In press version, In A. C. Nobre & J. T. Coull (Eds.)
Attention and Time

Chapter 9

Mental timing and the central attentional bottleneck

Eric Ruthruff and Harold Pashler

Time estimations are important in everyday life. When the stoplight ahead turns yellow, for example, one needs to estimate whether there is sufficient time to enter and exit the intersection. As noted elsewhere in this book, however, the ability to estimate time is impaired under conditions of divided attention (e.g. Hicks, Miller, and Kinsbourne, 1976; Brown, 1985, 1997; Mattes and Ulrich, 1998; Brown, Chapter 8, this volume). In many cases, authors have interpreted these results as reflecting a diversion of processing resources from the timing task to another task, so that both tasks receive a partial share of the available resources. The purpose of the present chapter is to evaluate the specific alternative hypothesis that timing might be subject to a discrete central processing bottleneck (Pashler, 1984; Welford, 1952), so that timing cannot take place until central operations have finished. To begin, we briefly review the evidence for a central bottleneck, and then relate this research to studies of timing under divided attention.

Central bottleneck model

Traditional dual-task studies (with non-temporal tasks) often reveal dramatic interference between tasks that require planning and production of responses (for reviews, see Pashler and Johnston, 1998; Lien and Proctor, 2002). There are many different dual-task paradigms, but perhaps the most widely used approach is to present two different stimuli, each requiring production of its own speeded motor response. By varying the time between these stimuli—known as the stimulus onset asynchrony (SOA)—we can vary the degree to which the tasks need to be performed concurrently. Typically, the task presented first (Task 1) is performed quickly at all SOAs. But response times to the task presented second (Task 2) are usually elevated by several hundred milliseconds at short SOAs (e.g. 50ms) relative to long SOAs (e.g. 1000ms). This dual-task interference effect has been termed the psychological refractory period (PRP) effect (see also Sigman, Chapter 5, this volume). The term 'refractory period' came from the hypothesis that the interference stems from a temporary cognitive sluggishness immediately following an act of cognition (analogous to the neuronal refractory period); although that hypothesis has long since been discarded, the name for the phenomenon stuck.

The robustness of PRP interference across a wide range of tasks, input modalities, and output modalities led Welford (1952) to propose the central bottleneck model. The key assumption, shown in Figure 9.1A, is that while central operations of one task are underway, central operations of all other tasks must wait. The term 'central operation' is rather vague, but is usually taken to refer to the decision-making processes that take place after perception but before response execution.

Note that the central bottleneck model implies a discrete view of dual-task interference, postulating a complete inability to carry out more than one central operation at a time.

