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Paying attention behind the wheel: a framework for studying the role of attention in driving

LANA M. TRICK†*, JAMES T. ENNS‡, JESSICA MILLS‡ and JOHN VAVRIK§

†Department of Psychology, University of Guelph, Guelph, Ontario, Canada
‡University of British Columbia, Vancouver, British Columbia, Canada
§Insurance Corporation of British Columbia, Vancouver, British Columbia, Canada

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Driver inattention is thought to cause many automobile crashes. However, the research on attention is fragmented, and the applied research on driving and attention is further split between three largely independent traditions: the experimental research, the differential crash rate research, and the automation research. The goal of this review is to provide a conceptual framework to unify the research—a framework based on the combination of two fundamental dimensions of attentional selection: selection with and without conscious awareness (controlled and automatic), and selection by innate and acquired cognitive mechanisms (exogenous and endogenous). When applied to studies chosen to represent a broad range within the experimental literature, it reveals links between a variety of factors, including inexperience, inebriation, distracting stimuli, heads-up displays, fatigue, rumination, and secondary tasks such as phone conversations. This framework also has clear implications for the differential crash literature and the study of automated systems that support or replace functions of the driver. We conclude that driving research and policy could benefit from consideration of the different modes of attentional selection insofar as they integrate literatures, reveal directions for future research, and predict the effectiveness of interventions for crash-prevention.

1. Introduction

Road safety experts and the driving public agree that many automobile crashes are caused by problems of selective attention (e.g. Treat *et al.* 1979, Goodman *et al.* 1999a, 1999b, Utter 2001). Specifically, drivers fail to select the appropriate information from the visual image (they look but fail to see) or they fail to select the appropriate response from their response repertoire (they know what to do, but do not do it). In the cognitive ergonomics literature, attention is central to two important theoretical constructs: mental load and situational awareness (e.g. Stanton and Young 2000). The number of things that are objectively relevant to the task at hand is often used as an index of mental workload. The construct of attention is used in a more subjective sense for situational awareness in order to predict which aspects of the current situation a person will become aware of. This means there is at present a theoretical gap between these constructs because it is extremely difficult to predict which of the dimensions of the overall workload

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*Author for correspondence. e-mail: ltrick@uoguelph.ca

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actually have an influence on a person's awareness. The goal of this paper is to propose a framework for studying this relationship, thereby forming a bridge between the literature on applied issues in driving and selective attention.

Bridging this gap is not easy because both literatures are diverse. In cognitive research, there are currently no over-arching theories of attention, but rather a series of competing micro-theories for specific experimental tasks (Reason 1990). The driving research is similarly fragmented (Sivak 1997), split between three largely independent traditions: experimental research, in which situational factors are manipulated and performance is measured on test tracks or driving simulators; differential crash rate research, in which a variety of psychological tests are used to identify the characteristics of what has historically been called the 'accident prone driver'; and automation research, in which artificial systems designed to augment or replace functions of the driver are evaluated. Nonetheless, we believe it is possible to identify common themes in this research, which when taken together, point to a new conceptual framework for organizing the research on driving and attention.

The remainder of this paper is divided into three sections. Section 2 presents a conceptual framework based on current research on the basic mechanisms of attention. Section 3 applies this framework to experimental research on driving. The final section uses the framework to highlight connections between the various driving literatures, directions for future research, and implications for public policy.

2. Conceptual framework for understanding selection in driving

2.1. *Varieties of selection*

The concept of selective attention is fundamental to key constructs in cognitive ergonomics, but the basic research on attention is itself fragmented. To begin, we will propose a way of understanding selective attention that cuts through much superficial diversity to reveal an underlying commonality. One source of conflict is a vestige of a controversy that raged early in the study of attention. Traditionally, there were two different explanations for why selective attention was necessary for human functioning. The first was that the world presents us with much more information than can possibly be channeled through the limited capacity of human working memory. Consequently, only a small amount of the available information is selected for full perceptual analysis, to be recognized and linked to long-term memory (e.g. Broadbent 1958). The second account was that there are too many things for us to respond to at once, and, therefore, selection is necessary to choose which actions will be performed (e.g. Deutsch and Deutsch 1963, Norman 1968). There was thus a ready-made debate about whether attention is required for perception (stimulus selection) or for action (response selection). However, at present, it is commonly conceded that attention is important for both (Reason 1990, Lavie 1995), especially given that the distinction between perception and action is now seen as being far less clear-cut than it was previously (Goodale *et al.* 1991). Certainly the difference seems arbitrary when so many of the operations necessary for stimulus selection involve overt actions, such as moving the eyes, rotating the head, and turning the body towards relevant stimuli.

A second source of conflict can be traced to William James (1890), who considered attention to be equivalent to conscious awareness, and suggested that external information from the senses and internal information (thoughts, memories) compete for access to awareness. His influence persists in the tendency for attention researchers to focus predominantly on deliberate conscious operations. Nonetheless, in recent years it has become apparent that it is impossible to understand conscious awareness without understanding unconscious processes, because these processes often determine what comes to awareness. Consequently, the concept of attention needs to be broadened to encompass mechanisms of selection that result from unconscious, as well as conscious, processes. Thus, there are two broad forms of selective attention—selection with awareness and selection without awareness—but both affect perception, decision-making, response execution, and memory.

2.1.1. *Selection with awareness.* This has been variously called attentive, conscious, or intentional in the literature. Stimuli that are selected in this way are given full perceptual analysis and transferred to working memory. This usually involves a focusing of the mind on a specific object, location, or stimulus feature. Although we have the impression that we have a very detailed representation of the world when we look at a scene, in fact little information receives full analysis, as shown by the phenomenon of change blindness (Rensink *et al.* 1997). Observers are blind to most changes that occur during a brief visual interruption of a scene, as occurs when eye and head movements are made, or when there is a cut in a movie sequence. Only changes to objects currently at the focus of conscious attention seem to be detected easily, and therefore appear to be richly represented. In a study by Rensink *et al.* (1997), when an image and a slightly modified version of the image were repeatedly alternated with a brief interval between images (80 ms or more), observers had great difficulty seeing the difference between the images. They required many iterations of the pair before they could see what changed from one image to the next unless their attention was drawn by a verbal cue to the part of the image that changed. The authors concluded that new information simply overwrites the old unless attention is deliberately focused on the part of the image that changes.

Actions can also be selected with awareness. This occurs when a person intentionally carries out an activity, and is especially likely to occur in novel situations where moment-to-moment feedback from the environment is required or when no stored motor program exists and an action plan must be constructed on-line (Rasmussen 1982, Reason 1990). Actions are also selected with awareness when an individual deliberately and strategically applies the motor program associated with one situation to another somewhat different situation (Rasmussen 1982, Reason 1990). In general, only a small number of activities can be selected with awareness, and when two are carried out simultaneously, there is interference such that actions take longer to carry out than they would in isolation, and consequently, more errors are made.

Although it is commonly conceded that attention is important in memory, memory is rarely discussed in the attention literature, which tends to emphasize perception and action. We would like to rectify that situation by including a discussion of selection in memory. Whenever information is deliberately and actively memorized, or whenever an individual deliberately and actively searches their long-term memory for specific information, then selection with awareness is involved.

2.1.2. *Selection without awareness.* This has also been called preattentive, inattentional, subconscious, unconscious, and unintentional by different authors. Some stimulus selection occurs even without the benefit of a focused mental state. Consequently, there are certain aspects of stimuli that are processed even when the focus of attention is elsewhere or on another task. For example, Mack and Rock (1998) reported a series of studies in which observers carried out a difficult discrimination (judging which of two lines in a cross was longer) in a briefly presented stimulus followed by a pattern mask. On some trials there were also one or more figures in the background with the cross (which covered a large area of the display). On the final trial, after the last display was masked and the longer line reported, observers were given a surprise test and asked to describe characteristics of the background figures in the display. Accuracy was poor for a variety of characteristics, such as object shape and line orientation, which prompted the authors to claim that there was 'inattentional blindness' for many stimulus attributes. Nonetheless, some information could be reported, such as whether or not any background figures were present, the color of those figures, and the number of figures when the number was small (1–3). This information was selected without awareness or intention at the time the display was presented, and that was why observers could report on it several seconds later even though they had not expected to do so.

Similar conclusions can be drawn for the auditory modality from the early studies of dichotic listening (e.g. Cherry 1953, 1954). When participants were presented with two simultaneous messages, one in each ear, and were required to attend to one and repeat it back, they were unaware of the meaning of the unattended message in most cases, and did not even notice when the language in the message changed from English to French. However, some information was still selected. Participants could indicate whether the unattended voice had changed in pitch (from a male to female voice) and whether their own name was pronounced in the unattended ear (the cocktail party effect). Some selection occurs even when an individual is asleep. This explains why even weak stimuli, such as a baby's cry, can waken an individual. There is also evidence of selection without awareness for events that occur while an individual is unconscious under anesthetic (Andrade 1995). Though there is usually no conscious memory for the event, implicit memory tests reveal that some of the information was selected and retained over the long-term.

Selection without awareness also occurs with actions. This is what makes well-practiced performance efficient and effortless, and allows skilled individuals to carry out several actions simultaneously with little interference (Rasmussen 1982, Reason 1990). A given action is repeated so many times in a certain stimulus context that the context begins to evoke the appropriate response directly (the appropriate motor program in long term memory is activated 'bottom up'), and the action no longer demands conscious awareness. It becomes a habit. Although this is efficient, there is a danger that these motor programs will sometimes be activated in situations where they are undesired.

There is also selection without awareness for memories. When information is recorded in long-term memory automatically, without an intention to learn, or when a specific bit of information is retrieved from long term memory unbidden, in response to some reminder in the environment or an associated thought, selection without awareness has occurred.

2.2. *Mechanisms of selection*

Selection is mediated by a number of specific operations carried out in different parts of the brain (e.g. Posner and Raichle 1994), which develop and change with age in different ways and at different rates (Plude *et al.* 1994). Each can potentially affect different aspects of the driving task. In the following section, five basic operations involved in selection will be identified. Historically, three have been more associated with stimulus selection (orienting, search, and multiple target tracking) and two more related to response selection (filtering and multiple action monitoring). Memory selection is incorporated into some studies of multiple action monitoring, specifically the ones with secondary tasks involving long term memory retrieval. These secondary memory tasks usually involve selection with awareness.

2.2.1. *Orienting*. This involves moving the attentional focus (often including the eyes) to a new location in the visual field so that new incoming information can be seen clearly. When driving, the orienting operation is important for moving the focus of attention to locations expected to yield important information (e.g. a traffic light about to turn from yellow to red), or changing the position of the attentional focus to respond to events occurring in unexpected locations (e.g. a child running out from behind a parked car).

The standard laboratory procedure for measuring orienting is the *cue validity paradigm* (Posner 1980). In this paradigm, observers are given a cue that warns them where to expect a stimulus, either in the form of a central arrow that directs them to the side of the display where the stimulus will appear (symbolic cue), or a flash of light near where the stimulus will appear (stimulus cue). When the cue correctly directs observers to the appropriate part of the display (valid cuing), detection of the stimulus is faster and more accurate than if it is in a non-cued location (invalid cuing) even if there is too little time between cue and stimulus to foveate the cued location. (Initiation of eye movements takes 200 ms on average. Head movements take even longer.) The difference in performance between trials with valid and invalid cues is seen as an index of *attention switching*, or the time required to disengage the attentional focus and move it to a new location (Keele and Hawkins 1982).

Attention switching in the auditory modality is often measured using a variant of the dichotic listening task (Kahneman and Ben-Ishai 1973). Participants are presented with separate messages in each ear, and are required to repeat one back. On a prearranged signal, participants are required to switch their attention and repeat back the message from the other ear. Immediately after the signal to switch ears, the number of missed words and intrusions from the inappropriate ear are measured to estimate how quickly attention can be switched.

