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Alcohol-Impaired Speed and Accuracy of Cognitive Functions: A Review of Acute Tolerance and Recovery of Cognitive Performance

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Much research on the effects of a dose of alcohol has shown that motor skills recover from impairment as blood alcohol concentrations (BACs) decline and that acute tolerance to alcohol impairment can develop during the course of the dose. Comparable alcohol research on cognitive performance is sparse but has increased with the development of computerized cognitive tasks. This article reviews the results of recent research using these tasks to test the development of acute tolerance in cognitive performance and recovery from impairment during declining BACs. Results show that speed and accuracy do not necessarily agree in detecting cognitive impairment, and this mismatch most frequently occurs during declining BACs. Speed of cognitive performance usually recovers from impairment to drug-free levels during declining BACs, whereas alcohol-increased errors fail to diminish. As a consequence, speed of cognitive processing tends to develop acute tolerance, but no such tendency is shown in accuracy. This "acute protracted error" phenomenon has not previously been documented. The findings pose a challenge to the theory of alcohol tolerance on the basis of physiological adaptation and raise new research questions concerning the independence of speed and accuracy of cognitive processes, as well as hemispheric lateralization of alcohol effects. The occurrence of alcohol-induced protracted cognitive errors long after speed returned to normal is identified as a potential threat to the safety of social drinkers that requires urgent investigation.

Keywords: alcohol, cognition, acute tolerance, impairment, speed, errors

The prized effect of alcohol as a social lubricant is well recognized, but it is a mixed blessing that also brings drinking-related accidents, injuries, and alcohol abuse. Research prompted by concerns over the safety risks of alcohol-induced behavioral impairment has been conducted for more than a century and has primarily assessed acute dose effects on various learned motor skills involved in driving.

When alcohol is consumed, blood alcohol concentration (BAC) initially rises swiftly to a peak and then gradually declines. These two phases are referred to as the ascending and descending limbs of the BAC curve and are illustrated in Figure 1. Early research on the biphasic effects of a dose of alcohol showed that the rising BAC associated with the onset of motor skill impairment was consistently lower than the BAC at the offset of impairment on the declining limb (Goldberg, 1943; Mellanby, 1919). This phenomenon is referred to as *acute alcohol tolerance.* Goldberg (1943) observed that light and heavy drinkers displayed acute tolerance and heavier drinkers showed greater acute tolerance (i.e., the offset of alcohol effects occurred at higher BACs). This finding is consistent with clinical reports of heavy drinkers having an exceptional degree of behavioral tolerance to alcohol and with the notion that tolerance increases as a function of repeated drug exposures. However, some investigators have suggested that acute tolerance may not be solely attributable to drug exposures because the procedure to identify the onset and offset thresholds of impairment requires repeated testing that would provide practice (e.g., Carpenter, 1962; Goldberg, 1943). The beneficial effects of practice could improve performance during the time course of the dose and thus weaken the effect of a given BAC on the declining limb of the blood alcohol curve.

Subsequent experiments designed to control or eliminate possible confounding effects of practice during an acute dose have customarily tested the same BAC on each limb of the blood alcohol curve. Figure 1 illustrates two tests (A and B) at matching BACs on each limb of the alcohol curve. In some cases, two groups receive alcohol and are tested once, during either the rising or the declining limb of the blood alcohol curve. In other experiments, alcohol is administered to one group and another receives a placebo. The alcohol group is tested on each limb of the blood alcohol curve, and the placebo group receives two tests at equivalent times. Studies using these experimental designs have indicated that acute tolerance is not solely an artifact of task practice. However, this conclusion rests primarily on research investigating learned motor skills (e.g., Vogel-Sprott, 1992). Evidence on the development of acute tolerance in cognitive tasks is limited, partly owing to the use of paper-and-pencil clinical tests whose durations span the time BAC rises and

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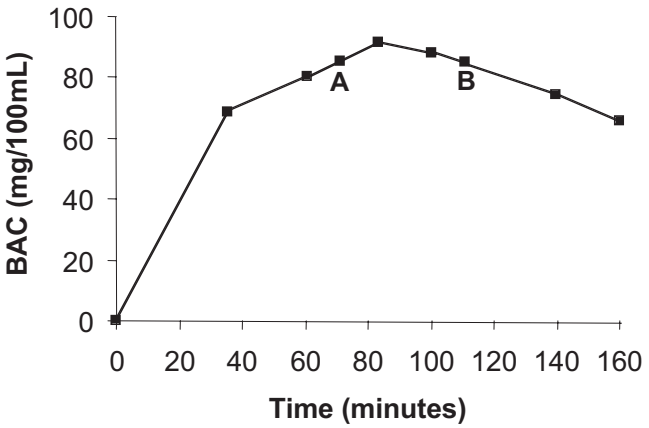

Figure 1. An example of rising and declining blood alcohol concentration (BAC) as a function of time (minutes) following an acute 0.65 g/kg dose of alcohol consumed in 10 min (data from Schweizer et al., 2005). Points A and B represent matching BACs on each limb of the alcohol curve.

begins to decline and whose measures of performance may be confounded by manual dexterity and learned motor skills (e.g., Hurst & Bagley, 1972; Vogel-Sprott, 1979).

