasks did not have a large impact on the ability to inhibit reflexive saccades or initiate antisaccades.

Saccade direction. We analyzed the proportion of saccades that were reflexive in a mixed ANOVA with order as a between-subjects variable and concurrent-load condition (no-load, repeat, shadowing) and cue side as within-subject variables. As shown in Figure 4(a), the degree of reflexive responding was similar across the three concurrent-load conditions. A marginally significant trend for load condition, $F(2, 48) = 2.7, p < .08$, reflected the somewhat lower proportion of reflexive responding in the no-load condition (M = 30%, SD = 24%) than in the repeat condition (M = 37%, SD = 22%) and shadowing condition (M = 38%, SD = 24%). The only other effect was for task order, $F(1, 24) = 5.4, p < .05$, which reflected overall less successful performance when the shadowing condition came first (M = 43%, SD = 20) than when the repeat condition was first (M = 26%, SD = 20%). The absence of a Task × Order interaction, $F(2, 48) < 1$, *ns*, however, indicated that task order did not differentially affect the two load conditions.

Saccade response times. The latencies of the initial eye movement were analyzed in a mixed ANOVA with task order as a between-subjects variable and response type (anti- and reflexive saccades) and concurrent-load condition as within-subject variables. As seen in Figure 4(b), antisaccades were considerably slower (M = 320 ms, SD = 47 ms) than reflexive saccades (M = 182 ms, SD = 29 ms), $F(1, 23) = 244, p < .001$, although there were no differences in latencies due to concurrent-load condition, $ps > .4$. Antisaccades were further analyzed to examine possible differences across load condition in the proportion of saccades that were visually triggered in response to target onset. Overall, the proportion of visually triggered antisaccades was low, and there were no differences due to concurrent load with either the 200-ms criterion (M = 2%, SD = 2%) or the 100-ms criterion (M = 9%, SD = 10 ms), $Fs(2, 48) < 1, ps > .5$.

Similarly, the latencies of corrective saccades to the target side after reflexive saccades did not differ as a function of concurrent load (overall M = 392 ms, SD = 51 ms), $F(2, 48) < 1, p > .5$, nor did the proportions of visually triggered corrective saccades differ (200-ms criterion: M = 2%, SD = 2%; 100-ms criterion: M = 14%, SD = 16%), $F(2, 48) < 1, ps > .5$.

Target Identification

Table 3 presents the percentages of correct target identifications as a function of concurrent load. The percentage of correct keypresses (overall M = 83%, SD = 12%) did not differ as a function of task order, cue side, or concurrent-task load, $ps > .1$.

Individual Differences and Working Memory

We examined the relations between performances on the span and the AS tasks (proportion of reflexive saccades, the median latency to make antisaccades, and the proportion of correct target identifications). Trials were combined across the three versions of the task. None of the correlations was significant, $ps > .1$.

Because of the low power inherent in each of the individual studies, we combined performance data across the experiments for the no-load version of the AS task to examine its correlation with the sentence span task (Experiments 1–3, 70 subjects total) and the counting span task (Experiments 2–3, 49 subjects total). The correlations were all statistically nonsignificant, as shown in Table 4.

Summary

Unlike the arithmetic load examined in Experiments 1 and 2, the repeat and shadowing loads had only a minor effect on the ability to inhibit reflexive saccades and had no measurable effects on the timing of anti- or corrective

