Does the Central Bottleneck Encompass Voluntary Selection of Hedonically Based Choices?

Harold Pashler[1], Christine R. Harris[1], and Keith H. Nuechterlein[2]

[1]University of California San Diego, La Jolla, CA, USA
[2]University of California Los Angeles, Los Angeles, CA, USA

Abstract. A large literature on multitasking bottlenecks suggests that people cannot generally make decisions or select responses in two different tasks at the same time. However, these tasks have all involved retrieving preinstructed responses, rather than spontaneously choosing actions based on anticipated hedonic consequences. To assess whether the same bottlenecks encompasses voluntary choices, a gambling decision was utilized as the second of two tasks in a psychological refractory period (PRP) design. Three decision-related factors were identified that affected latency of responding in the gambling task. All proved to be additive with stimulus-onset asynchrony (SOA) in dual-task blocks. The results indicate that making a choice to try to optimize outcomes is subject to the same processing bottleneck as the retrieval of preinstructed responses that has been the mainstay of attention and performance research.

Keywords: missing, please supply

Introduction

A variety of converging evidence indicates that when people attempt to perform two tasks at nearly the same time, each requiring the selection of an independent response, a rather stubborn bottleneck arises. This bottleneck imposes a constraint on the process of decision making processes and action planning, preventing more than one central decision process from operating at any given moment (Welford, 1967; Pashler & Johnston, 1998; McCann & Johnston, 1992). The bottleneck is seen most clearly in an experimental design called the *psychological refractory period* (or PRP) experiment. Here, subjects try to perform two nearly-simultaneous tasks as rapidly as possible. The classic PRP effect shows up as a slowing in the response on the second of two tasks, a slowing that increases as the stimulus-onset asynchrony (SOA) separating the two stimuli is reduced. While the bottleneck may sometimes be circumvented with very simple and highly practiced tasks (Lien, Ruthruff, & Johnston, 2006; Ruthruff, van Selst, Johnston & Remington, 2006), it seems likely that the conditions necessary to make this happen are probably rarely satisfied except in rather unusual situations. Thus, the bottleneck likely imposes a severe limitation on human multitasking performance both in and out of the laboratory (Levy, Pashler, & Boer, 2006).

PRP Literature: Where Are the Decisions?

It is a striking fact, however, that the large literature on the PRP effect has – to our knowledge – been restricted to tasks in which subjects were preinstructed about what response to make to each possible stimulus, or given some other rules that prespecified every action the individual would make throughout the experiment. For that reason, it would seem that none of the studies examining bottlenecks in decision making have examined anything that would, in common parlance, even be described as a decision. To put the point slightly differently, the subject's role in these experiments has been to recall decisions that were made for them in advance, not to make new voluntary decisions of their own choosing. Thus, there would seem to be little basis for assuming that whatever constraints govern the recall of instructions will necessarily also govern the making of spontaneous decisions.

Indeed, there are theoretical reasons that might argue either for, or against, the idea that making novel choices would be subject to the same bottleneck as recollecting and implementing instructed choices. Considerations drawn from cognitive neuroscience appear to argue – albeit rather weakly – in favor of a common bottleneck. Some writers have argued that the neural underpinnings of the bottleneck arise from broad cortical areas including many frontal structures (Dux, Ivanoff, Asplund, & Marois, 2006; Jiang & Kanwisher, 2003; Schubert & Szameitat, 2003; Szameitat, Schubert, Muller, & von Cramon, 2002), having some likely overlap with structures implicated in making decisions in anticipation of uncertain rewards and punishments (Manes et al., 2002).

On the other hand, it has often been contended that generation of affective responses is a quintessentially automatic process (e.g., Duckworth, Bargh, Garcia, & Chaiken, 2002). From this perspective, one might expect that affec-

DOI 10.1027/1618-3169.55.5.313

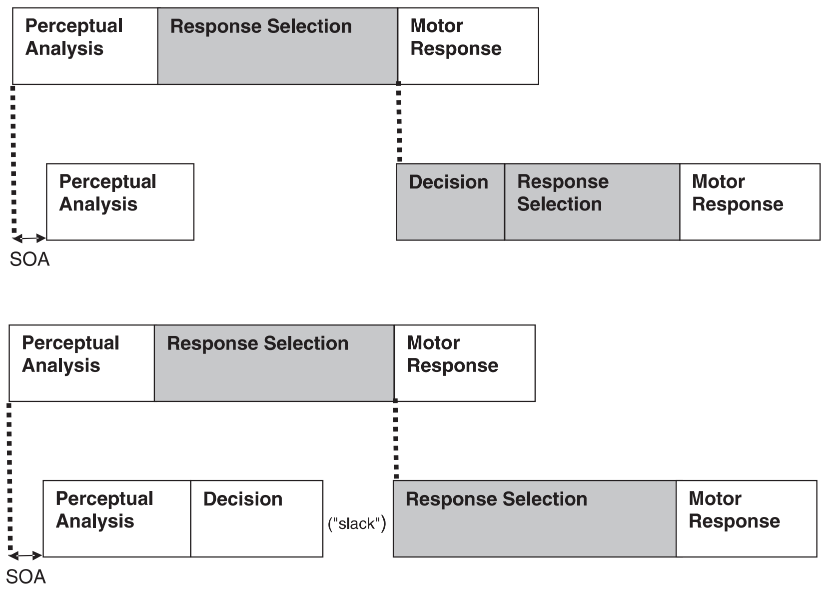

Figure 1. Two different scenarios for possible timeline of gamble decision making in dual-task context. Top panel: Decision making is subject to the same bottleneck as response selection, and thus task-2 decision is postponed until completion of task-1 response selection. Bottom panel: Decision making is not subject to the central bottleneck, and the only task-2 stage delayed is response selection. This generates "slack," whereby response selection in task 2 does not commence immediately after the decision in response 2 has been completed.

tively based choice processes based on affective outcomes of prior behaviors would proceed independently of unrelated central mental activity (although such a prediction would certainly go well beyond the data relating to affective responses).