There are also tasks that measure attention switching but do not involve switching attention between different locations. One such technique involves presenting a rapid stream of letters and digits at one location (typically about 10 items per second). Observers are required to respond to several designated target items and ignore the others. Raymond *et al.* (1992) noted when there was a stream with two targets in a sequence, identification of the second target was poorer if it occurred two or three items after the first target. They called this deficit the *attentional blink*. Presumably it occurs because attention must be switched from the first to second target after the first has been identified (Keele and Hawkins 1982).

2.2.2. *Searching*. This involves locating relevant information in a complex visual scene. When driving, searching is required to find a specific street sign or exit, and relates to the driver's ability to locate needed information when confronted with visual clutter. In laboratory search tasks, the observer is required to indicate as rapidly as possible whether a given target is present in a display (Treisman and Gelade 1980, Duncan and Humphreys 1989). The experimenter manipulates the number of other items present (called non-targets or distractors) and measures response time (RT) and accuracy. The most important measure is the RT slope: the increase in RT as a function of increase in the number of distractors (the display size).

There are two distinct patterns of performance in the visual search task. When targets and distractors are dissimilar, and distractors are similar to one another, display size has little effect on search times and the RT slope is small or even zero (Treisman and Gelade 1980, Duncan and Humphreys 1989). For example, finding a single long, black line among short ones takes about the same time regardless of the number of short lines. When target items 'pop out' in this way, the search is said to be preattentive (Treisman and Gelade 1980). Each additional distractor adds almost nothing to RT because the attentional focus is not required to distinguish targets from distractors. In contrast, when targets are not easily discriminable from distractors, or when distractors are very different from one another, display size has a large effect on latencies and the RT slope is large. This type of search is said to require attention. For example, finding a single long, black line in a field of long gray and short black distractors takes longer as a function of the number of distractors. Each distractor adds a substantial amount to the response time because the attentional focus is required to distinguish targets from distractors, and the items cannot all be checked at once (Treisman and Gelade 1980, Duncan and Humphreys 1989).

2.2.3. *Multiple target tracking*. This involves simultaneously monitoring several independently moving objects at different locations. In determining when to pass another vehicle on a busy multi-lane highway, or when to turn at a congested intersection with moving pedestrians, bicycles, and oncoming cars, multiple target tracking is essential. The laboratory multiple target tracking task involves several stages (Pylyshyn and Storm 1988). First, a number of items are presented on a screen and then a subset flash to indicate that they are targets. After that, all the items, targets and non-targets, become identical and are set into random independent motion. Some time later, one of the items flashes, and observers are required to decide if it is a target or non-target. Typically observers track 3–5 targets with good accuracy, but performance deteriorates with further increases in the number of targets.

2.2.4. *Filtering*. This involves responding only to the relevant aspects of the situation, screening out irrelevant or misleading information. Filtering is especially difficult when there is a well-practiced response associated with the irrelevant information. For example, drivers must resist the impulse to start across an intersection as the traffic light turns green when the sound of nearby sirens indicate a police car or ambulance is coming through. Similarly, drivers must be sure to respond only to the appropriate information when there are multiple lights for different lanes at an intersection (e.g. in the case of separate left-hand turn and through-lane traffic signals). The classic filtering task is the *dichotic listening task*, although it measures selection in the auditory modality rather than the visual (e.g. Cherry 1953). In this task, individuals are required to attend and repeat back the message in one ear and not the other. Performance is measured in terms of how many intrusions there are from the unattended side. An analogue in the visual modality is the *flanker task*, which measures the ability to respond only to the item in a designated position without being influenced by the identity of items on either side (e.g. Eriksen and Eriksen 1975). The most challenging of all visual filtering tasks is the *Stroop task* (Stroop 1935), in which observers have to resist the impulse to read a color word and instead name the color of the ink in which the word is written. What makes this task so difficult is that the competing responses are both associated with the same visual stimulus.

2.2.5. *Multiple action monitoring.* This involves carrying out several activities at once, thus coordinating a variety of different actions. Driving is a classic example of such a task because it requires one to simultaneously steer and control vehicle speed, with the wheel and the accelerator and brake respectively. Multiple action monitoring is typically measured in the laboratory using a dual-task design. Performance in conditions where participants are required to carry out two tasks at once is compared to conditions where they perform each task separately. If dual-task performance is poorer than single task, then the tasks are said to interfere with each other (e.g. Radeborg *et al.* 1999). This interference presumably occurs because of failures and inefficiencies in multiple action monitoring. Dual-task experiments are commonly used to monitor cognitive effort or workload while driving. Drivers navigate courses of different complexity and performance is assessed both on driving and on the secondary task (e.g. mental multiplication, verbal reasoning).

2.3. *Common themes*

Though the research is diverse, there are two main dimensions useful for organizing the literature. The first involves the distinction between automatic and controlled processes (Shiffrin and Schneider 1977); the second is between endogenous and exogenous processing (Theeuwes 1991, Jonides 1981). Although these distinctions are presented as dichotomies, it is better to think of them as end points on two orthogonal continua. Thus, processing can be more or less automatic or controlled, and more or less endogenous or exogenous. In the following sections, we will give a preliminary description of the endpoints on each dimension as a way of introducing a basic framework for studying the role of attention in driving.

2.3.1. *Automatic vs. controlled processes.* Automatic processes involve selection without awareness. These processes are effortless, fast, and can be carried out concurrently with other processes without compromising performance. Once automatic processes are initiated, they are difficult to modify. Also, automatic processes typically do not produce changes in declarative long-term memory. Consequently, a person may drive home from work on 'auto-pilot' and have no conscious memory of the trip.

In contrast, controlled processes involve selection with awareness. These are conscious processes, but they are also laborious and slow, and it is difficult to carry out several controlled processes at once. Controlled processes can be started, stopped, or modified at will, and can produce conscious changes in long term memory through learning. With practice, some controlled processes may even become automatic. Shiffrin and Schneider (1977) showed that the process of looking for a specific set of letters (e.g. four of the following letters: B, C, D, F, G, H, J, K, or

L) in a field of distractor letters (Q, R S, T, V, W, X, Y, Z) could be made automatic with enough practice, given that the same target letters and the same distractors were always used (consistent mapping). Some controlled processes, however, cannot be automaticized in this way. If letters were switched from being targets to distractors from one trial block to another (variable mapping), automaticization did not occur despite hundreds of trials.

2.3.2. *Exogenous vs. endogenous processes.* Exogenous selection occurs as a result of the way humans are built and it is initiated by the presence of specific stimulus configurations. In this case, external stimuli seem to trigger selection (it is exogenous), but the reason these stimuli produce this effect is because of the way the nervous system is built. Specifically, the nervous system is structured to respond to certain stimuli preferentially, so that there is a continuum of stimulus salience, with some types of stimuli more likely to receive exogenous selection than others. In general, when a person is in an unfamiliar environment, and thus has no specific expectations, exogenous processing is dominant. Similarly, if a person has no specific goals in a familiar environment, exogenous processing dominates.

Exogenous processing is easily confused with bottom-up or stimulus-driven processing, but it is not the same thing. When we refer to exogenous selection we mean something that is 'hard wired'. In contrast, bottom-up or stimulus-driven processing may also occur as a result of extended practice or learning, which are the result of internal (or endogenous) factors. For example, when a person repeatedly carries out a deliberate intention, after a while the response becomes so over-learned that it occurs automatically, and it may seem that the stimulus alone is 'driving' the behavior. Selection has been triggered by the stimulus (bottom-up) independent of any intentional goals (top-down). Nonetheless, this would not constitute exogenous selection in our sense because selection was not 'hard wired'; the association resulted from repeated conscious intentions to carry out a goal (Theeuwes 1991). Some processes are bottom-up but not exogenous.

Endogenous selection results from what people know about an environment and what they want to achieve. People actively search the environment for information relevant to specific goals or intentions; they perform these tasks in ways that are consistent with expectations and previous learning. Expectancies may act as a form of 'perceptual set' causing people to look for specific objects at certain locations. A perceptual set can be advantageous because it directs viewers to the goal-relevant information in a scene, and thus facilitates accomplishment of goals. An example would be looking for the exit ramp sign on a familiar freeway. Endogenous selection helps drivers react more rapidly, as occurs when they anticipate the need to brake (Johansson and Rumar 1971, Van der Hulst *et al.* 1999).

While endogenous selection can facilitate performance, it can also produce errors when drivers miss pertinent information because it is unexpected or does not pertain to current goals (Hills 1980, Rumar 1990). For example, many accidents occur because drivers turn left into oncoming motorcycles at intersections. These accidents are often attributed to the low visibility of motorcycles. However, Hancock *et al.* (1990) noted that this problem might be compounded by the fact that motorcycles are also less expected. Automobile drivers who are familiar with motorcycles are less likely to turn left into their path. Similarly, Rasanen and Summala (1998) analyzed 188 bicycle-automobile collisions in Finland and concluded that faulty expectations were often the cause. Because of the way that Finnish cycle paths are structured, drivers do not notice the cyclists because they come from unexpected directions at intersections. Conversely, cyclists typically notice the automobiles but interpret the slowing of a vehicle at an intersection as evidence that the driver has seen them. The cyclists most at risk are the ones who know that, by law, they have the right of way and thus expect drivers to stop. Although endogenous selection is similar to top-down or goal-directed behavior, it encompasses intentional processes that are so well practiced that they are automatic as well as those that are controlled.

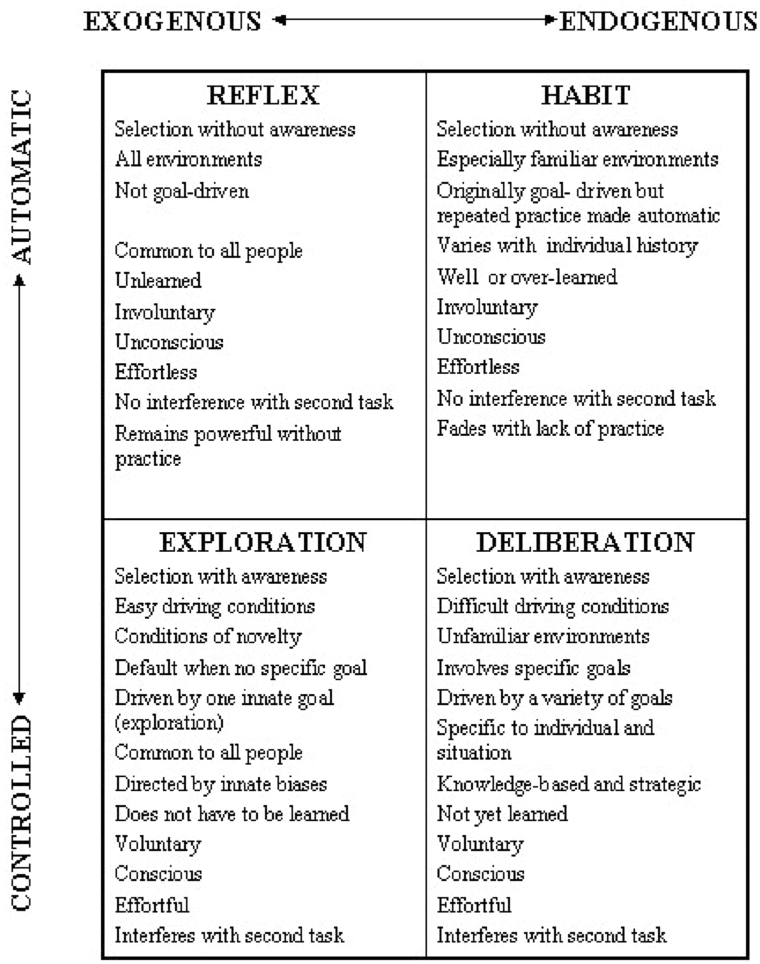
2.4. *Four modes of attentional performance*

By combining automatic and controlled processing with exogenous and endogenous selection, it is possible to derive four modes of performance relevant to the study of attention and driving. The first, automatic-exogenous, can be thought of as the collection of all reflexes that are initiated by stimuli. The second, automatic-endogenous, corresponds to processing that is habitual. The third, controlled-exogenous, corresponds to a mode of performance that occurs when a person's only goal is exploration. The fourth, controlled-endogenous, corresponds to deliberate goal-driven behavior. A summary of the features of the four modes is presented in figure 1.