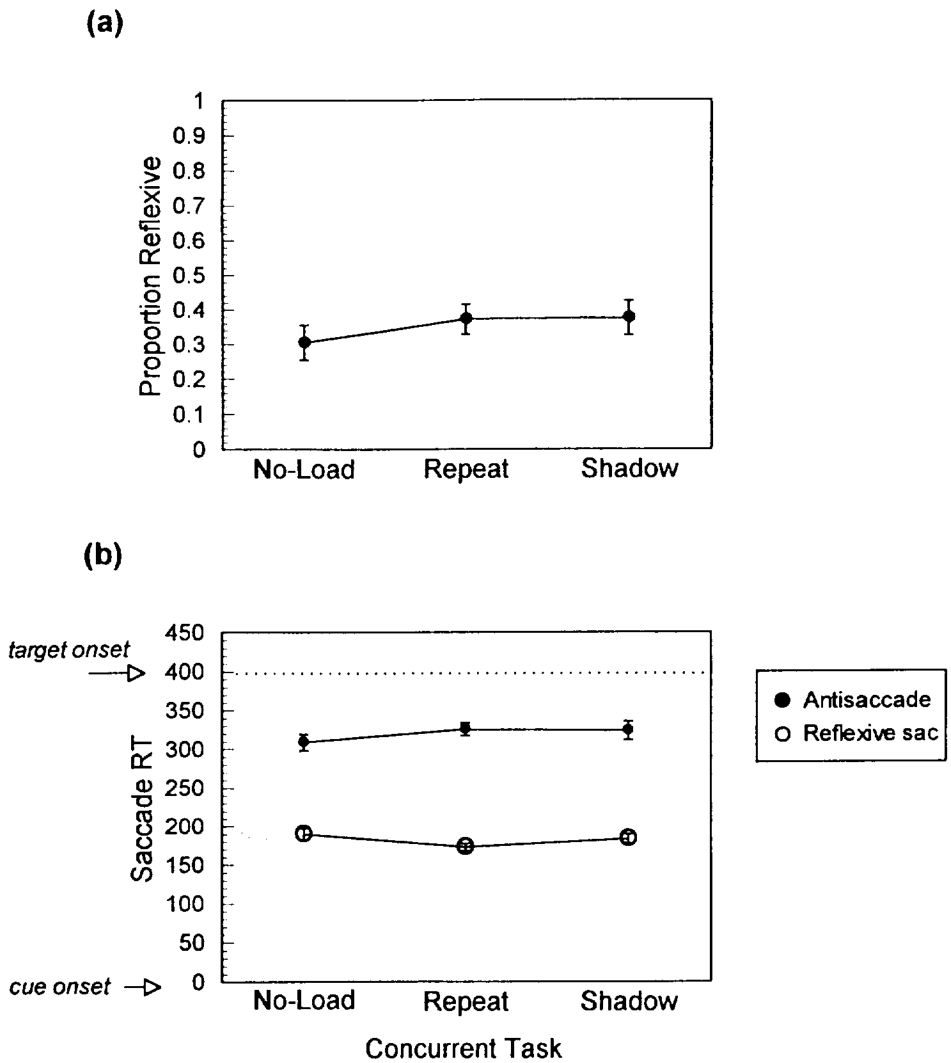

Figure 4. Panel (a): Proportion of reflexive saccades for each of the concurrent-load conditions in the antisaccade task in Experiment 3. Panel (b): Saccade response times (RT; in msec) for reflexive and antisaccades in each of the concurrent-load conditions in the antisaccade task in Experiment 3.

saccades. There were no differences between the shadowing and repeat tasks, suggesting that the additional requirement of encoding and verbalizing a changing stimulus over repeating a constant stimulus did not add enough demand to working-memory processes to make a difference in the AS task. The findings also suggest that individual differences in the working-memory span tasks are not associated with individual differences in the AS task, although further research with larger sample sizes will be required to confirm these findings.

General Discussion

Overview

The findings across the three studies indicate that the concurrent requirement of the arithmetic task disrupted performance on the AS task, whereas the shadowing and repeat concurrent tasks had minor or no effects on performance. All three tasks contained auditory and verbal components, and, according to Baddeley's (1986, 1992) theory of working memory, required a component of working memory referred to as the *phonological loop,* which is involved in the articulatory control and storage of speech. The arithmetic task, however, supposedly made greater demands on another working-memory component, the "central executive," which is viewed as having a coordinative and deliberate attentional function. Previous studies have shown that the arithmetic task disrupts primary tasks that are considered more demanding of this central-executive component of working memory (Logie et al., 1989; Logie, Zucco, & Baddeley, 1990). Whether one does or does not adopt Baddeley's theoretical partitioning of working-memory processes, it appears that the additional computational and

Table 4
Correlations Between the Antisaccade Task (No-Load Condition) and the Working-Memory Span Tasks Combined Across Experiments

	Antisaccade measures		
Span tasks	% reflexive	Antisaccade RT	Target ID
Sentence span[a]	0.12	0.03	−0.10
Counting span[b]	0.07	0.03	0

Note. All correlations are statistically nonsignificant, *ps* > .3. RT = reaction time; ID = identification.
[a] $N = 70$. [b] $N = 49$.