Present Experiment

The goal of the present study was to ask what happens if people are required to perform two tasks close together in time, where one of the tasks involves what would normally be described as genuine decision-making, i.e., freely making a choice in the hope of receiving a reward. To assess the nature of dual-task conflict in this situation, we combined two tasks. The first involved a conventional choice response to a tone (pressing one of three keys depending upon a sound). The second involved a task with some similarities to the "Iowa gambling task" (Bechara, Damasio, Damasio, & Anderson, 1994), in which subjects were offered the chance to accept or decline a card drawn from a deck of a particular color. Three different colors of decks were used. Two decks had a positive expected value, while the third deck had a negative expected value; however, of the two positive-expected-value decks, one delivered occasional large losses, while the other delivered only occasional small losses. Subjects performed this task for "real money" (i.e., they were allowed to keep any winnings), and in addition to the rewards tied to particular cards, they were given additional financial incentives for responding promptly. The stimulus-onset asynchrony separating the tone from the appearance of the card ranged from 100 ms to 1200 ms (1200 ms being longer than the typical response to a tone).

Following past PRP research, we anticipated that RT for the gambling responses should be slowed at the shorter SOAs (PRP effect). If the process of deciding whether to accept the card is delayed by the same central bottleneck as governs the response selection for the tone task (Figure 1, Top Panel), then factors affecting the duration of the process of deciding whether to accept the card or not should combine in an additive fashion with SOA. Additive interactions of this kind have been found, for example, with manipulations such as the Stroop Effect (Fagot & Pashler, 1992), stimulus-response compatibility (McCann & Johnston, 1992), degree of practice in recalling a paired associate (Carrier & Pashler, 1995), and difficulty of an arithmetic problem (Byrne & Anderson, 2001), as well as other variables that affect the time required to retrieve a prespecified decision.

On the other hand, suppose the creation of a voluntary decision does not wait for the tone task, and it is only the subsequent processes of selecting motor parameters of the response that are delayed by the first task (Figure 1, Bottom Panel). In that case, factors retarding the gambling decision itself should be "absorbed" into the slack indicated in the figure. That is, we should expect to find a subadditive interaction between SOA and these factors (with the factors having their normal slowing effect upon RT2 when the SOA is long, but having a smaller than normal effect when the SOA is short). (Readers interested in seeing timelines and figures illustrating how subadditive interactions of this sort emerge may find it useful to refer to Pashler & Johnston, 1998.) In the empirical literature, subadditive interactions between SOA and factors affecting the duration of perceptual analysis of S2 have been repeatedly observed (for review, see Pashler & Johnston, 1989, and additional references below).

Variables affecting decision making within the gamble task have not been identified in the literature, so we were not able to utilize "off the shelf" variables. However, as will be seen shortly, by its nature the gambling task offers up several variables that might plausibly affect the time taken to make a decision.

Method

Subjects

A total of 30 students from the University of California, San Diego, participated in a single experimental session.

Tasks and Stimuli

There were two tasks in this experiment (see Figure 2). The first is termed the *sound task.* This task involved hearing sounds of different pitches (200 ms tones at 50, 200, or 450 Hz) and pressing one of three possible response keys on a computer keyboard (z, a, or q keys using the index, middle, and ring fingers of the left hand, respectively). Note that this task mapped pitch onto height on the keyboard in a compatible fashion. The second task is termed the *gamble task.* Here, the subject saw a card on the computer screen (red, green, or yellow in color) and either accepted or rejected this card (pressing the "/" or "." keys using the index and middle fingers of the right hand, respectively). Upon making their selection, the subject was notified of their winning or loss. Table 1 shows the payoff probabilities for each of the three different card colors. Basically, the blue deck and the green decks are both relatively risky, in the sense that losses of 10–20 cents are possible. However, the blue deck has a negative 2.5 cent expected value and the green deck has a positive 2.5 cent expected value per trial. The yellow deck, on the other hand, has a 2.3 cent positive expected value but generates at most a 1 cent losses (on one-third of trials).

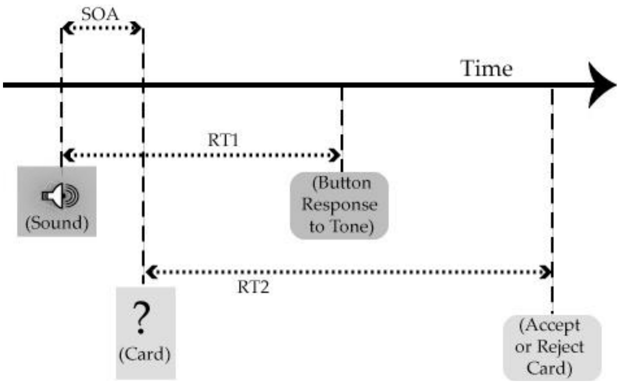

Figure 2. Primary events within a trial of the experiment. A sound (stimulus 1) is followed after some SOA (or 100, 250, or 1200 ms) by the visual presentation of a card (stimulus 2). The subject makes a button-push response to the sound, after a latency RT1, and accepts or rejects the card after a latency RT2. Immediately after the response, the subject is told how much they won or lost, if they accepted the card.