Research in cognitive science has led to the development of brief computerized tasks to assess cognitive processes that contribute to the performance of various cognitive activities. The past decade has seen an increase in research using these tasks to assess alcohol effects on cognition because their performance requires no learned motor skill (e.g., a button press) and their relatively brief duration allows tests at given BACs on each limb of the blood alcohol curve. Pihl, Paylan, Gentes-Hawn, and Hoaken (2003) have called attention to the need for more experiments using such tasks to test the development of acute tolerance and biphasic limb effects of alcohol on cognitive performance. To our knowledge, the results of such experiments have not been reviewed. This is of particular interest now because some current research has suggested that cognitive performance may not develop acute tolerance or recover from impairment during declining BACs (e.g., Fogarty & Vogel-Sprott, 2002; Pihl et al., 2003; Schweizer, Jolicoeur, Vogel-Sprott, & Dixon, 2004; Schweizer et al., 2006).

The following sections review the past decade of research examining biphasic effects of alcohol and acute tolerance in cognitive performance. We include only experiments that tested the effects of a moderate dose of alcohol (peak BACs $\leq$ 0.10 mg/100 ml) on both limbs of the BAC curve and identified the BACs when cognitive tasks were performed. Although much research during the past 10 years has adopted computerized cognitive tasks to assess alcohol effects on cognition, our review found that most studies had only tested during rising BACs. Our literature search yielded results on 19 cognitive tasks from experiments that reported the BACs during tests on each limb of the blood alcohol curve. The assessment of cognitive performance on these activities was based on speed, accuracy, or both. Our review compares the evidence from these two types of measures to explore the consistency of evidence on acute tolerance and on recovery from impairment in cognition. Results on acute tolerance and on recovery are presented in turn. This is followed by conclusions and a discussion of possible explanations, as well as the broad implications of the observed dissociation in speed and error measures of cognition.

Acute Tolerance

Acute tolerance experiments test performance at declining BACs that are equal ($\pm$1 mg/100 ml) to the rising BAC. Our review contained four experiments designed to test acute tolerance in inhibition (Fillmore, Marczinski, & Bowman, 2005), information processing (Schweizer et al., 2004), selective attention (Fillmore, Dixon, & Schweizer, 2000a), and learning (Pihl et al., 2003). Table 1 shows the rising and declining BACs when each task was tested, the presence or absence of impairment on each limb (yes or no), and the development of tolerance (yes or no) measured by reaction time (RT) and/or accuracy (errors). A description of each of these tasks and the interpretation of their results are presented below.

Inhibition

Tests of inhibitory control of behavior are of considerable interest because failures to inhibit inappropriate responses are commonly associated with alcohol intoxication (e.g., Lyvers, 2000). Interest in the effect of alcohol on inhibition has followed the lead of cognitive science, in which self-control of behavior is assumed to involve frontal brain areas and to depend on processes of response inhibition and activation (Fowles, 1987; Gray, 1976; Logan & Cowan, 1984). A basic task measuring response inhibition is the stop-signal task (Logan, 1994). It essentially requires fast choice responses (button presses) to go signals that are presented on 100% of the trials. Immediate inhibition of these responses is required on occasional go trials (i.e., 20%) that are followed by a stop, "no-go," signal. The high reliability of go signals (80%) elicits preparatory responses that generate a prepotent go response that must be inhibited whenever a stop signal occurs. The reaction time (RT) to go signals and failures to withhold a response to a stop signal are each measured. In the context of this task, errors are failures to inhibit (i.e., stop) a response, with more errors indicating weaker inhibitory control. A more complex version of the stop-signal task adds cues predicting the occurrence of go and stop signals. In this cued go–no-go task, an invalid cue erroneously predicting a go or stop signal makes the incorrect response prepotent. As a consequence, a correct go response is more vulnerable to disruption and a correct no-go response is more difficult to inhibit (Fillmore et al., 2005). Table 1 shows the results of a test for acute tolerance in cognitive inhibitory control when invalid cues predicted go and stop signals (Fillmore et al., 2005). Alcohol effects on RT revealed acute tolerance: A rising BAC of 71 mg/100 ml impaired (slowed) response speed, but no

Table 1
Occurrence of Acute Alcohol Tolerance and Impairment in Speed (Reaction Time) and/or Accuracy (Errors) in Cognitive Tasks Tested at Rising and Declining Blood Alcohol Concentrations (BACs)

	Test BAC (mg/100 ml)		Impairment				Acute tolerance		
			RT		Accuracy				
Cognitive tasks	Rise	Decline	Rise	Decline	Rise	Decline	RT	Errors	Reference
Inhibition	71	71	Yes	No	Yes	Yes	Yes	No	Fillmore et al. (2005)
Information processing	87	88	Yes	No	Yes	Yes	Yes	No	Schweizer et al. (2004)
Selective attention	61	60	Yes	No	—	—	Yes	—	Fillmore et al. (2000a)
Learning	80	80	—	—	No	Yes	—	No	Pihl et al. (2003)

Note. Dashes indicate that the measure was not obtained. RT = reaction time.

impairment was evident at this BAC on the declining limb. By contrast, alcohol-increased errors did not subside on the declining limb of the curve and therefore showed no acute tolerance.