storage demands of the Arithmetic task over the other concurrent tasks induced normal subjects to respond in a manner similar to frontal patient populations: Proportions of reflexive saccades doubled, antisaccades were slowed, and target identification dropped. In contrast, the timing of pro- and reflexive saccades was unaffected by concurrent load, which also holds true for frontal patients. Of course, these findings only suggest a behavioral similarity between frontal patients and normal subjects when under a high working-memory load. Further work is needed to determine more precisely which aspect(s) of the secondary task prove disruptive and whether it is specifically a working-memory deficit in frontal patients that accounts for difficulties in the AS task. Despite these caveats, the results provide tentative support for the hypothesis that a high working-memory load can produce behavior that is functionally similar to more permanent forms of frontal dysfunctioning and that this kind of error is similar to "action-slip" errors made in everyday activity.

Laterality Effects in the AS Task

The arithmetic concurrent load produced a slight laterality effect for reflexive responding, with left-sided cues producing more reflexive saccades than right-sided cues, although there were no such effects in any of the other load conditions of the AS tasks. A variety of hypotheses might explain this finding, but determination of the most likely candidate is complicated by the lack of data and the equivocal findings on laterality in general. If the arithmetic load produced a disproportionate amount of processing in one hemisphere (e.g., Aram & Ekelman, 1988; Ashcraft, Yamashita, & Aram, 1992; Earle, 1988; Jackson & Warrington, 1986; Osaka, 1984; Osborne & Gale, 1976), then the additional load might have interfered with processes in that hemisphere involved in detecting the cue, inhibiting the reflexive response, or generating the antisaccade. For example, parietal and frontal lesions can quicken attentional movements or the salience of objects in the ipsilesional direction of current attention (Kinsbourne, 1977; Ladavas, Petronio, & Umilta, 1990; Posner, Walker, Friedrich, & Rafal, 1987; Rizzolatti, Gentilucci, & Matelli, 1985). In the present case, the prepotency of the cue on the left side might have been heightened by increased processing in the left hemisphere during the arithmetic task. Another possibility is a lateralized disruption in the generation of the antisaccade. If right-going saccades are programmed in the left hemisphere, then an increased load in the left hemisphere caused by the arithmetic load could have disrupted antisaccade generation to the right and resulted in a higher proportion of reflexive saccades to the left. A third possibility comes from the analysis of left–right differences in the response times of prosaccades (Experiment 1), which indicated that saccades to left-sided cues were slightly faster (M = 193 ms, SD = 22 ms) than those to right-sided cues (M = 215 ms, SD = 42 ms), $F(1, 20) = 5.1$, $p < .05$; this effect did not differ as a function of concurrent processing load.[3] Thus, left-sided cues may be inherently more "attention grabbing" than right-sided cues, perhaps because of lateral asymmetries in the control of attention, eye movements, or both (e.g., Posner & Petersen, 1990; Sava, Liotti, & Rizzolatti, 1988). If the ability to successfully generate an antisaccade depends on a competitive interaction between working-memory processes and the strength of the prepotency, then the arithmetic concurrent load may have tilted the competitive balance far enough so that the slight a priori increase in the prepotency of left-sided cues disproportionately increased the probability of making a reflexive saccade to that side. Determining which of these or other explanations underlies the laterality effect will require further research.

Interaction Between Inhibition and Working Memory

Despite the slight laterality effect, it is important to note that the decrement in performance due to the arithmetic concurrent load was bilateral, supporting the hypothesis that the ability to inhibit a prepotent action interacts with the operations of working memory. It is conceivable that the requirement of solving simple addition problems would not have affected the incidence of reflexive responding in the AS task but would have introduced a global slowing or delaying of antisaccades because of the time required to juggle the extra demands. Although slowing occurred, the classic frontal difficulty in inhibiting the prepotent response was dramatic.

The interactive or competition framework presented in the introduction suggests that working-memory demand, working-memory resources, and the degree of prepotency jointly contribute to the probability of inhibiting the prepotent response. The present study focused on the working-memory side of the competition, but one result indirectly addresses how variation in prepotency affects performance. In the first study, the prosaccade task required subjects to look at the cue as quickly as possible. Although the latencies of these eye movements were not affected by load condition and showed little overall variability, individual differences in the latencies to make reflexive saccades were negatively correlated with the proportion of reflexive responses in the

[3] We did not report in the *Results* section left–right response time differences for antisaccades, because the number of trials for each side for each subject was highly variable and very low in some cases. However, when these data were analyzed, we found no side or Side × Load effects, *ps* > .2.