Table 1. Gains and losses associated with each deck

Deck	Option	Probability	Expected Value
Blue	Lose $.20	.25	–2.5 cents
	No gain or loss	.50	
	Gain $.10	.25	
Green	Lose $.10	.25	+2.5 cents
	No gain or loss	.50	
	Gain $.20	.25	
Yellow	Lose $.01	.333	+2.33 cents
	Gain $.04	.667	

Overview of Procedure and Design

The experiment was divided into four phases. The first consisted of two practice blocks (40 trials each) on the sound task. The second phase consisted of two practice blocks on the gamble task (each 60 trials). The third phase consisted of 6 dual-task blocks (40 trials each), during which the subject performed both the sound and the gamble tasks. Here, the SOA between the onset of the sound and the onset of the gamble-task card was 100, 250, or 1200 ms. SOA was a within-subject variable, and SOA values were randomly intermixed within a block with equal probability. The fourth phase consisted of a final block (60 trials) of the gamble task alone.

Instructions and Incentives

Incentives and instructions were devised to promote prompt but not reckless responding in both tasks. For the sound task, subjects received a bonus of 20 cents for every 100 ms that their mean RT fell below 1 s. Subjects were also told that there was a penalty for making more than 5% errors. For the gamble task, subjects were allowed to keep final winnings (if positive), i.e., they were betting with "real money." In addition, subjects received a bonus of 5 cents for every 100 ms their mean RT on the gamble task fell below 2 s. The incentives described above were explained to each subject, making the experiment completely transparent.

Detailed Procedure

Every trial was preceded by a fixation point (plus sign), which appeared for 500 ms, followed by a 500 ms blank period. If the subject rejected the card, a message saying "Card Rejected" was displayed for 1.5 s, followed by a 1 s interval before the fixation point for the next trial. If the subject accepted the card, they saw a message telling them what they had won or lost. This remained present for 2 s, followed by the same 1 s interval before the fixation point for the next trial. As is standard in PRP studies, response

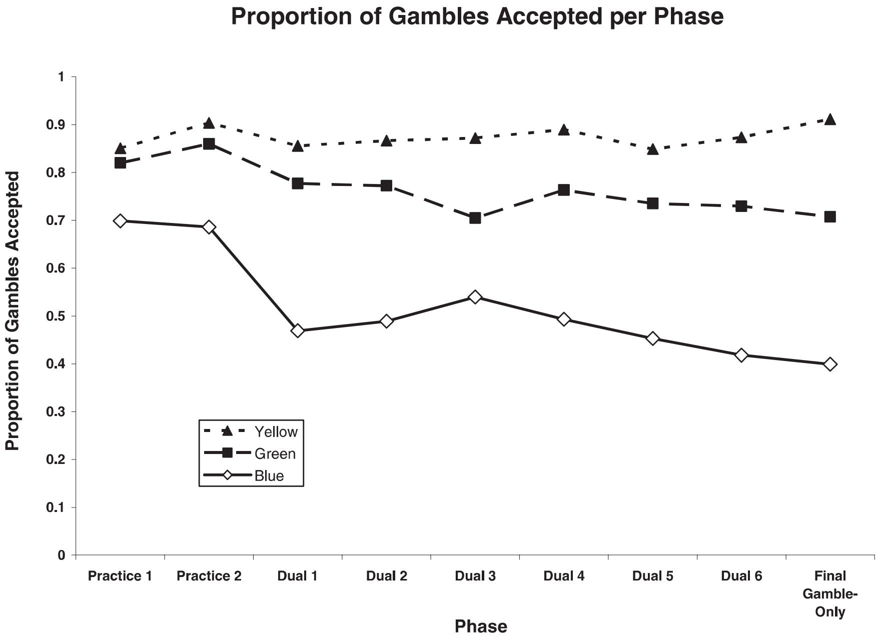

Figure 3. Mean proportion of gambles accepted for cards from each of the three different colored decks, for the different blocks unfolding over the course of the experiment.

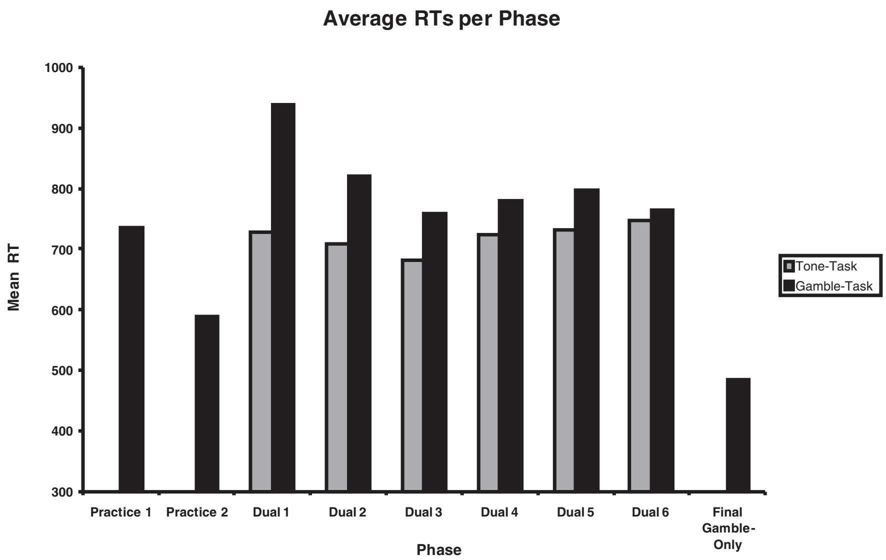

Figure 4. Mean response times for the tone task and the gamble task for each of the blocks in the experiment that included the gamble task. Gamble task RTs are slowed with respect to the phases containing gamble task performed alone (Practice 2 and Final Gamble-Only).