Information Processing

Information processing is widely assumed to involve perceptual and motor stages plus a central stage involving cognitive processes, such as interpreting signals, decision making, and planning (e.g., Welford, 1952). Although experiments have demonstrated that alcohol slows responses to a number of different information-processing tasks, such work cannot identify the specific stage of information processing affected by alcohol (e.g., Fillmore, Carscadden, & Vogel-Sprott, 1998; Moskowitz & Burns, 1971).

A dual-task paradigm has been developed in cognitive psychology to examine and isolate the central, cognitive stage of information processing (Pashler, 1994). When an individual performs two unrelated speeded choice-response tasks in rapid succession, the response to Task 2 is delayed as a function of decreasing the time between the two tasks (e.g., Tombu & Jolicoeur, 2003). This is explained by the assumption that the central, cognitive stage of processing can be performed for only one task at a time, so the central processing of Task 1 must be finished before that for Task 2 can begin. This produces a delay in responding to Task 2 that results in slower response times. Results of dual-task experiments examining the effect of rising BACs have supported the proposal that a moderate dose of alcohol impairs the central, cognitive stage of information processing by slowing or reducing processing capacity (Fillmore & Van Selst, 2002; Schweizer, Vogel-Sprott, Dixon, & Jolicouer, 2005). Although these experiments tested only the effect of rising BACs and could not be included in this review, their results indicated that rising BACs of more than 50 mg/100 ml are needed before the central, cognitive stage of processing is slowed sufficiently to delay responses to Task 2.

The findings on acute tolerance in information processing are based on a dual-task paradigm (Schweizer et al., 2004). Rising BACs of 86 mg/100 ml slowed RT, and the absence of impaired speed during comparable declining BACs indicated acute tolerance. In contrast, rising and declining BACs both increased errors. The evidence from RT and errors here implies that speed of information processing develops acute tolerance but that errors fail to do so.

Selective Attention

The ability to ignore distracting information and respond to a predetermined target is termed *selective attention.* This adaptive process has usually been examined using the Stroop color-naming task (MacLeod, 1991). In general, factors that impair selective attention slow response speed. The processes responsible for this result remain a matter of debate (see MacLeod, Dodd, Sheard, Wilson, & Bibi, 2003, for review). Interference, conflict, inhibition, and working memory capacity have all been suggested as possible candidates (e.g., Faust & Balota, 2007; Levine & Brown, 2007; Redick, Heitz, & Engle, 2007). Some studies have reported that rising BACs can impair response speed on tasks of selective attention and visual search (i.e., ability to ignore previously attended locations; Abroms & Fillmore, 2004; Fillmore, Dixon, & Schweizer, 2000b). However, our review identified only one experiment that investigated acute tolerance (Fillmore et al., 2000a). This experiment is listed in Table 1. The results are based on the Stroop task and show that a rising BAC of 61 mg/100 ml impaired (slowed) the ability to ignore irrelevant stimuli, and acute tolerance was evident by the return of response speed to drug-free levels on a test at the same BAC on the declining limb of the curve.

Learning

Our review identified one experiment designed to examine acute tolerance in an associative spatial learning task that required a set of cards to be related to randomly positioned lights (Pihl et al., 2003). Performance was assessed by errors, and the task was performed at rising and declining BACs of 80 mg/100 ml alcohol. Results showed that rising BACs had no effect on errors, whereas declining BACs increased errors, indicating intensified impairment. This evidence is exactly opposite to what is required to demonstrate acute tolerance.

Summary

The two experiments testing acute tolerance in inhibition and information-processing tasks measured RT and errors. These within-subjects measures control for individual differences in sensitivity to alcohol. As a consequence, the discrepant information about acute tolerance provided by RT and errors on the tasks can be attributed to the measures themselves. The other two studies of acute tolerance used only one measure of performance: RT assessed selective attention and errors assessed learning. Nonetheless, the evidence is in accordance with the studies that tested acute tolerance with both measures. RT developed acute tolerance, but errors failed to do so.

The review of acute tolerance in cognition was necessarily limited by the sparse amount of research on this topic. Yet the findings from tasks of inhibition, information processing, selective attention, and learning all reveal a striking incongruity between speed and errors in cognitive performance. RT consistently revealed acute alcohol tolerance, whereas errors failed to show any evidence of the phenomena.