AS task alone, $r = -.46$, $p < .05$, and in the AS task with the arithmetic load, $r = -.57$, $p < .01$. Thus, faster responding in the prosaccade task correlated with worse performance on the antisaccade tasks. Faster reflexive responding may reflect between-subject differences in the prepotency of the cue in the AS task and may suggest individual differences in the timing thresholds required for inhibiting a reflexive saccade (see below).

The interactive model also suggests that successful inhibition may often be an associated by-product of increased working-memory activation that underlies the production of the alternative response (cf. Goldman-Rakic, 1987). As long as working-memory resources are actively involved in preparing for the upcoming response, then likely alternative responses, which could be specific or nonspecific in nature, are inhibited. In the present case, the superior colliculus (SC) has been implicated in the production of reflexive saccades (e.g., Schiller & Sandell, 1983) and receives projections directly and indirectly from dorsolateral prefrontal cortex (Fuster, 1989; Goldman-Rakic, 1988). Working-memory processes in the prefrontal cortex that are involved in producing intentional goal-directed saccades, especially in anticipation of a currently unseen target (as in the AS task), may send inhibitory signals to the SC to prevent other unwanted, potentially conflicting saccades. If working-memory resources are not engaged in preparing for the upcoming action at some threshold level, then the degree of inhibition drops correspondingly, and the reflexive saccade becomes more probable. Another related hypothesis, suggested by Hallet and Adams (1980) and Guitton et al. (1985), is that a cancellation signal must be sent to the SC within a specific time frame after the onset of the cue. If the signal is later than some critical value, then the reflexive saccade will occur. Guitton et al. (1985) also suggested that the timing of the cancellation signal is proportional to "quantity of information processed" and the "rate at which this information can be processed by the nervous system." Although this explanation separates the inhibition and antisaccade-generation components, it still highlights the interactive nature between working-memory processes and inhibition.

This interactive framework also has implications for several measures of prefrontal functioning, as presented in Table 1. One implication concerns the striking and often-reported phenomena of frontal subjects behaving in such a way as to simultaneously give evidence of the correct and incorrect response. Examples include sorting perseveratively on color in the Wisconsin Card Sort Task while verbally indicating that color is not the correct category, and searching for the hidden object in the A-Not-B task in the incorrect location while looking at the new location. The interactive framework suggests this kind of equivocation would occur only when the competition between working memory and the strength of the prepotency is in very close balance, which would not be expected to occur often. This seems to be the case, because these equivocal responses are usually reported only anecdotally and, when examined specifically in one study that used the A-Not-B task, occurred only about 1% of the time (Janowsky, 1993).

Further Elaborating the Working-Memory Construct

A weakness of the interactive framework, and a difficult problem for the field in general, is how to best conceptualize and eventually differentiate working-memory processes. The construct, as applied to understanding the cognitive processes associated with prefrontal cortex, has the potential problem of becoming a catch-all concept that offers little explanatory power beyond what is already offered by other global descriptors, such as "executive functions." Fortunately, recent progress in cognitive psychology, primate neuroanatomical studies, and computational modeling of prefrontal functioning provides direction for better defining and differentiating the working-memory construct. One question concerns the degree to which there are separate working memories that are specialized for processing different types of information and the degree to which there are more global resources or bottlenecks that apply across domains (cf. Baddeley, 1992; Goldman-Rakic & Friedman, 1991; Wickens et al., 1983). There is evidence for domain-specific as well as domain-independent working memories. For example, Funahashi et al. (1993) convincingly demonstrated in rhesus monkeys that neurons in the prefrontal cortex (in and around the principal sulcus) maintain information about specific spatial locations that are relevant for generating upcoming actions. In humans, Logie et al. (1990) demonstrated a behavioral dissociation between a working memory related to a "visuospatial sketch pad" and a language-based "phonological loop." Much less is known about more centralized working-memory processes, although the primary characteristic associated with a central working memory, the coordination or integration across component processes, appears to be separable from the component working-memory processes themselves (Logie et al., 1990). In the present study, the bulk of the interference was assumed to derive from a more global working-memory bottleneck, although further studies with alternative secondary tasks will be required to examine the degree and type of interference associated with various types of concurrent task demands.