times (RTs) for each task were measured from the onset of the stimulus to which the response was being made.

Results and Discussion

Gamble Choice Patterns

Figure 3 shows the probability of accepting a card from each of the three decks, for each of the blocks in the study that included gambles. The figure makes it evident that cards from the blue deck, which had a negative expected value, were less frequently accepted than others, and were rejected more and more often as the experiment progressed. Meanwhile, cards from the yellow (low-risk low-positive-value) deck were most often taken, and their acceptance increased. Interestingly, yellow cards were more often accepted than green cards, even though the green cards actually had a slightly higher expected value. This can be interpreted as manifestation of the risk aversion which is a common feature of human decision-making (Pratt, 1964).

Gamble Winnings

Subjects' total earnings from the gambles varied between \$0.18 and \$8.99, with a mean winning of \$4.63.

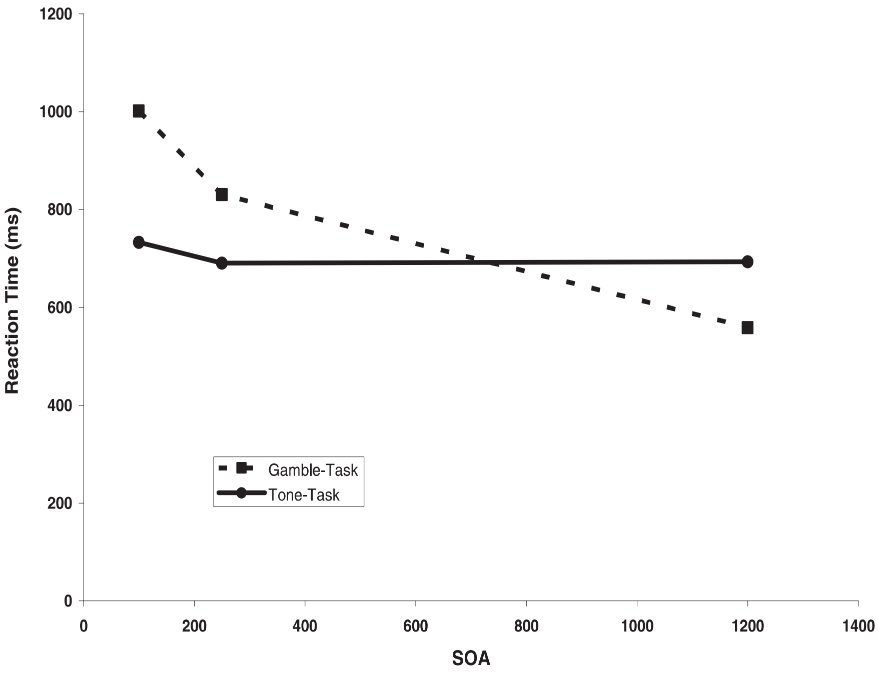

Figure 5. Mean response times for the gamble task within the dual-task blocks, as a function of the stimulus onset-asynchrony (SOA) separating the tone from the card (after truncation of outliers; see text).

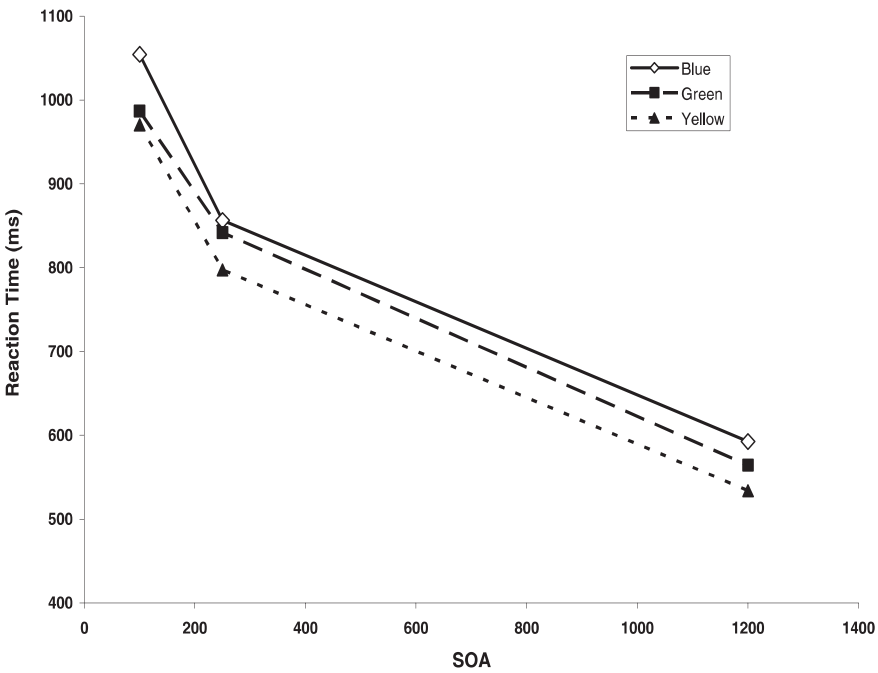

Figure 6. Mean response times for the gamble task within the dual-task blocks, as a function of the stimulus onset-asynchrony separating the tone from the card and the color of the card being responded to in the gamble task.