Recovery

A number of experiments have tested cognitive performance on both limbs of the blood alcohol curve but were not designed to test acute tolerance by matching the BACs on each limb. The majority of these studies tested task performance at a declining BAC that was lower than the rising BAC test. Given that a lower BAC could be expected to have a weaker effect, some recovery should be observed in the form of a reduction in the impairment exhibited during the rising BAC. Table 2 presents an evaluation of recovery in speed and/or accuracy of cognitive performance during declining BACs on a number of different tasks. This section describes these tasks and their results.

Inhibition

In Table 2, the inhibitory task used by Schweizer et al. (2006) showed that rising BACs of 87 ml/100 ml slowed response speed, and recovery from this impairment was evident at a declining BAC of 83 mg/100 ml. In contrast, failures to inhibit, measured by errors on the task, were increased by the rising BAC and showed no recovery (i.e., no reduction) during the declining BAC. The inhibitory task in this research was characterized by a weak (reduced-potency) go response that is similar to that obtained by the use of invalid cues in the inhibitory task testing acute tolerance in Table 1. The results are also analogous: Speed recovered from impairment during declining BACs, but errors failed to do so.

The remaining five experiments (see Table 2) testing biphasic alcohol effects on response inhibition were based on the stop-signal task. This task makes the go response prepotent and more difficult to alter or inhibit. Under these conditions, the go-response RT was unaffected by rising and declining BACs, and response speed was unchanged in four of the experiments that measured RT (Easdon & Vogel-Sprott, 2000; Fillmore & Vogel-Sprott, 1999, 2000; Mulvihill, Skilling, & Vogel-Sprott, 1997). All of these experiments also found that rising BACs increased failures to inhibit (i.e., errors) and that this continued unabated or increased during declining BACs. The fifth experiment measured only failures to inhibit (Addicot, Marsh, Tor-

Table 2
Recovery From Impairment in Cognitive Tasks Measured by Reaction Time (RT) and/or Errors on Rising and Declining Blood Alcohol Concentration (BAC) Tests

Cognitive tasks	Test BAC (mg/100 ml)		Impairment				Recovery		Reference
			RT		Accuracy				
	Rise	Decline	Rise	Decline	Rise	Decline	RT	Errors	
Inhibition	87	83	Yes	No	Yes	Yes	Yes	No	Schweizer et al. (2006)
	59	54	[a]	[a]	Yes	Yes	[a]	No	Mulvihill et al. (1997)
	52	60	[a]	[a]	Yes	Yes	[a]	No	Easdon & Vogel-Sprott (2000)
	50	54	[a]	[a]	Yes	Yes	[a]	No	Fillmore & Vogel-Sprott (1999)
	52	54	[a]	[a]	Yes	Yes	[a]	No	Fillmore & Vogel-Sprott (2000)
	80	60	—	—	Yes	Yes	—	No	Addicot et al. (2006)
Working memory	74	69	Yes	No	Yes	Yes	Yes	No	Grattan-Miscio & Vogel-Sprott (2005b)
	87	83	—	—	[a]	[a]	—	[a]	Schweizer et al. (2006)
Learning	87	83	Yes	No	No	Yes	Yes	No	Schweizer et al. (2006)
Information processing	87	83	Yes	No	[a]	[a]	Yes	[a]	Schweizer et al. (2006)
Verbal memory									
Short term	87	83	—	—	[a]	[a]	—	[a]	Schweizer et al. (2006)
Long term	87	83	—	—	Yes	No	—	Yes	Schweizer et al. (2006)
Visual memory									
Short term	87	83	—	—	No	Yes	—	No	Schweizer et al. (2006)
Long term	87	83	—	—	No	Yes	—	No	Schweizer et al. (2006)
Visual-spatial	87	83	—	—	No	Yes	—	No	Schweizer et al. (2006)

Note. Dashes indicate that the measure was not obtained.
[a] The rising and declining alcohol tests did not affect the measure.

rence, & Dougherty, 2006). In accord with the other four experiments, this research also showed that errors continued unabated during both rising and declining BACs.

Working Memory

The ability to access and hold information in mind is referred to as *working memory* (Sternberg, 1966, 1969, 1975). The process is of considerable interest because it is thought to influence the control and quality of higher order cognitive functioning, such as comprehension, reasoning, and flexibility (e.g., Baddeley, 1992; Kyllonen & Christal, 1990). The Memory Scanning task (Sternberg, 1975) is designed to assess active working memory. The task presents a set of items (e.g., letters) on a trial. After a brief (millisecond) delay, one item is presented, and participants indicate whether the item was from the previous set. The speed of working memory is indexed by correct response RT, and accuracy is measured by errors. The number of items in a set that can be held in mind at one time measures the span or capacity of working memory. The typical working memory capacity is four or five items, and working memory becomes slower and less accurate as the capacity requirement increases (Kane & Engle, 2002; Pearson et al., 2004).