This framework brings clarity to a confusion that exists within both the attention and driving literatures, namely, the conflation of the distinction between automatic versus controlled processes with the distinction between exogenous and endogenous processes. It is our view that this conflation amounts to confusing the nature of a process (the manner in which it works) with its origin (how it came to be that way). Thus, processes can be automatic or controlled in terms of how they work: either fast, effortless, and obligatory (automatic), or slow, effortful, and optional (controlled). However, this is independent of their origin, which may be either innately specified, and thus common to all (exogenous) or engendered by the specific goals of an individual at a given time and thus idiosyncratic and situation-specific (endogenous).

The model posits four basic modes of selection. Two involve so-called automatic processes, meaning that they are cognitively effortless and can be initiated and completed without conscious awareness, often in less than a second. These two types of process are reflexive (automatic-exogenous) and habitual (automatic-endogenous). There are a number of important differences between reflex and habit. First, though both are triggered by particular stimuli, these triggers are established in different ways. Reflexes are innately 'hard wired' into the system, whereas habits are automatic because a particular goal or intention has been repeatedly carried out. As a result, reflexes are common to all whereas habits are idiosyncratic, based on a given individual's specific learning experiences. Second, reflexes emerge on a developmental timetable and are stable once acquired, whereas habits can be formed at any time, and can also be replaced or fade at any time due to lack of practice or new learning.

Although the distinction between automatic and controlled processes is often discussed as if it referred to a strict dichotomy, it is probably more useful to consider it a continuum of automaticity. Some processes are more automatic than others in the sense that they are initiated more quickly, require less effort, are more likely to be evoked unintentionally in a given situation, and are thus more difficult to bring under deliberate control. In such a continuum, reflexes retain their position near the extreme end on the automaticity continuum, whereas habits change their level of automaticity based on the frequency with which they are practiced. Nonetheless,



REFLEX	HABIT
Selection without awareness	Selection without awareness
All environments	Especially familiar environments
Not goal-driven	Originally goal- driven but repeated practice made automatic
Common to all people	Varies with individual history
Unlearned	Well or over-learned
Involuntary	Involuntary
Unconscious	Unconscious
Effortless	Effortless
No interference with second task	No interference with second task
Remains powerful without practice	Fades with lack of practice
EXPLORATION	**DELIBERATION**
Selection with awareness	Selection with awareness
Easy driving conditions	Difficult driving conditions
Conditions of novelty	Unfamiliar environments
Default when no specific goal	Involves specific goals
Driven by one innate goal (exploration)	Driven by a variety of goals
Common to all people	Specific to individual and situation
Directed by innate biases	Knowledge-based and strategic
Does not have to be learned	Not yet learned
Voluntary	Voluntary
Conscious	Conscious
Effortful	Effortful
Interferes with second task	Interferes with second task

Figure 1. A two-dimensional framework for the role of attention in driving. Combining the dimensions of automatic-controlled with the dimensions of exogenous-endogenous leads to four importantly different modes of attention.

both reflex and habit are automatic, which is to say that both types of process await the appropriate environmental trigger and are constantly under some degree of readiness.

The other two modes of selection involve controlled processes, which are cognitively effortful, intentional, and relatively time consuming (taking 1 second or more). Most importantly, these processes interfere with the simultaneous execution of other controlled processes. We refer to these two modes of selection as exploration (controlled-exogenous) and deliberation (controlled-endogenous). Exploration is the default mode for controlled processing. It is carried out in absence of specific goals but it is goal oriented in that it fulfills a general need to acquire information about objects and events in the environment, and controlled because object recognition requires attention. In contrast, deliberate selection refers to the execution of a chosen attention-demanding process at the expense of other processes, and it is specific to a given individual in a certain situation. The most important distinction between the two modes of controlled processing is that exploration involves a generic goal, common to all human beings in any novel environment, whereas deliberation involves goals that reflect an individual's specific knowledge, plans, and strategies in a certain situation. Both deliberation (controlled-endogenous) and exploration (controlled-exogenous) involve selection with awareness, but only deliberation is top-down in the truest sense because it is guided by an individual's specific goals and expectations.

Though the distinction between these two types of controlled selection is, to our knowledge, unique to this paper, it is consistent with previous research in computational vision. In a now-classic paper Ullman (1984) proposed that the representation of properties in visual objects, by machine or biological visual system, required the application of *visual routines* (Ballard *et al.* 2000, Hayhoe 2000). Routines were described as sequences of primitive operations that require some sort of attentional focus. They are used to derive the basic spatial relations among image features necessary for both object recognition and visual-motor coordination—spatial relations such as enclosure or connectivity. These computations, by their very nature, require processes that are applied to one area of an image at a time. They are consequently time consuming. As a result, routines are assembled and applied intentionally to selected parts of the image only as needed by the viewer (top down). If an observer were looking for a specific object or trying to establish a particular spatial relation, they would deliberately select a specific visual routine and apply it to a specific location in the image. Applied to the present interest, an experienced driver may know with some efficiency where to look and what to look for to find out whether to stop, yield, or continue at an intersection. Sometimes, however, there is no specific goal, and when this happens, Ullman (1984) proposed that universal routines are carried out by default.

However, this leads us to one of the longstanding conundrums in vision. If object recognition requires the attentional focus, and many think it does, and if the attentional focus can only be at one location in the image at a time, how do we know where next to put the attentional focus in order to acquire the maximal amount of useful information quickly? This poses a dilemma because the attentional focus would have to have already visited the location in the first place to determine if the information was useful, as making that decision requires some degree of object recognition. We propose that when there are no specific goals or expectations, when there is nothing in the image that triggers automatic selection (habitual or reflexive), such as an individual's name or a flashing object, innate preferences guide the attentional focus to the most promising (i.e. salient) areas in the image: they guide the application of universal routines. That is what is meant by exploratory selection. It has been known for some time that there are biases to view some parts of the image as figure and other parts as ground. For example, symmetrical areas, or those that contain high spatial frequency information, are more likely to be judged as figure rather than ground (Hochberg 1971, Klymenko and Weisstein 1986). In the same way, we propose that there are common and innate biases to attend stimuli with certain characteristics (e.g. high contrast, moving, convex) in absence of more pressing needs to attend elsewhere based on either deliberate or automatic selection.

Section 3 describes each mode of performance more fully, as applied to the experimental research on driving.

3. Experimental studies on driving

In the following studies, performance is typically measured on the open road, a closed course, or a driving simulator. A wide variety of driving performance indices are used: lane tracking performance (average vehicle position and variability in the lane, time to cross the lane markers if the present course is maintained, heading error, number of steering reversals, etc.); driving speed and variability; braking reaction time; headway between vehicles (number of seconds to collision if the lead driver were to suddenly stop and the following driver continue at the current speed); glance length and variability; and number of driving errors (number of missed signs, percentage of time spent off the road, number if obstructions hit, etc.).

3.1. *Selection by reflex*

Some stimuli initiate effortless, unconscious, obligatory responses that occur even when counterproductive. These reflexes emerge on a developmental timetable and may even be present in the very young. Because these processes were not learned, they cannot be 'unlearned'. At best, when a reflexive process is counterproductive, the response can be reduced in intensity or 'undone' after the fact. In most situations, compensating for reflexive responses requires time, effort, and planning (controlled-endogenous processes). Although it may be possible to learn to compensate for a reflexive response with practice (using a habitual response), it is important to note that the reflexive response is always there. It must be brought under control by other processes if it is to be avoided.

The clearest examples of reflexive selection are visual illusions. These are cases where certain stimulus configurations are selected and processed to yield a percept at odds with reality. Processing is clearly automatic (because it occurs effortlessly, even when counter-productive and inaccurate), and it is exogenous (prompted by natural reactions to stimulus configurations). People do not learn to make these mistakes, and in fact, still experience the illusory percepts even after they have learned that they are inaccurate.

One class of visual illusions originates from the principles of perceptual grouping. The visual system is structured to locate contours in images and group them into clusters based on whether they are adjacent, similar, and can form continuous lines (the Gestalt principles). This is advantageous in most cases but sometimes these reflexive processes go awry, contributing to accidents. Hills (1980, cf. Olson 1996) describes such a 'perceptual trap' created when two non-connected roads appear to be coextensive from the driver's perspective. Drivers fail to notice the turn in the first road and drive right off the highway. Although posting signs to warn of the curve can prevent such accidents, overcoming the illusion requires processing time and effort.

Illusions created by reflexive selection can also be exploited to induce safe driving. Shinar *et al.* (1980) measured driving speeds on dangerous rural road curves, before, immediately after, and 30 days following the introduction of four different modifications designed to decrease driver speed. One involved increasing the visual angle of the inside lane on the corner and a second involved the Wundt illusion. A third used a series of transverse parallel lines that became closer together over distance, thus creating an illusion of acceleration as the driver crossed them. In the final modification, drivers were simply warned of the dangerous curve with a sign. (See figure 2, from Shinar *et al.* 1980, pp. 268–269.)

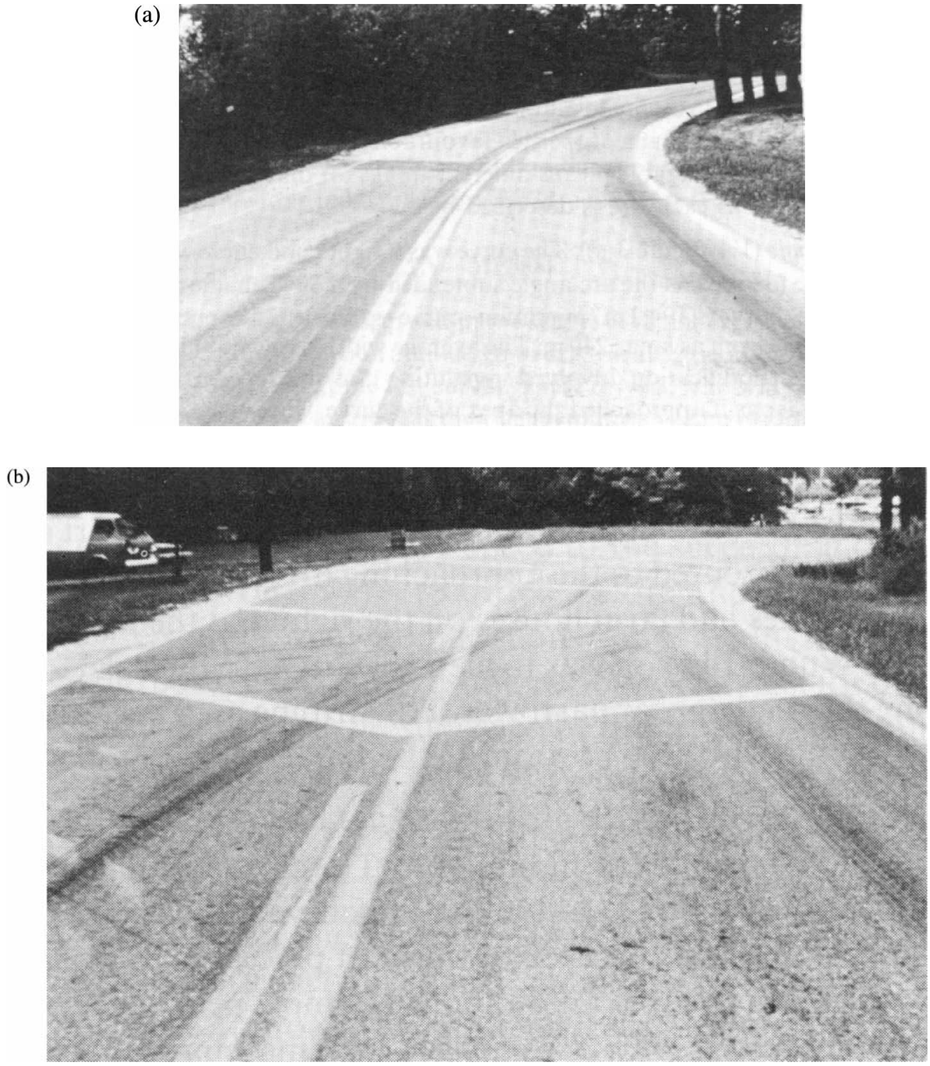


Figure 2. Techniques for slowing drivers at dangerous curves from Shinar *et al.* 1980, pp. 268–269: a) increasing visual angle of the inside curve; b) using the Wundt illusion to make the road seem narrower; c) decreasing the distance between adjacent transverse stripes on the road; d) posting a warning sign. Figure reprinted with permission of Taylor & Francis Ltd. (http://www.tandf.co.uk).