Overall Dual-Task Interference

Figure 4 shows the overall mean RTs (computed on all RTs) for each of the tasks in the same seven phases of the experiment. Dual-task RTs are averaged over stimulus-onset asynchrony (SOA). A marked dual-task interference effect on the gamble RTs is clearly seen (namely, slower gamble task responses in the dual-task blocks than in the gamble-alone blocks). There is also a practice effect apparent in the speedup of gamble RTs taking place over the three gamble-task-only blocks.

Basic PRP Effect

Averaging across the five dual-task blocks only, Figure 5 shows the mean RTs for each of the tasks as a function of SOA. The results show a very typical PRP effect: Marked slowing of RT2 as SOA is reduced, with only slight changes in RT1. This (and subsequent) analyzes were performed after outliers were excluded (defined as RTs below 250 ms or more than 3 *SD* above the mean within any given condition). The pruning made no difference to the patterns of effects seen in Figure 5, and merely reduced noisiness of the data to a small degree.

Factorial Effects on Latency in PRP

Within the three single-task gamble task blocks, the average RTs for decisions about blue, green, and yellow cards were 634 ms, 583 ms, and 552 ms, respectively. This difference was significant, as confirmed by an analysis of variance, $F(2, 58) = 7.4$, $p < .001$. These latency results mirror the probability of acceptance: Responses are faster to the cards that are more often accepted.

How does this variable affect responses in the dual-task blocks? Figure 6 shows the joint effects of deck color and SOA on RT for the gambling task within the dual task blocks. An analysis of variance was performed on gamble-task RTs from the dual task blocks, with two factors (color and SOA). The effect of color was significant, $F(2, 58) = 7.1$, $p < .002$, as was the effect of SOA, $F(2, 58) = 285.2$, $p < .000$. There was no reliable interaction between the two variables, $F(4, 116) = 1.2$, $.30 < p < .40$. The difference between the fastest condition (yellow) and the slowest condition (blue) was 83.9 ms, 59.0 ms, and 58.5 ms for the SOAs of 100, 250, and 1200 ms, respectively.

The fact that SOA and deck color combine in an additive fashion is consistent with the hypothesis that the decision process affected by option history/value is subject to the central bottleneck (Figure 1, Top Panel). The data are inconsistent with the hypothesis that this variable is affecting a prebottleneck stage (Figure 1, Bottom Panel).

An ANOVA was also performed on the effects of color and SOA on RT1. There was a significant effect of SOA, $F(2, 58) = 4.1$, $p < .05$, largely reflecting some slowing at the 100 ms SOA. Here the RT1 averaged 735 ms, as compared to 692 at 250 and 696 at 1200 ms. There was also a significant effect of color, $F(2, 58) = 3.3$, $p < .05$, but no interaction of SOA × color, $F(4, 116) = 1.45$, $.20 < p < .30$. This reflected the fact that RT1 averaged 720 ms when the card was blue, as against 702 when it was green and 700 when it was yellow.

The effects of SOA and of color on RT1 are not predicted by the central bottleneck model per se. Several plausible modifications of this model might account for the effects. For one thing, subjects are often noted to group responses (withholding R1 until R2 has been selected) on a small proportion of trials. Another possibility is that there is some small degree of capacity sharing in central stages (McLeod, 1977; Tombu & Jolicoeur, 2003). In any case, the effects of color strongly imply that the choice process itself is being delayed by the performance of the first task.

Effect of Choice

A second variable that could potentially affect the duration of the decision process is the outcome of the decision process (i.e., to accept or reject the card). Table 2 shows the overall RTs for gamble acceptance vs. gamble rejection responses. Looking within the dual-task blocks only, we examined the joint effect of SOA and accept vs. reject on RTs (see Figure 7). Rejections were significantly slower than acceptances, $F(1, 29) = 6.48$, $p < .05$, but the interaction of SOA × Choice was not significant, $F(2, 58) = 1.5$, $.20 < p < .30$. Reject responses were slower than accept responses by 76 ms, 136 ms, and 67 ms, for SOAs of 100, 250, and 1200 ms, respectively.[1]

Slower Responses for "Changes of Mind"

We were also able to identify a third variable that affected the latency of responding, related to "changes of mind." This variable was whether or not the decision outcome for a card of a given color was the same as, or different than, the decision outcome reached the last time that color of card was offered. Responses proved to be slower, for example, for a rejection of a yellow card if the last time a yellow card was an offer, it was accepted, rather than re-

Table 2. Mean RTs for accepting vs. rejecting a gamble

Condition	Choice	Mean RT (ms)	Reject – accept diff
Single task	Accept	573.7	122
	Reject	695.8	
Dual task (SOA = 100)	Accept	1014.3	76
	Reject	1090.2	
Dual task (SOA = 250)	Accept	800.3	136
	Reject	936.4	
Dual task (SOA = 1200)	Accept	553.9	67
	Reject	621.0	