Another question concerns what characteristics of working memory describe different aspects of its functioning. In cognitive psychology, many researchers have focused on concurrent storage and processing and on measurements of capacity (e.g., Carpenter & Just, 1989; Case et al., 1982). The span tasks in the present studies are examples of capacity measures. Some researchers have attempted to further differentiate the storage component from the computational requirements involved in processing. Another characteristic of working memory, which has been examined most frequently in the primate and human infant literature, is the maintenance of information over time (Diamond & Goldman-Rakic, 1989; Funahashi et al., 1993; Fuster, 1991). The infant or monkey must remember something (e.g., a location) that is useful for generating an upcoming response (e.g., an eye movement) over various time intervals. The significant variable of interest is time, not capacity, and performance typically worsens as time increases. Another characteristic, one that has not been as widely discussed but seems particularly relevant to the AS task, is vigilance, or level of activation at a particular moment in time. For example, the AS task does not appear to tax concurrent storage and computation (capacity) or maintenance over a delay. Instead, it seems to require a high degree of vigilance or activation at the somewhat indeterminate moment the cue flashes in the periphery. Within a relatively short time interval, the subject will be vulnerable to making the reflexive saccade. Generally, both frontal patients and controls evenly distribute reflexive and antisaccades across experimental trials, suggesting that the difficulty is not in forgetting the relevant information across the duration of the task; instead, successful performance seems dependent on maintaining a high enough level of activation of the relevant self-instructions to make an eye movement to the opposite side at the moment the cue is presented.

These characteristics of working memory—capacity (or storage and processing), maintenance over time, and level of moment-to-moment activation—as well as other possible characteristics, may interact, but they may also be separable defining features that are differentially assessed in various tasks. A suggestion that they interact comes from the current studies, where strongly taxing capacity (arithmetic concurrent load) presumably affected moment-to-moment activation levels of self instructions to prepare for an antisaccade. The degree of separability of various working-memory characteristics is an empirical question, but it appears that some working-memory and frontal neuropsychological tasks pull more strongly for one or another characteristic. Span tasks pull for capacity, problem-solving tasks (e.g., Tower of Hanoi, Wisconsin Card Sort) tax for on-line inferencing and computation, delayed-search tasks call for maintenance of information over delays, and tasks such as the antisaccade and Go–No-Go tasks require high levels of activation during the interval when a response is likely.

These and other attributes of working memory may partially explain why such tasks do not always show consistent intercorrelations. In the present studies, the lack of a relation between the antisaccade task and the span tasks may be due to the possibility that the two tasks measure different aspects of working memory: capacity and short-term vigilance. Although individual differences in these attributes may not correlate in a normal adult sample, extreme dysfunctioning related to one characteristic would presumably affect the other (such as in our arithmetic load condition and presumably in subjects with frontal lesions).

Various characteristics of working memory may also map onto different aspects of neural functioning, as reflected in some current connectionist models of frontal functioning and working memory. For example, recurrent models contain "hidden" processing modules that form internal representations. These modules send recurrent signals back to themselves to keep current representations active across time (e.g., Cohen & Servan-Schreiber, 1992; Elman, 1990). Different architectural features and operational parameters of these networks would conceivably relate to different functional working-memory characteristics, including the size of these modules (in terms of the number of individual processing units); the interconnections between units; the clarity, or directness, of the recurrence; the equations governing the activation of the units; and the nature of the connections (e.g., inhibitory ones) between these units and other areas of the brain. Similarly, different forms of transient and relatively stable dysfunctioning may be caused by breakdowns in one or more of these parameters, and such patterns may help explain similarities and differences in the manifestations of frontal dysfunctioning. The modeling work of Cohen and Servan-Schreiber (1992), Kimberg and Farah (1993), and Levine and Prueitt (1989) offer important starts in this direction. Clearly, further behavioral, neural anatomical, imaging, and modeling studies will contribute to a more elaborate and differentiated understanding of working memory.

Conclusion

The present studies demonstrate that increasing concurrent working-memory load increases reflexive responding and slows antisaccades in the AS task. The findings are consistent with the framework presented in the introduction, which describes a common interactive dynamic across many assessments of prefrontal functioning. The framework suggests that behavior results from an interaction between competing tendencies and the associated processes that underlie action alternatives. Many everyday action errors and the mistakes made by subjects with frontal lesions occur for different reasons but may reflect a common processing dynamic.

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