Shinar *et al.* (1980) found that although the sign was ineffective, the visual illusions reduced driving speed, particularly the parallel transverse lines (see also Hills (1980)). Each effect was specific to the curve with the modification and did not transfer to other curves. Oddly, the illusions were more effective in reducing the speed of cars than trucks, perhaps because cars are closer to the road and thus drivers could not see as many peripheral depth cues that contradicted the illusion. After 30 days, local drivers were no longer decreasing speed as much in response to the illusions, which suggests they had learned to override them. Nonetheless, the illusion-based modifications were deemed a success because the drivers most at risk

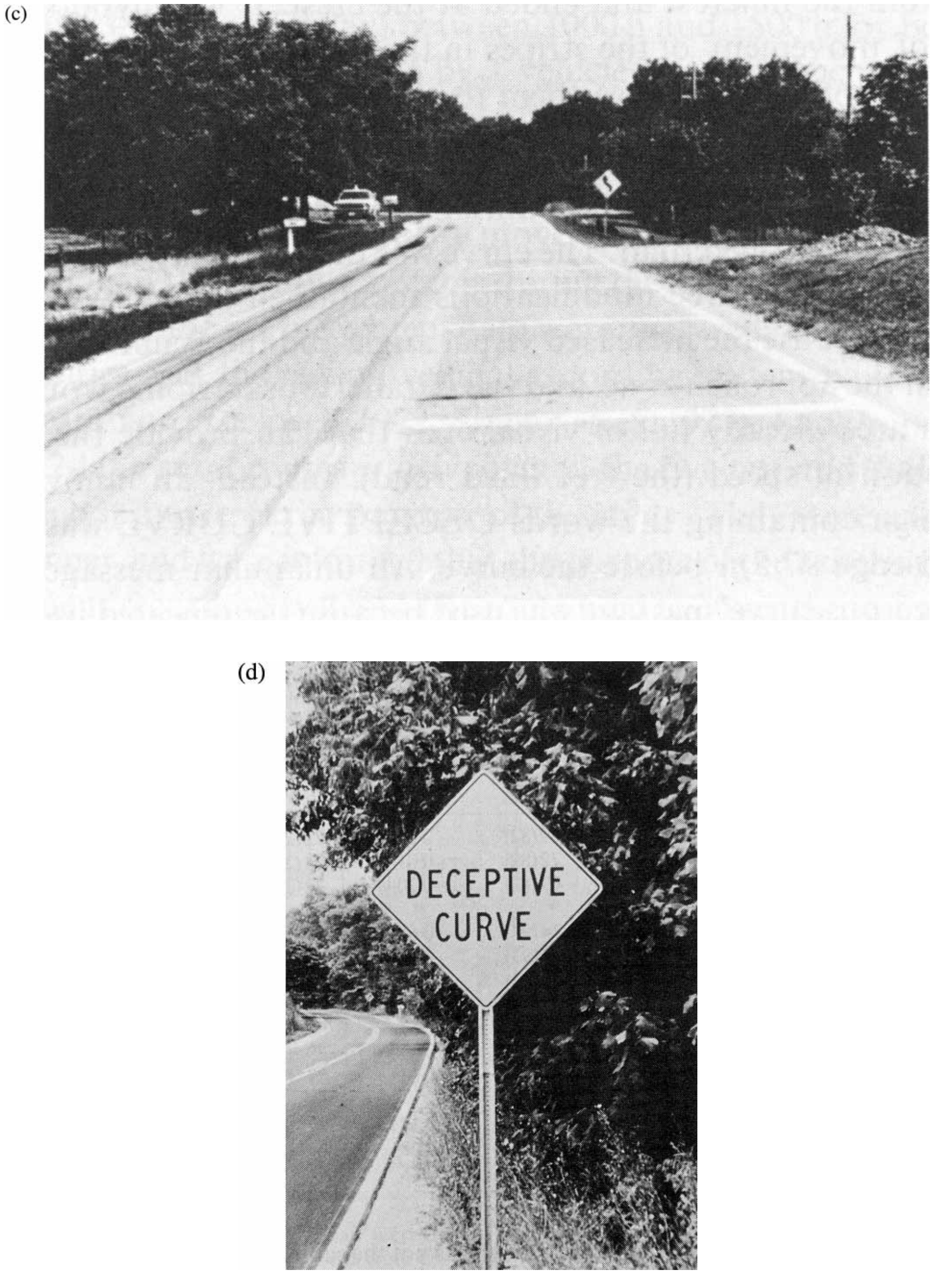


Figure 2. *Continued.*

were ones who were unfamiliar with the road. If these road-marking illusions involved reflexive selection, they should influence local drivers once again when drivers' attentional resources are depleted by inebriation or fatigue, but this prediction has yet to be tested.

Certain stimulus features, such as the sudden luminance increases that signal the presence of a new object (Yantis 1993), can trigger reflexive selection and consequent re-assignment of the attentional focus (automatic orienting). For example, in some cue validity studies, a sudden flash of light (a stimulus cue) at a particular location is used to prompt participants to move their attentional focus to the cued location in the field. This type of orienting seems to be reflexive in that it occurs even when the position of the cue does not predict that of the target. If the cue falls on the location that the target will occupy, this can speed processing, but in the majority of cases, where the cue does not predict the location of the target, this impedes target processing (e.g. Jonides 1981).

Similarly, in *search* tasks, attention is drawn to a flashing item first even the flashing item is seldom, if ever, the target (Jonides and Yantis 1988). In some situations our eyes and our attention can be drawn to locations where we do not want them to be (Theeuwes *et al.* 1998). However, it is possible to overcome this type of capture with adequate preparation beforehand (e.g. deliberately directing attention to another location, Yantis and Jonides 1990, Theeuwes *et al.* 1998) or compensation afterwards, though this typically takes time and deliberate effort (deliberate processing). The issue of reflexive attentional capture is of special relevance given the current practice of using flashing lights for turn signals and emergency vehicles such as police cars and ambulances.

Reflexive cues can also be exploited to signal drivers when they are going off the road, which may be especially helpful when visibility is poor. For example, Blaauw (1985) suggests using raised pavement markers to aid in lane keeping. Driving over these markers might be expected to produce sounds and vibrations that are selected automatically. Because drivers do not need to learn to select these cues, there is good reason to believe this tendency would be exogenous.

Thus far, we have been discussing cases of reflexive selection of stimuli. There may also be cases where one action causes the reflexive selection of another. Although most actions performed by drivers in vehicles are learned rather than reflexive, there are possible exceptions. Consider an effect often observed by driving instructors. There is a tendency for novice drivers to turn the steering wheel in the same direction as they move their eyes: steering to left when looking left, for example. This can cause accidents, and novice drivers have to be trained not to do it. Because this tendency can be observed even in young children learning to drive tricycles, this may represent an example of reflexive selection of actions.

3.2. *Selection by habit*

When a goal is enacted repeatedly, carrying it out can become habitual and unconscious, and the processes associated with it may become effortless. Although habits are often thought of as over-learned actions, we propose that there can be habits of stimulus selection as well, even though these may not result in overt motor response. In a search task, targets defined by an arbitrary conjunction of features, or even by an arbitrary set of spatial relations among forms, can ‘pop out’ after extensive training (Heathcote and Mewhort 1993, Wang *et al.* 1994). This presumably lies behind the efficiency of visual search involving over-learned stimulus sets such as letters and digits (Egeth *et al.* 1972). Moreover, even the spatial arrangements of search displays are learned unconsciously, if they are predictive of the target’s location (Chun 2000). In the auditory modality, well-learned pertinent stimuli such as an individual’s name may draw attention automatically, because of a habitual tendency to seek self-relevant information (e.g. Cherry 1953). These responses are adaptive in that they efficiently draw the attentional focus to relevant information.

Repeated actions also become automatic with practice; this is commonly what is meant by skilled behavior. Reason (1990) claims that one of the principle differences between novices and experts is that experts possess a larger number of skills: motor programs that can be automatically activated by conditions in the environment. In this case, it seems as if the stimulus is controlling the behavior, but in fact it only does so because the processes involved in achieving a certain goal in a certain situation have become automatic with practice. Because the word ‘skill’ has positive connotations, we prefer the more neutral word ‘habit’ to refer to these automatically evoked motor programs.

In many cases these habits are adaptive. They allow us to perform efficiently in familiar situations, and carry out several actions at once. However, habitual performance is subject to certain kinds of error. For example, in filtering tasks, the well-learned and habitual response of reading an individual word impedes performance when the task is to simply name the ink color of a written word (Stroop interference). Reason (1990) talks about a variety of different slips of action that occur in skilled performance because of faulty monitoring of automatic processes. One is the double capture slip, so named because it involves two distinct types of capture. First, the controlled processing resources are ‘captured’ by distracting thoughts or external stimuli. Second, the control of action is ‘captured’ by a well-rehearsed or dominant automatic motor program. A classic example occurs when drivers resolve to take a novel route home so that they can perform an important errand. As soon as they start thinking of something else, they might find themselves traveling their usual route despite their intentions. The well-practiced motor program for driving that familiar route takes over. Better monitoring of the automatic processes would have prevented this, but that would require the attentional resources that were usurped by the distraction.

The studies of most relevance to selection by habit involve the acquisition of driving expertise. It is undeniable that inexperienced drivers are extraordinarily prone to accidents (Ranney 1994, McGwin and Brown 1999, Groeger 2000), an effect only partly attributable to personality characteristics associated with youth. One reason may be that inexperienced drivers lack knowledge necessary for good judgments (controlled-endogenous selection: knowledge- and rule-based performance, Rasmussen 1982, Reason 1990). Another may be that inexperienced drivers lack driving habits (skills) that permit them to carry out routine driving tasks while attending to something else, an idea supported by many studies that show experienced drivers have less difficulty carrying out secondary tasks while driving (Summala *et al.* 1996, Shinar *et al.* 1998, Wikman *et al.* 1998). At this point, however, it is not entirely clear which aspects of driving become automatic. Truly automatic processes occur even when they are counter-productive; they permit two tasks to be performed as easily as one. It seems unlikely that every component of driving has become automatic given such stringent criteria. Truly automatic behavior can be maladaptive because it is so stereotypic and inflexible. It is more probable that only certain components are selected by habit, but these components are monitored and coordinated by supervisory processes that involve deliberate selection (Groeger 2000). Nonetheless, a number of studies have suggested some candidates that might fit the criteria for selection by habit.