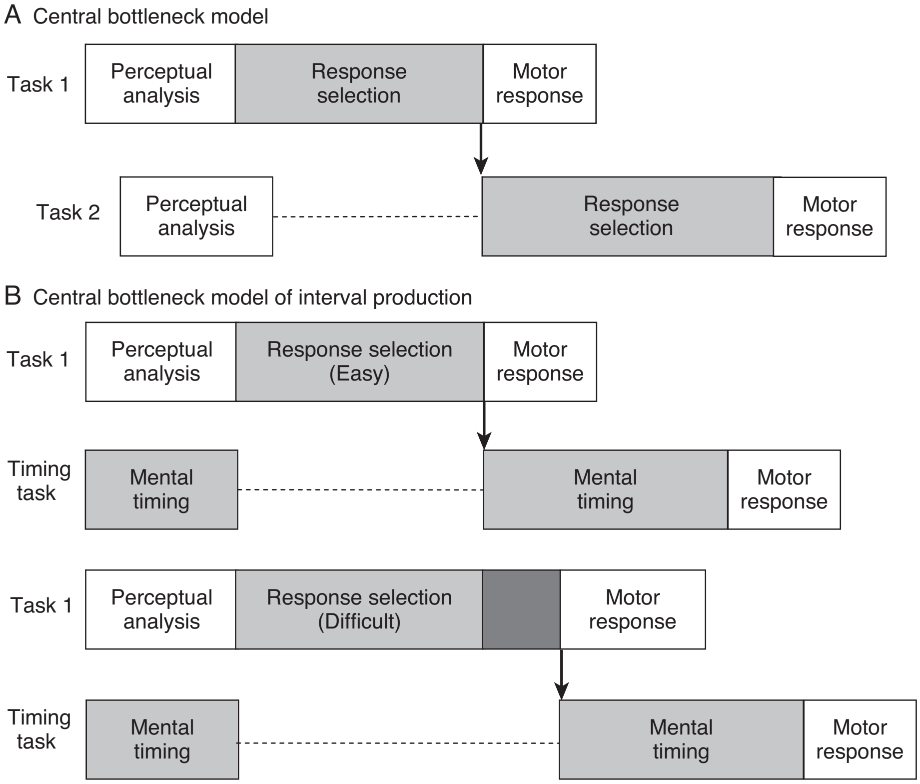

Fig. 9.1 A) The central bottleneck model, as applied to a traditional dual-task experiment. At short stimulus onset asynchronies (SOAs), like the one shown in the figure, the central stage of Task 2 (e.g. response selection) must wait for the central stage of Task 1 to finish. B) The central bottleneck model as applied to a mental timing task (interval production). The key assumption is that mental timing cannot take place while central operations are underway for any other task.

Dual-task interference thus is assumed to result primarily from processing delays (represented by the dotted line in Figure 9.1A), not from a slowing of mental processes that run concurrently (e.g. Kahneman, 1973). There is considerable evidence to favour this discrete view (e.g. Pashler, 1984, 1994; McCann and Johnston, 1992; Ruthruff, Pashler, and Hazeltine, 2003; Sigman and Dehaene, 2005), although there continues to be controversy about whether graded sharing of capacity among central processes can be ruled out (Navon and Miller, 2002; Tombu and Jolicoeur, 2002, 2003; Miller, Ulrich, and Rolke, 2009).

One major goal of research on this topic has been to determine the precise processing locus of the 'central' bottleneck. Studies have demonstrated convincingly that response selection is subject to the central processing bottleneck (e.g. Pashler, 1984, 1994; Pashler and Johnston, 1989; McCann and Johnston, 1992), at least relatively early in practice (see Hazeltine, Teague, and Ivry, 2001; Schumacher et al., 2001; Ruthruff et al., 2006; Maquestiaux et al., 2008). Subsequent studies have associated the bottleneck with a wide range of additional mental processes, including mental rotation (Ruthruff, Miller, and Lachmann, 1995), encoding into short-term memory (Jolicoeur, 1999; Ruthruff and Pashler, 2001), long-term memory retrieval (Carrier and Pashler, 1995; Byrne and Anderson, 2001), complex stimulus categorizations (Johnston and McCann, 2006), and even the discrimination of facial expressions (Tomasik et al., 2009). The diversity of mental processes subject to the processing bottleneck suggests the existence of a single very general-purpose processing mechanism, perhaps analogous to the CPU (central processing unit) of a computer (although not necessarily anatomically localized). We refer to this putative mechanism or resource as the *central mechanism*.

Of course, not all mental processes require the central mechanism. If tasks were performed entirely sequentially, with no temporal overlap in any mental processes, then the time to complete two tasks in dual-task conditions would be equal to the *sum* of the times to complete the tasks in single-task conditions. Dual-task interference is rarely ever this severe, however, suggesting that some mental processes can overlap in time. Research indicates that perceptual processes often do not require the central mechanism; specific examples include letter identification (Pashler and Johnston, 1989; Luck, 1998; Johnston and McCann, 2006), word identification (at least for skilled readers; Ruthruff et al., 2008), and retrieval of images from long-term memory (Green, Johnston, and Ruthruff, 2007).

It appears that response-execution processes are also not subject to the bottleneck, under many circumstances. To study this issue, Osman and Moore (1993) used one task that required either a left-hand or right-hand response (Task 1, presented first) and another task that required a left-foot or right-foot responses (Task 2, presented second). With such tasks, one can determine when subjects begin preparing a response by measuring lateralized readiness potentials—the difference in brain potentials between the motor cortices of the left and right hemispheres. Osman and Moore found that preparation of the manual response to Task 2 began before the foot response to Task 1 had been completed (i.e. response executions overlapped). Lien et al. (2007) found similar results with a vocal task followed by a manual task. Behavioural studies have yielded similar conclusions. If motoric processes are sequential then, at short SOAs in the PRP paradigm, any manipulation that prolongs Task-1 response execution should also delay the Task-2 response. Contrary to this prediction, Pashler and Christian (1994) found that increasing the complexity of Task-1 response execution (e.g. saying 'one' versus saying 'one two three four five') increased response times to Task 1 but had relatively little effect on response times to Task 2 (see also Bratzke et al., 2008). Thus Task-2 response execution does not generally need to wait until Task-1 response execution has finished. Ulrich et al. (2006), however, found that increases in the complexity of the manual response to Task 1 (short versus long movements of a lever) increased response time to Task 1 and also caused a similar increase in response times to Task 2, which also required a manual response. A tentative conclusion from these studies is that response execution is not wholly subject to the central bottleneck, at least when the tasks use distinct response modalities (e.g. vocal versus manual).