The Memory Scanning task has been used to investigate the acute effect of alcohol on each limb of the BAC curve when sets of two, four, or six items are held in working memory (Grattan-Miscio & Vogel-Sprott, 2005b). Measures of RT and errors detected little alcohol impairment when two items had to be held in working memory, but both measures showed that impairment intensified as the demand on working memory capacity increased from four to six items. Compared with placebo, rising BACs of 74 mg/100 ml slowed response RT, and recovery from this impairment was shown during declining BACs of 69 mg/100 ml. Errors were also increased by the rising BAC test but showed no reduction at the declining BAC. The failure of errors in working memory to recover during the declining BAC test is in stark contrast to the recovery in speed of working memory.

Table 2 also lists the results of alcohol research using a three-item working memory task (Schweizer et al., 2006). Rising and declining BACs of 87 and 83 mg/100 ml, respectively, had no detectable affect on errors. Speed of working memory was not measured, but the evidence on errors suggests that more than three items might have to be held in memory before alcohol impairs working memory.

Other experiments investigating the effect of moderate doses of alcohol on speed and accuracy of working memory have tested performance on each limb of the blood alcohol curve (e.g., Farquhar, Lambert, Drummond, Tiplady, & Wright, 2002; Tiplady, Franklin, & Scholey, 2004; Tiplady, Hiroz, Holmes, & Drummond, 2003). However, the findings could not be included in this review because the BACs during each test were not reported, and the measures of performance on the two limbs of the alcohol curve were averaged. Another experiment by Casbon, Curtin, Lang, and Patrick (2003) tested working memory only on the rising limb of the BAC curve and could not be included in the review. However, the results are of interest because they showed that alcohol-induced errors in working memory were increased by requiring greater memory capacity (i.e., more items) and when the prepotent set to execute or withhold a response was incorrect.

Learning

The learning task in Table 2 required individuals to learn to associate numbers and abstract symbols and to recall the learned material after a short delay. Measures of speed and accuracy of recall assessed what had been learned. Tests showed a rising BAC of 87 mg/100 ml slowed (impaired) RT, and recovery from this impairment was evident at a declining BAC of 83 mg/100 ml. On the other hand, the rising BAC test had no detectable effect on errors, but the declining BAC significantly increased errors. Although intensified impairment of accuracy during declining BACs may seem odd, this same effect was also obtained on the learning task used in the acute tolerance experiment (see Table 1).

Information Processing

The recovery from impairment during declining BACs on speed and accuracy of information processing is shown in Table 2 and is based on a task that requires the processing of information from abstract symbols. Unlike the task used to test acute tolerance (see Table 1), this task did not distinguish the particular stage of information processing. However, the effects on speed of information processing were similar in that RT was impaired during rising BACs of 87 mg/100 ml, and recovery was evident during declining BACs of 83 mg/100 ml. Entirely different results were obtained from error measures. Neither the rising nor the declining BAC had any detectable effect on accuracy. The task appeared to involve some learning because the RT of the placebo control group improved from baseline (i.e., became swifter), whereas the performance of the alcohol group remained relatively constant. The potential confounding effect of practice on RT clouds the interpretation of the impairment shown in the alcohol group.

Verbal Memory

Studies that administered short- and long-term verbal memory tasks at rising BACs of 87 mg/100 ml and declining BACs of 83 mg/100 ml have used only one measure of performance (errors) to assess recovery from impairment. The results of these experiments are listed in Table 2.

Short term. After the presentation of 12 words, the errors in short-term (2-min delay) memory under rising and declining BACs did not differ from placebo treatment. Although these results provide no information about the recovery of accuracy during declining BACs, they suggest that BACs higher than 87 mg/100 ml may be needed to impair the accuracy of short-term verbal memory.

Long term. This more difficult task tested memory for the set of words after a 20-min delay. Under these conditions, the rising BAC impaired accuracy, and recovery from this impairment was shown by a reduction in errors when BAC declined.

Visual Memory

Short and long term. These tasks measured only errors in memory for abstract designs at rising and declining BACs. The short- and the long-term memory tasks both showed that the accuracy of memory for the designs was unaffected at a rising BAC of 87 mg/100 ml. However, this did not indicate a general resistance to the impairing effect of alcohol because the test at a lower descending BAC of 83 mg/100 ml increased errors on the tasks. These findings clearly contradict the expectation of reduced impairment and recovery as BACs decline.

Visuospatial memory. This task presented a set of symbols in a matrix. The location of the symbols had to be remembered to identify a change in their positions when the matrix was presented after a brief delay. The effect of rising and declining BACs on errors in this task (see Table 2) shows that the rising BAC did not impair accuracy from placebo levels, but the lower descending BAC generated impairment by increasing errors on the task.

Summary. Taken together, the results from the memory tasks suggest that the effects of rising BACs in the range of 87 mg/100 ml are insufficient to increase errors in short-term verbal memory. In contrast, rising BACs in this range may impair the accuracy of longer term verbal memory, and recovery from these effects occurs during declining BACs. Alcohol-induced impairment of visual memory revealed a very different pattern. Accuracy in short- and long-term visual memory, as well as in visuospatial memory, was unaffected by rising BACs, but errors in these tasks were increased by declining BACs that were lower than the rising BACs.