To date, there has been relatively little investigation of how stimulus selection develops with experience. This may be because it is hard to know which stimuli are selected in driving studies. This is true even when the information is selected with awareness. In the past, there have been two approaches to this problem: questioning drivers about what they notice as they drive (Cole and Hughes 1984, Hughes and Cole 1986) and monitoring eye movements on the assumption that foveated information is attended (Moray 1990, Land and Horwood 1995). In the case of perceptual selection without awareness, it is even more difficult. One approach is to look for instances where drivers use non-foveal (presumably unattended) information in order to accomplish some driving tasks while foveal (attended) information is used for other tasks. Ideally, to make the argument that this is the result of habitual processes, these studies should also show that this tendency to use non-foveal information develops with driving experience and persists even in situations where it is not helpful, as habits are wont to do.

To this point, there has never been such a demonstration. However, a close approximation exists in a study that used a forced peripheral vision paradigm (Summala 1998). Experienced and inexperienced drivers were required to drive along a short test track while foveating an in-car display that was below the line of sight by either 7, 23, or 38° (the level of the dashboard, speedometer, and radio respectively). Their task was either to name all digits in the display (presented 1/s) or all the digits containing the number 4 (presented 4/s). The proportion of the test track that was traveled before the drivers crossed the road margins was measured. Summala (1988) found that the performance of experienced drivers did not deteriorate until the secondary task was far below the line of sight (38°). In contrast, the inexperienced drivers had difficulty keeping the car within road margins when fixated on a display only 23° below the line of sight (at the level of the speedometer). Subsequent studies established that experienced drivers were no more likely to use kinesthetic cues to maintain lane position (they were no better than inexperienced drivers when driving blindfolded). These results suggest that experienced drivers may have learned to select peripheral visual cues to keep the car on the road while looking and attending elsewhere, and that may explain why experienced drivers move their eyes differently than inexperienced drivers (Mourant and Rockwell 1972). However, these peripheral cues were not useful for all tasks. Summala *et al.* (1998) found that experienced drivers had no advantage over inexperienced drivers when the forced peripheral vision paradigm was used and drivers were required to respond to a braking car ahead.

Wikman *et al.* (1998) studied a different type of stimulus selection process. The ability to make appropriate eye movements is an important component of stimulus selection, and monitoring glance duration is necessary for appropriate eye movements. Wikman *et al.* (1988) found that the standard deviation of glance duration decreases with driving experience, which would be expected if glance duration control was becoming habitual and automatic. Inexperienced drivers made more dangerously long (over 2 s) or ineffectively short (less than 500 ms) glances towards a variety of secondary tasks (taking out a cassette, dialing a mobile telephone, tuning the radio) while driving. Habitual behaviors are characteristically rigid and stereotyped, and this would explain the decrease in glance duration variability with driving experience.

Though it is difficult to demonstrate the automaticity of perceptual selection processes when driving, it is easy show that motor responses are automatic. ‘Habit lag’, the inappropriate intrusion of old automatic behavior into new tasks is a case in point (Mannell and Duthie 1975). For example, when drivers switch from regular to anti-lock brakes they often go through a difficult transition period where they continue to pump their brakes when they try to stop suddenly. Similarly, Korteling (1994) demonstrated that steering and using the accelerator were automatic in experienced drivers by trying to get them to reverse the polarity of their actions (i.e. turn the wheel right when they wanted to go left, and hit the gas when they wanted to slow down). Steering was so strongly automatic that the participants could not unlearn it in the course of the experiment, and kept going 'off road' in the driving simulator and getting lost. The participants eventually did learn to hit the gas pedal in order to slow down, however.

The strongest evidence for habitual selection comes from studies that demonstrate 'habit lag', because these highlight the obligatory nature of automatic processing, but another way to study this type of processing is by using a dual-task. Shinar *et al.* (1998) studied gear shifting in cars that had manual and automatic transmissions. Drivers were either inexperienced (approximately 1.5 years driving) or experienced (8+ years), and were tested in their own car, which had either a manual or automatic transmission. Their secondary task was sign detection. The relevant signs were located near intersections, at places where gear shifting would have to occur for vehicles with manual transmissions. For inexperienced drivers, significantly more of these signs were detected by those with automatic transmissions than manual, but this difference was not significant in the experienced drivers who had 8 or more years of practice. This finding suggests that some time after 1.5 years of practice, shifting gears becomes automatic for drivers of manual transmission vehicles, or more specifically, any components that are still controlled do not impede sign detection to a statistically significant extent (Groeger 2000).

There are times when the habits that develop with experience put the driver at risk. Duncan *et al.* (1991) compared the performance of three groups: novice drivers (who had received their driver's license in the last year), experienced drivers (who had their driver's license for at least 5 years), and expert drivers (veteran drivers who had passed a very difficult course from the Institute of Advanced Motorists). In some ways, novices were more similar to experts than the experienced drivers were. Novices checked their mirrors more often and were more likely to brake at a safe distance from an intersection. Novices were better than the other two groups in leaving an adequate distance when following another car. Duncan *et al.* (1991) concluded that the driving environment is too forgiving to properly train a good driver through reward and punishment. Drivers may speed and follow too closely on a daily basis and yet avoid accidents. Although these actions may initially be chosen deliberately, if there are no negative consequences they will be repeated and may become automatic. They may even supplant good habits taught in driving class if they are practiced more frequently. Once a response is automatic it is difficult for a driver to suppress if the triggering conditions are met. For example, drivers may leave the house resolved to drive slowly because of black ice warnings, but may find themselves speeding as usual once they reach a familiar expressway and start attending to something else (Reason 1990).

It would be good if safe habits developed as easily with experience, but Reason (1990) noted that it was difficult to get individuals to learn to avoid dangerous situations; people tend to learn more from 'near misses' than safe behavior. Near misses seem to give drivers a sense of mastery and control. They may see them as an opportunity to practice emergency maneuvers (rapid steering and braking, pulling out of a skid). What drivers learn from these experiences is how to barely avoid disaster rather than how to drive safely. They may learn inadvisable rules (e.g. 'If

I cannot yet read the license plate of the car ahead then I can approach closer'), and if rules are practiced enough they become ingrained as habits, that is, processes activated automatically by stimulus conditions.

3.3. *Selection through exploration*

Some visual stimuli are processed preferentially when a person is exploring an unfamiliar environment, with no goal other than to gain new information. Some actions are performed even though there is no particular reason to carry them out, simply for the pleasure of manipulating a novel object. Stimulus attributes can direct controlled processing when the goal is simply to explore, and the perceptual system is structured to give some stimuli more emphasis than others. With selection through exploration, salient stimuli attract attention; they do not command attention, as they do in reflexive orienting. Selection through exploration is effortful, and when necessary, it can be modified, aborted mid-way, or even avoided altogether without undue planning or practice. All that is required is that the attentional focus be given a specific assignment. Exploratory processing is under conscious control, in that it involves selection with awareness, but it tends to occur when there are no specific goals to guide behavior. This occurs when the demands of the task are so low that the driver feels they can afford to relax and explore.

Selection through exploration is the least researched of the four modes of attention, and to this point, the clearest examples involve stimulus selection. Experienced drivers adjust their pattern of eye movements in ways that are consistent with the goal of maneuvering their vehicle through a particular driving environment (Crundall and Underwood 1998). However, in aimless and unguarded moments, when the driving task is not too demanding, more open-ended exploration may occur. Hills (1980: 189) discusses how skilled drivers indulge in 'eyeball exercises', random eye movements that are directed by events in the periphery, when drivers are not perceptually loaded by the driving task. As soon as there is a specific task to perform, however, attention can readily be devoted to driving without much effort.

What stimulus attributes produce selection through exploration? Cole and Hughes (1984) and Hughes and Cole (1986) discuss how the 'sensory conspicuity' of an object, its tendency to stand out even when not being sought, is determined by its retinal size, eccentricity from the center of gaze, and contrast with the background. They compared this with the conspicuity of an object when drivers specifically set out to find it. In their study, participants were required to drive along a road and report things that they noticed as they saw them. In one condition they were directed to look for white disks on the side of the road, and in another they were told to report everything that attracted their attention. Very few disks were reported unless the drivers were specifically directed to look for them, though it was more likely for the disks to be reported in areas where there were few other things to look at (in residential areas as opposed to shopping areas). When drivers were specifically told to look for white disks, more were reported. Thus, although the disks were conspicuous enough when observers specifically set out to look for them, when there was no specific goal, these disks did not stand out that much from the background. They lacked 'sensory conspicuity', that is, they were not exogenously selected. People tended to look at other things instead, and the more other things there were to attract attention, the less likely it was that the disks were noticed. A similar principle may explain why signs are more likely to be noticed and later recognized at night than during the day (Shinar and Drory 1983).

There are periodic concerns about the effects of roadside advertising, low flying planes, etc., on driver attention. Based on a review of a number of studies, Smiley (1994) concluded that although these stimuli can draw driver attention away from the road, they typically do not pose a significant problem because skilled drivers can readily refocus their attention and 'shed' irrelevant information. Moreover, it may be impossible to prevent drivers from exploring their visual environment. If driving does not require the drivers' full attention, they devote their attention elsewhere. For example, if they do not attend roadside advertising, they attend trees and the scenery (Cole and Hughes 1984, Hughes and Cole 1986). The danger occurs when the driving situation suddenly and unpredictably changes, and split second timing is required. Attention switching may require a second or more.

Sometimes the stimuli that attract attention are inside the vehicle. Exploratory selection is especially likely to occur in conditions of novelty, and this may explain why drivers spend a disproportionate amount of time looking at in-vehicle devices when they are new (e.g. Dingus *et al.* 1997). Many such devices are engineered with colorful, high contrast displays to maximize readability and consequently they may compete successfully with stimuli external to the vehicle for controlled-exogenous selection.

This may be particularly problematic if the display for the in-vehicle device is superimposed on the outside world, as it is with 'heads-up' displays. Tufano (1997) argues that the salience of heads-up displays makes it difficult to see what is actually going on in the outside world, and this is especially true if the outside event is unexpected. This problem with conspicuity is complicated by the fact that the heads-up display projects onto a different depth plane than the important objects in the world. This may produce an illusion whereby objects outside appear smaller and farther away than they actually are (Tufano 1997), or at the very least leave the objects slightly out of optical focus (Wolffsohn *et al.* 1998).

3.4. *Selection through deliberation*

Individuals often deliberately and consciously form specific goals and then endeavor to achieve them. This too involves selection with awareness, but in this case the observer's particular goals, plans, and conscious expectations determine what is selected. For example, in laboratory orienting tasks, observers will deliberately move their attentional focus in response to an arrow cue in the center of a screen (a symbolic cue) if they know that the arrow predicts the actual location of the stimulus with a high probability: they will not do so otherwise. This is in contrast to what happens with stimulus cues, which produce obligatory re-assignment of the attentional focus, as in reflexive stimulus selection.

In driving situations where stimulus information is degraded, as in fog or a blizzard, selection through deliberation may be used to compensate for low quality perceptual information. The attentional focus serves to increase the visibility of items within the attended area so that they can be responded to more quickly and accurately (Posner 1980). In complex perceptual tasks, such as reading lines of text, deliberate selection is needed. Similarly, in search tasks, when there is need to locate a particular stimulus in a background of distractors and stimuli are complex, or when the principle underlying the visual discrimination is abstract, controlled-endogenous processing is required. Looking for a specific landmark or sign in an unfamiliar area would involve this type of selection.