In sum, results from recent dual-task studies are generally consistent with the original claim that the bottleneck generally encompasses central processes (loosely defined as deciding how to respond to the stimulus), but not necessarily perceptual processes or response execution. However, the precise boundary between bottleneck and non-bottleneck processes is still being mapped out.

Mental timing under divided attention

Most studies examining attentional limitations in mental timing have asked subjects to estimate time while performing some fairly continuous distracting task (Brown, Chapter 8, this volume). The mental activities required in these tasks have been quite diverse, ranging from perceptuo-motor coordination (e.g. mirror drawing) to fine perceptual discriminations (e.g. loudness or brightness) to demanding cognitive operations (e.g. problem-solving). Typically, the subject reports either a numerical estimate of the duration of some event (*time estimation*), pushes a button after a specified time interval has elapsed (*interval production*), or reproduces the duration of some recently experienced event (*interval reproduction*). Sometimes, subjects are asked to judge durations after the fact (*retrospective timing*), although the present article concerns only cases where subjects know in advance that they are to record the duration of some interval (*prospective timing*).

Overwhelmingly, these studies show that concurrent tasks interfere with prospective timing (Hicks, Miller, and Kinsbourne, 1976; Zakay, Nitzan, and Glicksohn, 1983; Brown, 1985, 1997; Fortin and Rousseau, 1998; Zakay and Block, 1996, 1997; Mattes and Ulrich, 1998; Zakay, 1998; Rammsayer and Ulrich, 2005). Specifically, performing a concurrent task usually leads to a foreshortening of perceived time and an increase in the variability of time estimates. These interference effects typically become more severe as the difficulty of the concurrent task increases (e.g. Zakay, Nitzan, and Glicksohn, 1983; Brown, 1985, 1997).

As an example, Brown (1985, Experiment 1; Brown, Chapter 8, this volume) asked subjects to perform one of three tasks on a 6-pointed star: (1) attend the star (no response required); (2) trace the outline of the star; or (3) trace the star using a mirror. After either 16 or 32 seconds of performing these tasks, the experimenter then asked the subject to verbally report how much time had elapsed. Half were tested under prospective conditions (they knew in advance they would be asked to make time judgements) and half under retrospective conditions. Of primary interest here is the observation that the mean prospective time estimates decreased (by about 27%) as the difficulty of the concurrent task increased.

Previous findings clearly indicate that time perception benefits from ‘attention’, in the most global sense of that term (and, conversely, suffers from a lack of attention). However, they do not tell us whether mental timing is subject to the central bottleneck (see Figure 9.1B). Indeed, the link between these literatures has rarely been discussed. One limitation of most previous timing studies—with respect to evaluating a central bottleneck account—is the use of continuous concurrent tasks, which require central mechanisms only intermittently. If subjects switch back and forth between the timing task and the concurrent task, at times of their choosing, the central bottleneck hypothesis makes no clear predictions regarding the amount of interference. Another limitation is that researchers typically compare timing performance in dual-task versus single-task blocks, which differ not only in the availability of central mechanisms, but also in overall mental load. Even in studies that compared multiple dual-task conditions differing in difficulty (e.g. the different curve tracing conditions of Brown, 1985, Experiment 1), the different conditions are completed in separate blocks of trials or even using different groups of subjects. So load is still confounded with competition for central mechanisms. The problem is that, as mental task load increases, the quality of advance preparation for any particular task decreases, and task performance suffers (Gottsdanker, 1979; Rogers and Monsell, 1995). Even if mental timing is not subject to the central bottleneck, timing accuracy might degrade in dual-task blocks due to poorer preparation for timing. As a simple analogy, it would take longer to launder two heavy blankets together (compared to laundering only one) because the heavier load would prolong drying time. This load effect reflects a kind of capacity limitation, but it is clearly not the case that the dryer somehow deals with each blanket one at a time. Furthermore, this confound between load and task difficulty makes it nearly impossible to generate precise predictions from the central bottleneck model. Indeed, the success of the PRP paradigm (which varies SOA, the time between stimuli, rather than the number of tasks) stems largely from the fact that it reduces the impact of task load. A further concern is that, in some previous studies, the concurrent task was initiated prior to the onset of the stimulus whose duration is to be timed. Consequently, it is possible that the interference reflects not a difficulty in timekeeping per se, but rather a failure to detect the onset of the interval to be timed (see Lejeune, 1998).