With the exception of the relatively simple short-term verbal memory task, the other memory tasks agree in showing that declining BACs impair accuracy when no impairment was evident at higher rising BACs. All of these observations are restricted to the measure of errors only, so whether speed would also show this trend is not known. Nevertheless, the impairment observed in accuracy is clearly contrary to the normally expected recovery from impairment during declining BACs, and these findings are similar to the seemingly counterintuitive results on acute tolerance (see Table 1) that show errors either increase or fail to reduce on the declining limb of the BAC curve.

Discussion

Our review identified 19 cognitive tasks that were tested at specific BACs on each limb of the blood alcohol curve. Errors were measured on 18 of the tasks, and 17 (94%) failed to show acute tolerance or recovery. Instead, a continuation or increase in errors was exhibited during declining BACs. In contrast, RT was measured on 11 tasks, and 100% of them showed acute tolerance and recovery during declining BACs. Most compelling evidence for the discrepancy between impairment in RT and errors is provided when both measures are obtained on a task performed by the same individual. Tables 1 and 2 contain a total of 10 tasks on which RT and errors in performance were both measured. All (100%) of the RT measures on the 10 tasks showed less impairment (i.e., recovery or acute tolerance) during declining BACs. Conversely, errors showed no reduction on all but 1 of these tasks.

Four tasks were used in experiments testing acute tolerance in cognitive performance. RT and errors were both measured on two tasks (inhibition and information processing). Performance on the other two tasks was measured either by RT (selective attention) or by errors (learning). In all cases, RT revealed the development of acute tolerance, but errors remained or intensified during declining BACs. This lingering impairment in accuracy has not previously been documented, and we use the term *acute protracted error* to characterize the phenomenon.

The findings in this review are based on measures of RT and/or errors in the performance of a variety of cognitive tasks that were tested at various rising and declining BACs. In spite of these potentially important differences between tasks and experimental test conditions, the evidence, taken together, clearly indicates that measures of speed and accuracy of cognitive performance do not necessarily agree in identifying either acute tolerance or recovery from impairment during declining BACs.

The acute protracted error in cognitive performance during declining BAC is particularly curious because the intensity of a drug effect would normally be expected to lessen as the drug–blood concentration diminishes. The recovery from alcohol-impaired response speed during declining BACs is consistent with this general expectation, but the perpetuation or increase in errors is counterintuitive. Why would a drinker's speed of performance recover while his or her accuracy remains impaired or intensifies? This mismatch in the detection of impairment during declining BACs is unlikely to be an artifact of the continuous versus discrete nature of the two measures. A discrete measure, like frequency counts of errors, would ordinarily be considered coarser or less sensitive or precise than a continuous measure, like RT. However, errors appeared to be more sensitive to alcohol effects during declining BACs because they detected impairment when RT failed to do so.

RT as Speed of Cognitive Operations

Considerable research has demonstrated that complex learned motor skills can develop acute tolerance to a dose of alcohol and show a reduction in the intensity of impairment as BACs decline (e.g., Vogel-Sprott, 1992). Cognitive tasks also involve some motor reactions (e.g., button press), but they are much simpler than complex motor skill tasks. Nonetheless, it might be argued that the speed with which a simple button press is executed could contribute to the RT measures of cognitive tasks and might be slowed by alcohol. If this were the case, then the recovery in RT observed in

cognitive tasks could reflect acute tolerance in the motor movement component of the button press rather than in the speed of cognitive processes. Experiments have addressed this possibility by testing the effect of alcohol on the RT of a simple button-press response to a signal, when the RT is divided into two components: cognitive (premotor) RT and movement (motor) RT (e.g., Hernández, Vogel-Sprott, Huchín-Ramirez, & Ake-Estrada, 2006). Contrary to the proposal that alcohol slows simple motor processes, the motor RT component is unaffected by BACs as high as 100 mg/100 ml even though these BACs greatly slow cognitive premotor RT. Additional support for the failure of moderate doses to affect the speed of simple motor responses has also been provided in studies of dual-task performance (e.g., Schweizer et al., 2004). This research shows that alcohol has a specific direct slowing effect on the speed of the central, cognitive stage of information processing, and acute tolerance develops to this effect. Thus, it appears more likely that measures of RT on cognitive tasks are reflecting the speed of cognitive operations.

Speed and Accuracy of Cognitive Operations

Many tasks in this review (e.g., inhibition, working memory, information processing, and learning and visual memory) revealed that errors in performance failed to abate or increased during declining BACs, even though the speed of cognitive operations showed acute tolerance or recovery from impairment. This curious interaction between the limb of the blood alcohol curve and the impairment of speed and accuracy suggests that the measures might assess independent cognitive processes. This possibility has also been raised by research showing that caffeine or rewards for cognitive performance diminish alcohol-impaired response speed, but do not reduce errors (Grattan-Miscio & Vogel-Sprott, 2005b; Marczinski & Fillmore, 2006).