Selection through deliberation is necessary when learning how to carry out a new action because the action plan must be formed with on-line control, using feedback from the environment to guide further actions (cf. Reason 1990: *knowledge based* processing). It may also be necessary when two familiar tasks are performed together for the first time (Korteling 1994). When an individual deliberately invokes the motor program associated with one task in order to accomplish another very different task, it involves selection through deliberation (cf. Reason 1990; *rule based processing*). Both determining which of two incompatible processes should occur first and monitoring and overcoming inappropriate automatic processes require this type of selection (Reason 1990, Shallice and Burgess 1993, Groeger 2000). In general, selection through deliberation is required whenever a problem occurs or an error has to be remedied (Reason 1990). Certainly, the ability to go beyond the stimuli in the immediate environment to project events into the future requires deliberate selection (Level 3 situational awareness: (Endsley 1995)).

Of all the types of processing, controlled-endogenous is the most flexible and responsive to new information because it is conscious and internally directed. With this type of processing, there is hope of changing behavior rapidly (within seconds) in response to symbolic information, such as an oral command or the written messages on signs. The disadvantage of this type of processing is that it is difficult to perform several controlled activities simultaneously. There is a limitation in the amount of information that a person can be consciously aware of at any one time. This limitation explains ‘bounded rationality’, the tendency to only consider a subset of the relevant information when solving problems (Simon 1983, Reason 1990), and restrictions in situational awareness (Endsley 1995).

Selection through deliberation is also noticeably effortful. When the demands of deliberate processing becomes high, it is manifested in self-report measures of cognitive strain such as the NASA multidimensional task load index (NASA-TLX), and in physiological measures such as eye blink rate (e.g. Hancock *et al.* 1990), heart rate and heart rate variability (e.g. Richter *et al.* 1998).

There are a large number of studies relevant to selection through deliberation, and most involve the dual-task paradigm. In these studies, driving is typically coupled with another deliberate task that does not intrinsically go with it, such as mental multiplication, reasoning, holding numbers in memory, etc. There is often interference between tasks (Noy 1987, 1990, Hancock *et al.* 1990, Harms 1991, Zeitlin 1995, Liu 1996, Radeborg *et al.* 1999, Haigney and Westerman 2001). The amount of interference produced on the secondary task has been used to measure attentional workload generated by driving. Workload increases as the driving task becomes more difficult, as it changes from straight to curved roads, or from country roads to more urban environments (Hancock *et al.* 1990, Noy 1990, Harms 1991).

When people monitor or use devices such as radios, climate control devices, heads-up displays, there is also interference and increased perceived workload (Noy 1990, Beh and Hirst 1999, Wollfsohn *et al.* 1999, Verwey 2000), and work has already begun on relating traffic accidents to the demands of various in-vehicle devices (Wierwille and Tijerina 1998). There are a number of studies that demonstrate the deleterious effects of in-vehicle telephones on performance (Brown *et al.* 1969, Goodman *et al.* 1999, Lamble *et al.* 1999a, Reed and Green 1999, Garcia-Larrea *et al.* 2001, Utter 2001), and there is evidence to suggest that interference occurs regardless of whether the system is handheld or hands-free. Strayer and Johnston (2001) argue that conversing on cellular telephones interferes more than other secondary tasks such as holding the phone, listening, or repeating a spoken word, because it diverts drivers' attention into an engaging cognitive context that is unrelated to driving. Though drivers may endeavor to compensate for the increased risk by slowing down (Haigney *et al.* 2000), as they sometimes do when there is another person in the car (Baxter *et al.* 1990), it is clear that cellular telephones pose a risk to many drivers. There is also evidence that in-vehicle traveler information systems may interfere, though the level of interference depends on the way in which the information is delivered (Liu 2001).

Overall, in dual-task studies, the interference between tasks has been explained in terms of a limited attentional resource that must be shared between tasks. When task demands exceed the attentional resources, performance on one or both of the tasks suffers. Debate has centered on whether there is one or more fixed resource that must be shared by all tasks, tapped to different degrees by different tasks (Wickens 1992), or whether attentional resources can be expanded as a result of mental effort (Kahneman 1973, Matthews *et al.* 1998).

3.4.1. *Rumination and self-monitoring*. Although the dual task studies typically involve two or more physical responses, it is possible that a task can interfere, even if it does not result in an overt action. For example, it is possible that rumination can act as a secondary task and thus compromise performance on other tasks. There is a large body of literature that suggests that 'self-spectatoring' can impede performance in a variety of domains (Sarason *et al.* 1996), and this has been used as evidence that self- monitoring and self-evaluation act as secondary tasks (Kuhl and Koch 1984).

This may be especially true for those who tend to be negative in their evaluations. Matthews *et al.* (1998) identified a group of drivers who exhibited negative self-appraisals about their driving and a tendency to become self-critical when stressed, which he called high DIS drivers. (DIS stands for dislike; DIS correlates only moderately with neuroticism.) High DIS drivers spent more time thinking about their driving performance as they drove (task-related cognitive intrusions, Matthews *et al.* 1996). Interestingly, though high DIS drivers made more driving errors in the simulator (e.g. driving off the road, getting into collisions), they were no worse than other drivers when the task was to detect a pedestrian. They were also no more likely to be in traffic accidents outside the laboratory (Matthews *et al.* 1998), perhaps because they were cautious drivers. In a dual-task situation, when the demands of a secondary reasoning task were increased, high DIS drivers reported fewer task-related cognitive intrusions, as might be expected if the secondary task partially displaced self-evaluation (Matthews *et al.* 1996).

3.4.2. *Inexperience*. The dual-task paradigm has also been used to study the effects of experience. Though most of these studies confound inexperience with the youth of the driver, some of the effects can even be observed when older and more experienced drivers use a rental car (Al-Balbissi 2001). Inexperienced drivers rely more on controlled-endogenous selection. There are a number of studies showing that inexperienced drivers have greater difficulty driving while performing another task (Summala *et al.* 1996, Shinar *et al.* 1998, Summala 1998, Wikman *et al.* 1998). In fact, they may have difficulty simply keeping the vehicle on the road while maintaining a designated speed, as shown in a study by Ellingstadt, Hagen and Kimball (1970, cited in Reason 1990). The inexperienced drivers progressed through three stages. First they drove far below the required speed and devoted all their efforts to keeping the car on the road. Second, they were able to keep the car on the road but their speed fluctuated wildly between too fast and too slow. In the final stage, the drivers managed to keep the car on the road while maintaining the desired speed, as would be expected if the tasks had become automatic. Certainly, multiple action monitoring is improving.

3.4.3. *Alcohol.* Although there are a wide variety of substances that influence attention as it relates to driving, alcohol is the most frequently discussed. The general theme that characterizes the influence of alcohol on driving performance is depression in neural activity. Depressed neural activity has an immediate and significant effect on all cognitive-motor processing, ranging from decreased sensory acuity (Hellekant 1965) to delayed and aberrant judgment and decision making (Mongrain and Standing 1989) to slowed motor responses (Varma and Malhotra 1988, Loke 1992). Furthermore, chronic use of alcohol seems to have a cumulative effect in slowing sensory-motor responses (Dennis 1993). Because processes that involve deliberate selection are normally the most time consuming, it is deliberate selection that suffers most with slowed processing. However, alcohol may also compromise the quality of the stimuli that serve as input to automatic processes, and if the automatic processes are no longer operating properly, it puts even greater demands on selection through deliberation if performance is to be maintained. (The focus of attention can be used to partly compensate for poor quality sensory information for example.) Though alcohol influences both reflexive and deliberative processing, we will focus on its effects on selection through deliberation in this section.

Laboratory studies have examined the rate at which an observer can switch attention from one attribute of a display to another (Sekuler and MacArthur 1977, Phillipson and Harris 1984), the ability to sustain attention in a visual vigilance task (Rohrbaugh and Stapleton 1988), visual search (Maylor and Rabbitt 1987, 1988), target detection in the visual periphery (Gustafson 1986), visual-motor tracking (Maylor and Rabbitt 1990), and word categorization (Maylor and Rabbitt 1988). The results are uniform in indicating that even moderate levels of blood-alcohol content (within legal limits) impair these abilities significantly and larger doses produce impairments that are catastrophic. One finding that is particularly troubling concerns the role of alcohol in impairing judgments of size and distance. Alcohol impaired observers behave as though objects are smaller and more distant than they actually are (Farrimond 1990, Neill and Delahunty 1990, Miller 1991, Nicholson and Wang 1992).

Studies concerned with driving under the influence of alcohol leave even less doubt about its dangers (Vanakowski *et al.* 2000). Alcohol-impaired drivers are more likely to weave from lane to lane (Louwerens *et al.* 1987, cited in Brookhuis 1995) and follow leading cars too closely (Fairclough and Graham 1999). Also, alcohol is associated with slowed responses and exaggerated difficulties in carrying out secondary tasks while driving (Mascord *et al.* 1995, Ryan *et al.* 1995), and the effects are further aggravated by driver inexperience, age, or fatigue (Krull *et al.* 1992, Krull *et al.* 1993, Mascord *et al.* 1995, McGwin *et al.* 1999, see Vanakowski *et al.* 2000 for a different perspective).

3.4.4. *Fatigue*. Fatigue has been defined as the unwillingness to continue a task that comes with exhaustion (Brown, 1994, cited by National Center on Sleep Disorders Research/National Highway Traffic Safety Administration [NCSDR/NHTSA] 1998). Sustained physical labor, mental load, and sleep deprivation can all produce fatigue and sleepiness, and there is an extensive literature on circadian rhythms as they affect vigilance, fatigue, sleepiness, and vehicle crashes (Lauber and Kayten 1988, Brown 1994, Folkard 1997, Connor *et al.* 2001). When drivers are fatigued they progressively withdraw the attentional resources needed for safe driving, either because fewer resources are available or because drivers fail to match their efforts to the difficulty of the task (Desmond and Matthews 1998). Accidents produced by fatigue have certain characteristics: they are inclined to be serious single vehicle crashes that occur at high speeds with drivers who are driving alone, in their own car, typically on dry and uneventful stretches of the highway (NCSDR/NHTSA 1998, Sagberg 1999). Because controlled processing requires more effort than automatic, it would be expected to deteriorate more with fatigue. Drivers may be less inclined to curtail resources for controlled processing in the face of challenging driving conditions or a secondary task that demands deliberate selection, however.

Which processes deteriorate with fatigue? An early study showed that prolonged driving *per se* could produce a reduction in performance, and some aspects deteriorated more than others with time on task (Brown 1967). Two groups of drivers were compared. One made two short drives, one in the morning and one in the afternoon. The other group also drove in the morning but was required to continue driving straight through until the afternoon testing (7 hours with a 15 minute break). The group that drove all day made more perceptual errors (anticipation of traffic changes, inappropriate positioning on the road, delayed response to unexpected events). This group also showed a marked reduction in driving courtesy (use of turn signals, adherence to speed limits, and giving appropriate precedence to other drivers at junctions). These aspects of performance may well require controlled processes—specifically deliberate selection. In contrast, the use of vehicle controls did not deteriorate over the course of the day, as would be expected if these processes were habitual and thus automatic. More recently, Van der Hulst *et al.* (2001) showed that performance on high-priority subtasks, such as hazard avoidance, does not deteriorate as much as other aspects of driving performance with extended time on task.