Table 3. Mean RTs as a function of repetition or prerepetition of decision outcome

Condition	Same decision outcome	Different decision outcome
Single task gamble	552.7	731.6
Dual gamble SOA = 100	972.8	1063.8
Dual gamble SOA = 250	792.9	930.2
Dual gamble SOA = 1200	547.9	627.2
Dual tone SOA = 100	734.3	751.3
Dual tone SOA = 250	685.9	730.2
Dual tone SOA = 1200	705.5	733.2

[1] Still more fine-grained analyses of the data were performed that conditionalized on acceptance vs. rejection of cards of particular colors; these analyses did not yield reliable and interpretable findings, partly because of small numbers of trials; this problem was exacerbated by the fact that many subjects had no responses or virtually no responses in particular cells, simply because of their own choice patterns. Therefore, those analyses will not be presented here.

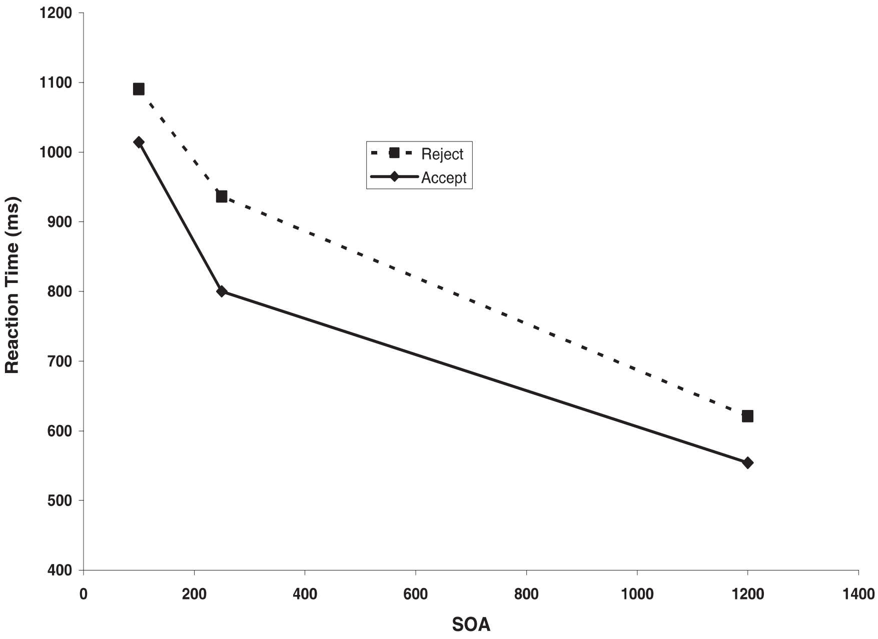

Figure 7. Mean response times for the gamble task within the dual-task blocks, as a function of the stimulus onset-asynchrony separating the tone from the card whether the card was accepted or rejected in the gamble task.

jected. This slowing effect is seen in Table 3. Looking only at the gamble task RTs in the dual-task blocks, there was an effect of response repetition, $F(1, 29) = 9.9$, $p < .004$, but this effect, too, failed to interact with SOA, $F(2, 58) = 1.4$, $p = .25$. This effect sounds at first blush very similar to the repetition effect found in "ordinary" choice reaction time tasks (e.g., Kornblum, 1969; Pashler & Baylis, 1991), which is also additive with SOA in the PRP design (Pashler & Johnston, 1989). However, the effect seen in the present study is importantly different from that effect. Here, the repeated-outcome trials are typically separated by several intervening trials from the last time the same color was offered, so the decision outcome repetition examined here does not imply any repetition of the response made on the preceding trial.

Sequential Effects: Once Burned Twice Shy?

We also examined the effect of the immediate reinforcement history of a given card color on gamble responses. More specifically, we looked at whether the last time the subject had accepted a card of a given color, they had won or lost money. Table 4 shows the average proportion of accept vs. reject responses and mean RTs broken down by this variable, also conditioned on whether the current choice was to accept or reject. On average, responses to a card of the same color that had previously generated a loss were very slightly slower, whether this response involved accepting the card, or rejecting it. However, this difference did not approach significance, either for acceptances, $t(58) = .34$, $.70 < p < .80$, or for rejections, $t(58) = .27$, $.70 < p < .80$.

Table 4. Mean RTs for accepting vs. rejecting a card from a deck that yielded a win or a loss when last presented

Previous outcome	Choice	% of trials	Mean RT (ms)
Win	Accept	.868	665.3
	Reject	.132	876.5
Loss	Accept	.823	681.3
	Reject	.177	905.4

Looking at the pattern of choices themselves, there was a tendency for subjects to be more likely to reject cards of a color that had generated a loss the last time a card of that color was accepted, as against a win. Though this effect was significant by a Chi Square test, $\chi^2(1) = 34.5$, $p < .001$, it was very small in size. At first glance, the small size of this effect might seem surprising: How can people be learning from experience if they do not tend to avoid decks that have produced a bad outcome? Busemeyer and Stout (2002) provided an illuminating formal model of the choice process in a gamble task, and in terms of this model, the sequential effect just noted would be interpreted as reflecting a parameter they termed the "updating rate." This parameter typically takes an intermediate value closer to zero than to 1 (a rate of 1 would be mean that decisions were exclusively sensitive to the most recent events, while a rate of zero would indicate no particular sensitivity to recent as against temporally distant events).