Although such findings raise the possibility that speed and accuracy measure different types or aspects of cognitive functions, the nature of these processes remains in doubt. Some investigators have proposed that response execution and inhibition involve frontal brain areas and represent different basic processes of cognitive control that underlie most cognitive tasks (e.g., Fillmore, 2003; Gray, 1976). From this perspective, it might be that errors depend on processes governing response suppression and inhibition, whereas response RT depends on processes of activation.

Another possibility arises from the proposal that cognitive control of behavior depends on conscious (intentional) and unconscious (automatic) processes (e.g., Jacoby, 1998). Accordingly, some research has shown that alcohol impairment of intentional responses is diminished by environmental rewards or a stimulant such as caffeine, but automatic responses are unaffected by these factors (Grattan-Miscio & Vogel-Sprott, 2005a). Thus, it may be that intentional processes are more likely to govern RT, whereas automatic processes may govern errors. A specific link between alcohol and its detrimental effects on errors has also been suggested by Ridderinkhof et al. (2002). These investigators found alcohol reduced the amplitude of the error-related negativity brain wave thought to be associated with the commission of errors and proposed that alcohol exerts a preferential affect on the frontal brain network thought to be responsible for error monitoring. However, this conclusion has been challenged by others who consider that the pattern of error-related negativity results obtained by Ridderinkhof et al. (2002) are best explained by alcohol-impaired stimulus processing, not by error monitoring (e.g., Holroyd & Yeung, 2003). Whether alcohol selectively impairs cognitive error-monitoring ability still appears to be an open question.

Lateralization of acute alcohol intoxication. The results of this review also raise the possibility that rising and declining BACs preferentially affect one brain hemisphere over the other. Visual memory, visuospatial working memory, verbal memory, and learning are cognitive tasks that are known to preferentially engage left or right cortical structures (Carlesimo, Perri, Turriziani, Tomaiuolo, & Caltagirone, 2001; Goldstein, Canavan, & Polkey, 1988). In our review, speed and accuracy on these tasks were differently affected by rising and declining BACs. Schweizer et al. (2006) noted a trend for left-hemisphere tasks (e.g., long-term verbal memory) to be more disrupted by rising BACs and right-hemisphere tasks (e.g., visuospatial working memory) to be more adversely affected by declining BACs. In addition, rising BACs seemed to most detrimentally affect RT, whereas declining BACs only detrimentally affected errors. A right-hemisphere link to errors on the descending limb of the blood alcohol curve was also proposed by Pihl et al. (2003), who found that accuracy on a right-hemisphere learning task was more profoundly impaired by descending than ascending BACs.

Some support for the idea that cognitive processes of speed and accuracy might be lateralized in the brain comes from neuroimaging research in healthy participants and studies in patients with focal brain lesions (Garavan, Hester, Murphy, Fassbender, & Kelly, 2006; Konishi et al., 1999). These studies indicated that response suppression and inhibitory processes critical for error performance are dominated by right hemisphere networks. In contrast, activational processes critical for fast, speeded responding are dominated by left hemisphere and superior medial structures (Stuss et al., 2005). Some electrophysiological and positron emission tomography studies have examined alcohol effects on frontal brain areas and hemispheric processing (e.g., Easdon, Izenberg, Armilio, Yu, & Alain, 2005; Schreckenberger et al., 2004). However, to our knowledge, no such research has tested the biphasic effects of alcohol on cognitive performance. Future research should address a wider spectrum of cognitive tasks that are tested at BAC levels on each limb of the curve. In vivo imaging research using techniques such as functional MRI and positron emission tomography and testing performance on cognitive tasks strongly lateralized to one hemisphere or the other would be an ideal test of the lateralization hypothesis.

Acute tolerance. A drug-opposite, physiological adaptive process is widely thought to underlie acute and chronic alcohol tolerance. The adaptive process is assumed to produce tolerance by reducing the intensity of drug effects and

to strengthen as a function of drug exposure (e.g., Kalant, 1987, 1989; Kalant, LeBlanc, & Gibbins, 1971; Radlow, 2006). As a consequence, the use of higher doses of alcohol to reinstate the initial effects could increase the risk of alcohol abuse. However, physiological adaptation seems unable to account for protracted errors during declining BAC when response speed shows acute tolerance. It is not clear how such an adaptive process could explain why the presence or absence of acute tolerance in cognition depends on whether speed or accuracy is measured.

One important consideration here may be the fact that the adequacy of complex motor skills is rarely assessed by separate measures of RT and errors. Because more efficient motor performance is characterized by swift errorless responses, a single measure is commonly used that incorporates both aspects of performance, such as time to complete the task or the degree to which the task is completed in a limited time period. If alcohol-impaired speed of motor performance recovers as BAC declines but errors do not abate, then their combination in a single measure would still likely consistently reveal recovery or acute tolerance in motor skills. A single measure that incorporates speed and accuracy could also be used to assess cognitive performance (e.g., number of items in a cognitive task that are correctly completed in limited time). It would be important to determine whether such a measure of cognitive performance reveals acute tolerance or recovery from impairment during declining BACs.