Some selection continues even when controlled processing is withdrawn, which explains why certain stimuli are registered even when an individual is asleep or unconscious under anesthetic. Automatic (reflexive and habitual) selection persists, and this may explain why fatigued drivers sometimes ‘rise to the occasion’. Fairclough and Graham (1999) had participants driving in a simulator and induced fatigue by sleep depriving the drivers either for 4 or 8 hours. They found that sleep deprived drivers, like inebriated drivers, made lane-keeping errors. In contrast, Summala *et al.* (1999b) found no deterioration in lane position variability when they had drivers navigate a 1200 km course from Helsinki to Oslo and back in an instrumented car. The drive took place between 8 p.m. and 8 a.m. and a passenger accompanied the driver on the trip. Drivers and passengers were encouraged not to talk with each other. Although the drivers maintained their performance, they blinked more frequently as the night progressed (an indication that greater effort was being expended to stay awake), and they had periodic micro-sleeps, as did the passengers. Interestingly, sleeping drivers seemed to rouse themselves at critical moments, when another car approached or they had to make a turn. Passengers did not. Verwey and Zaidel (1999) also noted that drowsing drivers sometimes roused themselves at critical moments, though their study used a driving simulator. They found that their drowsy drivers would routinely drive off the road, but tended to rouse themselves for an oncoming car. There were surprisingly few collisions even though the drivers were often asleep again by the time the car passed. This may be because some aspects of the stimulus display evoked automatic exogenous or endogenous selection, and as a result, increased the arousal for just long enough for the driver to make the appropriate response. Unfortunately, these stimuli were not always available. Some types of auditory and tactile information are selected automatically, and one approach to crash prevention involves using buzzers and rumble strips to alert drowsing drivers. It is also possible that certain visual cues, such as sudden dramatic changes in brightness, may filter through closed eyelids and trigger automatic selection even when drivers are asleep.

Fatigued drivers may not withdraw as many of their resources when put in situations that demand increased deliberate selection. In fact, their performance may actually improve when the task is made more difficult or when an attention-demanding secondary task is introduced, which is in contrast to what happens with alcohol. Desmond and Matthews (1998) induced fatigue by having drivers perform a difficult task for long periods of time (deciding whether the only digit in a 7 character string was odd or even on signs that occurred every 40 m). They found that though lane-keeping performance deteriorated over time, this effect was most pronounced on easy driving tasks rather than harder ones—more for straight roads than curved. In another study, Ellingstad and Heimstra (1970) had drivers steering from 8 a.m. to 11:45 p.m. (~15 hours with three breaks) while performing a variety of secondary tasks. Lane keeping deteriorated with time, but secondary task performance was variable and vigilance tasks actually improved. (Vigilance usually deteriorates over time.)

There have been several attempts to use secondary tasks to prevent fatigue-related automobile crashes. Verwey and Zaidel (1999) achieved good results with a 'gamebox', an auditory device that gave the driver a choice of 12 games to play while driving. Fatigued drivers who used the gamebox were less likely to fall asleep. At this point it is unclear whether the gamebox would be more effective than other secondary tasks or if it would continue to be effective once the novelty wore off. Desmond and Matthews (1997) tried to use evaluation anxiety as a secondary task to increase arousal levels. They manipulated this by periodically telling drivers that their performance was 'now' being assessed. The message did produce some improvement in driving but only late in the drive and on the straight roads (the easy driving condition). Overall, the finding that secondary tasks can prevent drivers from falling asleep is consistent with reports from professional drivers, who claim that citizens' band radios and cellular telephones help them stay awake (Goodman *et al.* 1999). At present, however, the best strategy for the drowsy driver is to get off the road and get some rest; even a 20 minute nap will help, as will two cups of coffee (NCSDR/NHTSA 1998).

3.4.5. *Spatial factors.* Although limited-resource theories easily explain the difficulties inherent in carrying out two tasks at once, they have less success explaining why a secondary task restricts the size and perhaps even the shape of the visual field that a person can attend. Attention demanding tasks can limit the area that is processed in the periphery. Ball *et al.* (1988) required observers to make difficult perceptual discriminations for centrally presented faces, and also to indicate the position of a round face in a field of square distractors in the periphery (displays were shown for 90 ms and then masked). They found that the more difficult the central task, the more localization performance deteriorated in the periphery. Round targets typically 'pop out' in search among square distractors, and indeed performance was not affected by whether there was 23 or 47 distractors, as would be expected if search was preattentive. However, the central task seemed to limit the area over which this preattentive search could take place, and the limitation was exaggerated when the central task was made more difficult. Rantaanen and Goldberg (1999) found that when observers counted auditory tones of different frequencies, the size and shape of their visual field changed, as measured by the kinetic version of the Goldmann Perimetry Test. If visual and attentional fields narrow with factors that tax or impede controlled endogenous processing, this may also explain the 'cognitive tunnel vision' that occurs when an individual is anxious (Moray 1990, Endsley 1995, Matthews *et al.* 1998, Janelle *et al.* 1999) and the reduced responsiveness of fatigued and inebriated drivers to events in the periphery (Mascord *et al.* 1995). This 'useful field of view' is one of the best predictors in the differential crash risk research on older drivers (Owsley *et al.* 1991).

The influence of secondary tasks on the size and shape of visual or attentional fields has implications for positioning of in-vehicle displays. Lamble *et al.* (1999b) measured the ability to detect sudden braking in the car ahead while performing an attention demanding foveal task (identifying all the fours that occurred in a rapid stream of random digits). They manipulated the vertical and horizontal position of the foveal task and found that detection was best when the display was located on top of the dashboard 17° to the right of the steering wheel. This may be the optimal location for an attention demanding display, at least for purposes of avoiding rear-end collisions. In contrast, detection was very poor when the display was located in the center of the steering wheel or in the position of the rear view mirror. Similarly, performance was unsatisfactory when the foveal display was positioned in the location used for heads-up displays—4° to the right of the steering wheel—or where the speedometer is normally installed.

4. Summary and implications

As noted at the outset of this review, the research on attention and driving lacks cohesion. This situation is hardly ideal. In this paper we propose a framework to help integrate the driving literature, one that has implications for future research and public policy. In particular, this article makes four important contributions.

1. Our framework contributes to theory insofar as it brings to light the importance of a new variety of selection: controlled-exogenous selection (exploration). Exploration is the default mode for controlled processing and occurs when drivers are not fully occupied by specific tasks related to driving. These conditions are most likely to occur when visibility and road conditions are good and experienced drivers travel on roads that do not unduly tax their abilities. Under these circumstances, innate preferences may guide what aspects of the environment are attended first, and it may thus be possible to predict where drivers will engage their attentional resources when they are no longer concentrating on carrying out specific driving-related tasks.

2. The proposed framework provides a way of conceptualizing selective attention that integrates the research. It is hoped that this will combat the divisive influences that have served to obscure important issues and erect barriers between researchers who are doing related research. One divisive influence might be traced to William James, whose original definition of attention stressed 'consciousness' and thus prompted neglect of automatic processes (processes that involve selection without awareness). This neglect is particularly pronounced when it comes to automatic processes in perception, even though these determine what comes to consciousness as a result of automatic orienting (reflexive or habitual). As well, these automatic processes initiate perceptual processes and actions that must be overcome using deliberate (conscious) processes.

   This conceptualization also explicitly merges stimulus and response selection. Historically, stimulus selection theorists tended to study orienting, searching, and multiple target tracking to the exclusion of action. Response selection theorists studied multiple-action monitoring to the exclusion of perception. This promoted fragmentation in the basic research and produced gaps in the research on attention and driving, which still tends to be dominated by research paradigms best suited for investigating response selection (the dual-task paradigm, best suited for multiple action monitoring). Although a great deal of progress has been made, at this point much could be gained by diversifying, using paradigms better suited to measure other attentional mechanisms, such as orienting, search, filtering, and multiple target tracking. These abilities are also important in day-to-day driving, and some, such as multiple target tracking, may be important for understanding common types of crash, such as those that occur when an individual tries to turn left in busy traffic.

   Such diversification may be necessary to settle unresolved disputes raised by dual-task research. Many studies show that secondary tasks interfere with driving, but it is becoming apparent that the interference is not entirely the result of competing motor responses. What causes the interference? Some propose a central bottleneck in all cognitive processes, as suggested by research on the attentional blink and the psychological refractory period (Pashler 1984, Jolicoeur 1999). Others contend that secondary tasks restrict the 'useful field of view' (Ball and Owsley 1991, Pauzie *et al.* 1998, Williams 1989, Crundall *et al.* 1999, Janelle *et al.* 1999, Sekuler *et al.* 2000), thereby rendering information from beyond the fovea of little effect. A recent study suggests that drivers go into a mental state that makes them oblivious to their surroundings when the secondary task is talking on a cellular telephone (Strayer and Johnston 2001). Some studies suggest that the type of interference may be specific to specific components of the driving task, for example, spatial tasks interfere with eye movements while verbal tasks interfere with other aspects of performance (Recarte and Nunes 2000). The dual-task paradigm is useful in determining whether processes interfere with each other, but in absence of a complete theory for each of the individual tasks, it will not necessarily indicate why the processes interfere (Noy 1987, Haigney and Westerman 2001).

   The framework reveals varieties of selection that need further study. Although deliberate selection is investigated frequently, there is much less research on the other modes of selection (reflex, habit, and exploration). For example, at present it is unclear which information is selected reflexively and what type of responses reflexive selection can prompt. Nonetheless, there are intriguing preliminary findings. Shinoda *et al.* (2000) conducted a change blindness study in which drivers were given the task of following another car in a simulated driving environment while obeying the road signs. Unbeknownst to them a 'No parking' sign suddenly changed into 'Stop' sign as they approached it. Most drivers reported no awareness of the change, and more important, failed to stop. Nonetheless, they were more likely to direct an eye movement toward the sign after the change than they were when no change occurred, as if the change had been registered at some lower level in the visual system, one responsible for initiating reflexive eye movements, but this information was inaccessible to conscious awareness. This is consistent with the studies of 'blindsight', which suggest that visual information can take more than one neural pathway through the visual system, and that only some of these pathways make their perceptual operations available to conscious awareness (Goldstein 1999).

Similarly, there are many unanswered questions about habit. Learning to drive is commonly thought to involve making certain driving-related functions automatic. Although it is clear that the use of vehicle controls becomes automatic, an important component of learning to drive involves stimulus selection (Kirsner 1995). What aspects of stimulus selection become automatic? Although it is especially difficult to study stimulus selection processes that occur without awareness, a promising approach has been to manipulate the information available for drivers to select, and then observe changes in performance (Cavallo *et al.* 1998, Higgins and Tait 1998, Hildreth *et al.* 2000). If depriving drivers of certain types of information interferes with their driving, there is evidence to suggest that that information is normally selected. The next step is to demonstrate that drivers with different levels of experience are impeded to different extents by these manipulations. It is also noteworthy that there has been very little investigation of the dark side of selection by habit, namely, habit lag, slips of action caused by double capture, memory lapses that produce omissions and repetitions, and the over-confidence that sometimes occurs when a process becomes effortless with practice (Reason 1990).

Exploratory selection has rarely been studied and poses many unanswered questions. Where does attention drift when a person has no specific goal? What innate preferences guide exploration of complex novel environments? Sayed and Lim (1999) proposed that items are selected based on their opacity (partially occluded are less likely to be attended), clarity, size, and longitudinal and latitudinal velocity (the velocity at which they approach or pass across the visual field). Their ideas need to be put to empirical test. Furthermore, more needs to be learned about the nature and consequences of attention switching, as when a person goes from exploring the environment to deliberately performing some specific task. Because of the recent and growing popularity of heads-up display systems, it is also important to study attention switching when two different items occupy the same retinal location but different locations in space, as occurs when a driver peers through a heads-up display to see the road beyond.