Conclusions

This is, to our knowledge, the first experiment to look at patterns of dual-task performance when one or both tasks involved genuine decision-making, as that term is used in ordinary life, i.e., to refer to a free choice made by a person seeking to maximize the desirability of the outcomes resulting from their actions. By contrast, within the vast PRP literature, subjects have normally been instructed by the experimenter about what response to make to every possible stimulus.

In the present study, subjects accepted or rejected cards from one of three different-colored decks, each deck carrying different payoff probabilities. Three decision-related variables were identified that had reliable effects on the speed of gamble choice responses: The color of the deck, the nature of the response being made (accept vs. reject), and whether the decision outcome for that color matched the decision outcome the last time a card of that color was offered. Subjects were slower to respond to decks associated with higher risk, slower to reject cards than to accept them, and slower whenever they made a different response to a given color of card than what they made the last time a card of that color was on offer. None of these effects were found to interact with SOA. Had the processing stage(s) affected by these variables not been subject to a delay attributable to the central bottleneck, then we would have expected SOA to combine in a strikingly subadditive fashion with these manipulations. This is because the extra time for carrying out these stages would merely have been pushing the decision process farther into the "slack" phase indicated in the bottom panel of Figure 1. The fact that such a pattern of subadditivity was not observed favors the idea that the central bottleneck encompasses the decision process, and by inference, that it may generally encompass any process of making spontaneous affectively based decisions (as in the scenario depicted in the top panel of Figure 1).

Limitations and Counter-Arguments

As noted above, this study represents, to our knowledge, the first chronometric analysis of a "free choice" task. For that very reason, there is limited evidence available to guide us in fixing a specific interpretation on each of the latency effects identified here. That kind of analysis will be a substantial task in itself, and could obviously benefit from the existence of formal models of the processes involved in reinforcement learning, such as the one proposed by Busemeyer and Stout (2002).

For the present conclusions, however, what is critical is that these effects operate during the choice decision process. For the basic conclusion of the current paper to be erroneous, it would have to be the case that all three of the effects described here operate, not in the decision process per se, but rather in a later motor-related processing stage (if they affected predecision processes, then an underadditive pattern would have been expected). If true, that claim would of course undercut the interpretation offered here for the additive pattern of effects, and open up the possibility that the decision making is *not* subject to the central bottleneck. However, this account seems to us implausible, and especially so for the third variable described here (repetition of decision outcome). As noted above, condition associated with faster responding (same choice made on two subsequent appearances of the same color) did not entail any repetition of the actual motor response from the preceding trial – which could obviously affect speed of motoric processing. The decision outcome effect indexed a "change of mind" by the subject about what to do *when offered a particular color of card* dating from the last time that color was presented, typically several trials earlier. It would seem quite implausible to attribute this stimulus-contingent slowing to slower motoric processing, whereas a decisional locus would seem intuitively plausible.

A finding of additivity relies, statistically speaking, on a failure to reject the null effect. Does that weaken the force of the current results? We would argue that it does not, because the hypothesis being rejected here – that the decision process takes place during a period of slack, with subsequent stages being subject to postponement – does not merely predict some unspecified degree of interaction (as with "additive factors method" interpretations). Rather, it predicts that the effect should virtually *disappear* at the shortest SOA (due to the fact that RT2 was being slowed by a much greater amount than the factor effects themselves). Indeed, that sort of strong interaction has been repeatedly observed in the PRP literature whenever variables targeted prebottleneck perceptual stages of task 2 have been altered (e.g., Jolicoeur, Dell'Acqua, & Crebolder, 2001; Oriet & Jolicoeur, 2003; Pashler, 1984; Pashler & Johnston, 1989; Ruthruff, Johnston, & van Selst, 2001; Ruthruff et al., 2006; van Selst, Ruthruff, & Johnston, 1999). Thus, we would suggest that the lack of even any measurable reduction in the effect of any of the three factors examined here argues quite strongly that the processes modulated by these decisional variables are subject to complete or virtually complete postponement due to ongoing central processing in task 1.

It should also be noted that the present analysis is restricted to those aspects of the decision process that occur between the presentation of a choice option and the making of a response. We are assuming here that subjects do not "predecide" in advance of every trial what decision they would make about each possible card color, and then when the card is presented, simply recollect what they had already decided to do with that card. If this were what is happening, then our findings would actually pertain to a special form of response selection, rather than to the decision itself. While we think that such a scenario is most unlikely, it is still the case that important aspects of the decision-making process probably *do* take place outside of the stimulus-response interval, in the phase when feedback is provided and interpreted. Chronometric studies that measured not only the time taken in the stimulus-response phase, but also the time taken for interpretation of feedback, might shed light on this issue.

In summary, the present results indicate that the central bottleneck that has emerged from several decades of PRP research encompasses not only the recollection and implementation of experimenter-provided instructions about what responses to make, but also includes the process of making what, in ordinary language, is usually termed a 'decision': A "free" choice as to what action to choose for the purpose of optimizing later outcomes. More generally, the results suggest that the time course of voluntary decision making can profitably be investigated with chronometric methods.

Acknowledgments

This work was supported by grants from the National Institute of Mental Health (R01-MH45584, H. Pashler, PI, and P50 MH066286, Keith Nuechterlein, PI). Noriko Coburn, David Cun, Christopher Shum, and Shirley Leong provided technical assistance, and Allen Osman provided useful comments.