Duration and intensity of acute protracted errors. The results of our review of cognitive tasks showing errors increase or continue unabated during declining BACs raise a number of important questions that have theoretical and practical safety implications. The length of time acute protracted errors continue is not known. Future research testing cognitive performance at intervals as BAC declines to zero and 12 hr later could determine whether errors remain until some critical low declining BAC is reached or whether these errors in cognitive performance linger and might contribute to hangover symptoms.

Some of the research in our review indicated that prepotent responses (i.e., environmentally cued, with a strong response set) are less likely to succumb to the effects of a dose of alcohol and might therefore provide some protection from protracted errors in cognition. More research is needed to test the possibility that settings with environmental cues for appropriate responses will reduce protracted errors in cognitive performance during declining BACs.

Another issue that requires research attention concerns individual differences in vulnerability to acute protracted errors during declining BACs. There is no information on this question at present, but the results from the stop-signal task in our review may be pertinent to this question. A high incidence of errors on this task is customarily used to assess inhibitory deficits in individuals with oppositional defiant disorder or residual attention deficit/hyperactivity disorder and in children with attention deficit/hyperactivity disorder (Oosteriaan & Sergeant, 1996; Schacher, Tannock, Marriott, & Logan, 1995). Our review showed that alcohol intensified errors (i.e., failures to inhibit) on this task. Taken together, these observations prompt the speculation that individuals with such diagnoses might be more susceptible to protracted cognitive errors during declining BACs.

Safety risks. Acute protracted errors during declining BACs could seriously jeopardize the safety of social drinkers after speed of processing returns to normal. Because BAC declines much more slowly than it rises, the detrimental error-inducing effect of alcohol on this limb of the drug curve could compromise cognitive functioning for an extensive period of time. An expanded duration of impairment would extend the risk of accidents and injury in activities undertaken by drinkers. Moreover, the threat may be exacerbated by the difficulty in self-evaluating alcohol effects. Studies have shown that social drinkers tend to underestimate their level of intoxication and degree of impairment (e.g., Beirness, 1987; Harrison & Fillmore, 2005), and this is particularly evident during declining BACs (Bois & Vogel-Sprott, 1974; Ogurzsoff & Vogel-Sprott, 1976). To the extent that self-assessments of functioning under alcohol provide some basis for decisions about engaging in potentially hazardous activities (e.g., driving), an inability to appreciate protracted inaccuracies in cognitive performance could create a dangerous situation.

Conclusions

This review of research on the recovery from cognitive impairment and the development of acute tolerance during a dose of alcohol is based on cognitive tasks that were tested at specific BACs on each limb of the blood alcohol curve. Although the sample was small and the experiments examined a variety of tasks, the evidence led to the conclusion that speed and accuracy in cognition were differently affected by declining BACs. Rising BACs tended to slow (impair) social drinkers' speed, and recovery from this effect occurred during declining BACs in a fashion consistent with acute tolerance. In contrast, accuracy of cognitive performance by the same drinkers tended to be impaired to a comparable degree during both rising and declining BACs.

The consistency of acute protracted error in cognition during declining BACs has not previously been documented, and we considered many questions raised by this phenomenon. Some issues dealt with the fact that alcohol-induced protracted error in cognition is inconsistent with the theory attributing tolerance to physiological adaptation. It also raises the possibility that measures of RT and errors may assess different aspects or types of cognitive processes. Other factors that might play a role in causing accuracy to deteriorate and speed to improve during declining BACs concerned the degree to which cognitive processes were under intentional or automatic control and whether speed and accuracy were independent measures of basic cognitive processes controlling response execution and inhibition, respectively. We also raised the possibility that the potential lateralization of alcohol effects could be investigated using various imaging techniques combined with the performance of tasks lateralized to one hemisphere or the other. We consider the occurrence of acute alcohol protracted errors in

cognition long after speed has returned to normal to pose important threats to the safety of social drinkers. We also note that the current absence of information on the duration of protracted errors during declining BACs adds urgency to the safety issue.

The conclusions and implications of this review highlight a great need for more research testing acute alcohol tolerance and recovery from cognitive impairment by measuring task performance on each limb of the BAC curve. Although much research during the past decade has adopted computerized cognitive tasks to test the acute effects of alcohol on cognition, most studies have only tested the effect of rising BACs. This oversight may seem surprising because more than 60 years ago the seminal review of alcohol effects by Jellinek and McFarland (1940) emphatically warned researchers that the findings were only meaningful when the BAC at the time of the test on each limb of the alcohol curve was also reported. The relative disregard of this experimental procedure in contemporary research might have been encouraged by the extensive accumulated evidence on motor skills that shows that impairment intensifies and diminishes in accord with rising and declining BACs and acute tolerance develops to these effects. However, the present review identifying acute protracted errors in cognitive performance during declining BACs highlights the important need for information obtained by measuring cognitive performance on each limb of the blood alcohol curve and reporting the BAC at time of test.

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