3. Our framework reveals common themes in the different driving literatures, by revealing links between phenomena that might otherwise seem unrelated. This is nowhere more evident than for selection by deliberation, the most studied of the four modes in the framework. A variety of factors, including inexperience, pre-occupation, inebriation, and fatigue, all reduce the capacity for deliberate selection, though for different reasons. Regardless, all would be expected to produce the following effects: (a) special difficulties in dealing with unexpected or novel circumstances; (b) reduced sensitivity to information in the periphery; (c) special problems dealing with increases in image complexity or decreases in the quality of sensory information; (d) difficulty dealing with additional information or tasks; (e) difficulty bringing reflexive processes under control, for example, overcoming the reflex that draws the eyes and attentional focus towards bright flashing lights, or the reflex causing drivers to turn the steering wheel in the same direction as they move their eyes; (f) difficulty monitoring and bringing problematic habitual behavior under control; (g) difficulty producing rapid motor responses that require advance planning; (h) problems anticipating long term consequences based on information that must be deliberately accessed from long term memory. Because these four factors all affect the same mode, they would be expected to produce synergistic effects when applied in combination.

   This perspective has implications for the differential crash rate literature, insofar as individual differences among people that predict crash risk are related to selection by deliberation. For example, the individual difference factor that is the single best predictor of crash risk is the age of the driver: the youngest and oldest drivers are involved in more accidents per mile of exposure than the other age groups (Klein 1991, Hakamies-Blomqvist 1994, McGwin and Brown 1999). We believe that this finding may be partly explained by factors related to deliberate selection. In particular, we propose that the oldest and youngest drivers are more likely to over-extend their resources for deliberate selection—though for different reasons (Trick *et al.* 2004). Although a propensity for risk-taking may explain some of the crash risk associated with youth (especially in young males), another important factor is inexperience (Groeger 2000). Inexperienced drivers lack habits, motor programs that can be evoked automatically in the appropriate driving situations, and must rely more on deliberate selection for routine driving functions. In contrast, older drivers may find their deliberate selection processes overwhelmed for two different reasons: (a) they receive lower quality sensory information than other drivers because of deficits in sensory function, and as a result have to devote focal attention to compensate (Klein 1991); (b) they have problems performing motor responses rapidly, and consequently need to anticipate and plan more than other drivers in order to compensate (Hardy and Parasuraman 1997). These problems may be exacerbated by the fact that attention switching seems to require more time for older adults (Plude *et al.* 1994, Brodeur and Enns 1997). Given that young (inexperienced) drivers and older drivers both have extended demands on deliberate selection, it is not surprising that secondary tasks impede their performance more than these tasks impede performance in other age groups (studies involving inexperienced drivers: Summala *et al.* 1996, Shinar *et al.* 1998, Summala 1998, Wikman *et al.* 1998; studies involving older drivers: McDowd and Craik

1988, Brouwer *et al.* 1990, Brouwer *et al.* 1991, Parasuraman and Nestor 1991, Korteling 1994, Reed and Green 1999, Liu 2001). Deliberate selection is involved whenever it is necessary to coordinate several attention-demanding tasks that normally do not go together.

Other predictors of crash risk are related to problems of impulse control (controlling habitual or reflexive processes), a process that also demands selection by deliberation (Trick *et al.* 2004). This is a way to understand the disproportionate crash risk experienced by adults with Attention Deficit Hyperactivity Disorder (Barkely 1997, National Highway Traffic Safety Administration 1997, Cox *et al.* 2000, Faraone *et al.* 2000, Woodward *et al.* 2000, Jerome and Segal 2001). Given that personality is often construed as a habitual way of seeing and responding to the world, this framework also predicts that situational factors that compromise selection by deliberation will exaggerate the influence of the personality factors associated with dangerous driving (Elander *et al.* 1993).

In addition, this framework has ramifications for the literature evaluating automated systems to aid driving (Stanton and Young, 1998, 2000). One class of automated system provides remote information to the driver (e.g. in-car navigation systems, devices that warn a driver when they are following too close). Deliberate selection is relevant here because acquiring this information typically requires processes that are themselves under deliberate control (e.g. reading, symbol interpretation). The framework proposed in this article suggests that it is important to test these systems on drivers for whom selection by deliberation is overloaded, either as a result of difficult driving conditions (busy traffic, poor visibility, unfamiliar areas) or characteristics of the driver (inexperienced, elderly, pre-occupied, inebriated or fatigued). Although it is under these conditions that drivers may benefit maximally from such automated systems, it is also under these conditions that such systems would interfere most with safe driving (Dingus *et al.* 1997, Lansdown 2000, Liu 2001).

Another class of automated system replaces functions of the driver. Stanton and Young (2000) suggest that one of the dangers of this type of system is underload, a condition where the mental workload or cognitive effort is less than optimal. Ultimately, the danger of this type of automation is that it may change driving from an active task to a passive one: a passive vigilance task where drivers function is simply to monitor and supervise the operation of various automated systems, awaiting signals that inform them that they have to do something. The less frequently signals occur, and the more time spent waiting for a signal, the more vigilance performance deteriorates. This is because selection processes are designed to prepare individuals for action: selection of relevant stimuli and responses so the appropriate behavior will be produced. If the necessity for action decreases, and in particular the resources for controlled processes are not adequately employed, these resources will be allocated elsewhere. Drivers will daydream, occupy themselves with some other task, explore the environment, or sleep. On the rare occasions when drivers do need to make a response, perhaps because of an emergency or device malfunction, they will experience impoverished situational awareness, the disorientation that has been called the "out of the loop" effect (Endsley, 1995).

For this type of automated system, the habitual mode of selection is of relevance because with this type of automation, as with habit, there is a need to monitor fast, effortless processes that are not under deliberate control. Studies documenting the negative side of habitual processing, such as memory lapses, have direct analogs here. The other modes of selection are relevant insofar as they can provide insight into what the drivers will be doing instead of devoting their attentional resources to driving once some of their functions are taken over by an automated system. Studies of exploration and deliberate processing are pertinent—particularly the operations involved in switching attention from area to area or task to task—as are investigations of what happens when resources for controlled processes are gradually withdrawn, as occurs with fatigued drivers. Reflexive processes are of relevance insofar as it may be necessary to design displays that exploit reflexive selection, using stimuli that command the attentional focus to bring it back to the driving task when things go wrong.

4. The proposed framework has clear ramifications for public policy. Policy-makers have two general strategies open to them when endeavoring to prevent crashes. The first is to modify the driving environment by changing road and vehicle design. The second is to modify driver behavior by changing their personal goals, expectations, and behavioral repertoire. The framework we have described is valuable to policy makers in sofar as it identifies the problems that are best remedied with environmental interventions and those that require behavioral interventions, and suggests how behavioral interventions should be applied for maximal effect.

   As a general rule, the origin of the process dictates the most efficient solution to the problem. The exogenous processes that govern reflexive and exploratory selection occur because the nervous system gives some stimuli preferential treatment. Therefore, problems engendered by exogenous selection (reflex or exploration) are most efficiently remedied by changing the stimulus environment. This is especially true for reflexive processes because they operate more rapidly than the intelligent (controlled and deliberate) processes that govern reflection, planning, self-monitoring and self-correction. Though exploratory selection is not as difficult to manage because people can easily re-direct their attention when given a specific alternative task, when designing road environments and in-vehicle displays, it may be easier to change the environment, so that important information has a high probability of attracting attention through its appeal to the built-in biases of vision. There are three ways this could be done: (a) increase the sensory conspicuity of the information; (b) increase the number of times the information is presented, thus increasing the probability it will be noticed; (c) reduce the salience of competing information by getting rid of as much visual clutter as possible. The latter may be the best course in areas where driving conditions change suddenly from safe to dangerous, as at intersections.

   Problems produced by endogenous selection (habit or deliberation) are governed by personal expectations and intentions (goals), and are thus more amenable to modification by behavioral interventions. There are a variety of behavioral interventions (e.g. driver education and training, incentives, threatened punishments, advertising campaigns) but all require drivers to learn and then retrieve information from long-term memory. When deciding which intervention to use, it is important to consider that memory selection can also occur with or without awareness (e.g. controlled or automatic retrieval). Controlled memory retrieval is effortful and relatively slow and it interferes with processes that involve deliberate selection. Automatic memory retrieval is effortless and fast, and it does not interfere with other processes. However, initiating automatic retrieval requires some sort of cue in the immediate environment (a stimulus or related thought). Interventions that require drivers to recall long term consequences (punishments or rewards) or abstract principles require deliberate memory selection. Such interventions can be effective providing two stipulations are met: (a) the ongoing driving conditions do not over-extend the driver's deliberate selection processes; (b) the problematic behavior is deliberate, because habitual behaviors are executed rapidly, before there is a chance for deliberate selection. The choice of the appropriate behavioral intervention should thus depend on whether the problematic behavior is deliberate or habitual. For example, if drivers sped deliberately, the best approach would be driver education, advertising campaigns, incentives and threats of punishment aimed at changing attitudes, goals, and expectations. If drivers sped habitually it would be far more efficient to install a warning buzzer (an environmental cue) to remind the driver every time they exceeded the speed limit. Note that such a buzzer system would be less effective for drivers who sped deliberately. Such drivers would simply disconnect the buzzer or intentionally ignore it. Many dangerous driving practices are maintained by both habit and deliberation, and in these cases interventions aimed at both levels would be necessary.

To conclude, in this article we propose a way to draw together the disparate driving literatures in the hope that there might some day be a more comprehensive theory of driving, one that can encompass driver perception, motivation, problem-solving, learning, and memory. We believe that the four modes of selective attention outlined here are a start in this direction, and this framework will prove useful in other task domains as well.

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About the authors

Lana M. Trick is an Associate Professor in the Department of Psychology at the University of Guelph (Guelph, Ontario, Canada). She obtained her PhD in Psychology from the University of Western Ontario (London, Ontario, Canada) in 1990, and was granted a Killam post-doctoral fellowship to carry out research at the University of British Columbia. While there, she began her investigations of age differences in visual attention and driving performance in collaboration with the Insurance Corporation of British Columbia. In September 2000, she came to work at the Department of Psychology at the University of Guelph. Her research has been supported by grants from the Natural Sciences and Engineering Research Council, British Columbia Health, the Insurance Corporation of British Columbia, the Canadian Foundation for Innovation, and the Ontario Innovation Trust. She is a member of the Human Factors and Ergonomics Society as well as the Psychonomics Society.

James T. Enns is a Professor in the Department of Psychology and Graduate Program in Neuroscience at the University of British Columbia (Vancouver, British Columbia, Canada). His obtained his PhD in Psychology from Princeton (1984). A central theme of his research is the role of attention in perception. This includes studies of how the visual world is represented inside and outside of focused attention, how attention changes the contents of consciousness, how perception changes with development, and how to design visual displays for optimal human performance. He is currently an Associate Editor for *Psychological Science* and *Visual Cognition*. His research has been supported by grants from NSERC, BC Health, Nissan Car Corporation & NATO. He has edited two research volumes on the Development of Attention, 1990, 1997), coauthored two textbooks *(Sensation & Perception* 1986, 1999) and has written a book under contract to WW Norton *(The Thinking Eye, The Seeing Brain)*. In 2002 he was appointed a Fellow of the Royal Society of Canada.

Jessica Mills obtained her BSc in Psychology from University of British Columbia, Vancouver, British Columbia, Canada in 1999. Jessica Mills earned her BSc studying biopsychology at the University of British Columbia with an interest in sensation and perception encouraged by her professor, Dr Jim Enns. She has graduated from medical school at the University of British Columbia with plans to pursue a residency in pediatrics.

John Vavrik is Director of BC SMART (British Columbia Centre for the Strategic Management of Risk in Transportation) at the Insurance Corporation of British Columbia, Vancouver, British Columbia, Canada. He obtained his PhD from the Deptartment of Education and Counseling 1995 from University of British Columbia (Vancouver, British Columbia, Canada) and became a registered psychologist in 1997.