References

Bechara, A., Damasio, A.R., Damasio, H., & Anderson, S.W. (1994). Insensitivity to future consequences following damage to human prefrontal cortex. *Cognition, 50,* 7–15.

Busemeyer, J., & Stout, J.C. (2002). A contribution of cognitive decision models to clinical assessment: Decomposing performance on the Bechara gambling task. *Psychological Assessment, 14,* 253–262.

Byrne, M., & Anderson, J. (2001). Serial modules in parallel: The psychological refractory period and perfect time-sharing. *Psychological Review, 108,* 847–869.

Carrier, M., & Pashler, H. (1995). Attentional limits in memory retrieval. *Journal of Experimental Psychology: Learning Memory and Cognition, 21,* 1339–1348.

Duckworth, K.L., Bargh, J.A., Garcia, M., & Chaiken, S. (2002). The automatic evaluation of novel stimuli. *Psychological Science, 13*, 513–519.

Dux, P.E., Ivanoff, J., Asplund, C.L., & Marois, R. (2006). Isolation of a central bottleneck of information processing with time-resolved fMRI. *Neuron, 52,* 1–12.

Fagot, C., & Pashler, H. (1992). Making two responses to a single object: Implications for the central attentional bottleneck. *Journal of Experimental Psychology: Human Perception and Performance, 18,* 1058–1079.

Jiang, Y., & Kanwisher, N. (2003). Common neural substrates for response selection across modalities and mapping paradigms. *Journal of Cognitive Neuroscience, 15,* 1080–1094.

Jolicoeur, P., Dell'Acqua, R., & Crebolder, J. (2001). The attentional blink bottleneck. In K.L. Shapiro (Ed.), *The limits of attention* (pp. 82–99). New York: Oxford University Press.

Kornblum, S. (1969). Sequential determinants of information processing in serial and discrete choice reaction time. *Psychological Review, 76,* 113–131.

Levy, J., Pashler, H., & Boer, E. (2006). Central interference in driving: Is there any stopping the psychological refractory period? *Psychological Science, 17,* 228–235.

Lien, M.C., Ruthruff, E., & Johnston, J.C. (2006). Attentional limitations in doing two things at once: The search for exceptions. *Current Directions in Psychological Science, 15,* 89–93.

Manes, F., Sahakian, B., Clark, L., Rogers, R., Antoun, N., Aitken, M., & Robbins, T. (2002). Decision-making processes following damage to the prefrontal cortex, *Brain, 125,* 624–639.

McCann, R., & Johnston, J.C. (1992). Locus of the single-channel bottleneck in dual-task interference. *Journal of Experimental Psychology: Human Perception and Performance, 18,* 471–485.

McLeod, P. (1977). Parallel processing and the psychological refractory period. *Acta Psychologica, 41,* 381–391.

Oriet, C., & Jolicoeur, P. (2003). Absence of perceptual processing during reconfiguration of task-set. *Journal of Experimental Psychology: Human Perception and Performance, 29,* 1036–1049.

Pashler, H. (1984). Processing stages in overlapping tasks: Evidence for a central bottleneck. *Journal of Experimental Psychology: Human Perception and Performance, 10,* 358–377.

Pashler, H., & Baylis, G. (1991). Procedural learning: 2. Intertrial repetition effects in speeded choice tasks. *Journal of Experimental Psychology: Learning, Memory and Cognition, 17,* 33–48.

Pashler, H., & Johnston, J. (1989). Chronometric evidence for central postponement in temporally overlapping tasks. *Quarterly Journal of Experimental Psychology, 41A,* 19–45.

Pashler, H., & Johnston, J.C. (1998). Attentional limitations in dual-task performance. In H. Pashler (Ed.), *Attention* (pp. 155–189). Hove, UK: Psychology Press/Erlbaum.

Pratt, J. (1964). Risk aversion in the small and in the large. *Econometrica, 32,* 122–136.

Ruthruff, E., Johnston, J.C., & Van Selst, M.V. (2001). Why practice reduces dual-task interference. *Journal of Experimental Psychology: Human Perception and Performance, 27*, 3–21.

Ruthruff, E., van Selst, M., Johnston, J.C., & Remington, R. (2006). How does practice reduce dual-task interference: Integration, automatization, or just stage-shortening? *Psychological Research, 70,* 125–142.

Schubert, T., & Szameitat, A.J. (2003). Functional neuroanatomy of interference in overlapping dual tasks: An fMRI study. *Cognitive Brain Research, 17,* 733–746.

Szameitat, A.J., Schubert, T., Muller, K., & von Cramon, D.Y. (2002). Localization of executive functions in dual-task performance with fMRI. *Journal of Cognitive Neuroscience, 15,* 1184–1199.

Tombu, M., & Jolicoeur, P. (2003). A central capacity sharing model of dual-task performance. *Journal of Experimental Psychology: Human Perception & Performance, 29,* 3–18.

Van Selst, M.V., Ruthruff, E., & Johnston, J.C. (1999). Can practice eliminate the psychological refractory period effect? *Journal of Experimental Psychology: Human Perception and Performance, 25*, 1268–1283.

Welford, A.T. (1967). Single-channel operation in the brain. *Acta Psychologica, 27,* 5–22.

Received May 12, 2007
Revision received August 15, 2007
Accepted August 17, 2007

Harold Pashler

Department of Psychology 0109
UC San Diego
La Jolla, CA 92093
USA
E-mail hpashler@ucsd.edu