Time production

We have investigated the attentional demands of time perception using a new type of procedure (Ruthruff and Pashler, 2008). Our specific goal was to determine whether mental timing must be postponed while central mechanisms select a speeded response to a concurrent task (see Figure 9.1B). Because the concurrent task requires subjects to rapidly decide which of several responses is appropriate for a given stimulus (decision-making), it should engage central attentional mechanisms.

As a starting point, we examined the ability to produce a fixed time interval in parallel with a concurrent task requiring a comparison of the brightness of two filled squares. As shown in Figure 9.2A, subjects were required to make their brightness response in less than 1 second and then press a key when 1.5 seconds had elapsed since stimulus onset (time production). Because the stimulus used for the brightness task was also used for the timing task, there was no danger that divided attention would cause subjects to fail to notice the onset of the interval to be timed. We assumed that the brightness task would receive priority in dual-task blocks because of the requirement to respond quickly. Consistent with this assumption, brightness discriminations were just as fast in dual-task blocks as in single-task blocks.

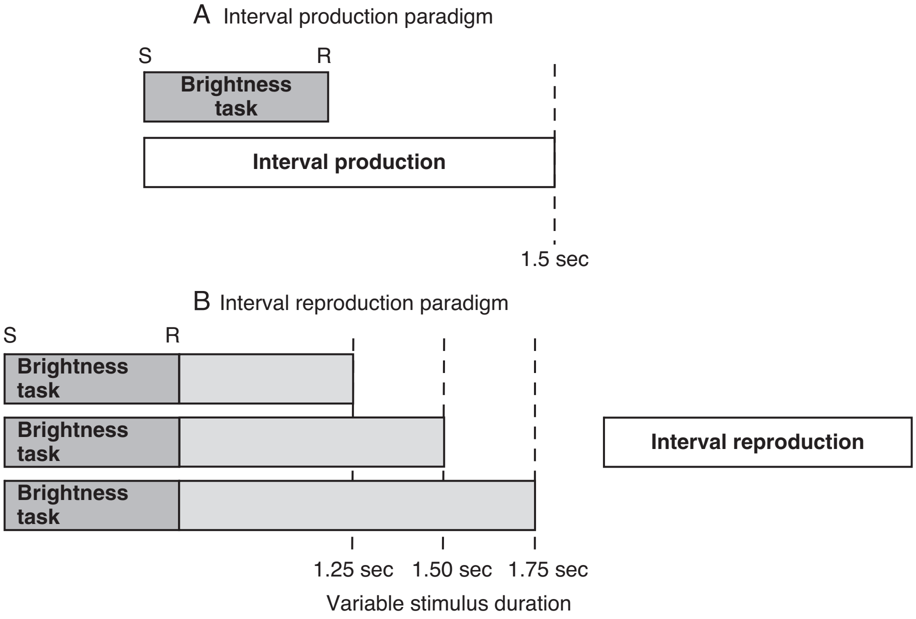

Fig. 9.2 A) Dual-task condition with interval production. Upon stimulus onset, subjects were to perform the brightness discrimination and to begin producing a 1.5-second interval. B) Dual-task condition with interval reproduction. Upon stimulus onset, subjects were to perform the brightness discrimination and also to estimate the stimulus duration (the actual duration was 1.25, 1.5, or 1.75 seconds). They could reproduce this duration any time after stimulus offset.

The key manipulation was the difficulty of the brightness judgement. In the easy condition the brightness difference was large, whereas in the difficult condition the brightness difference was much more subtle. These conditions were randomly intermixed within dual-task blocks, so that difficulty would not be confounded with load (i.e. the number of pending tasks to be prepared was the same). In single-task blocks, decreasing the difference in brightness increased the time to complete the brightness discrimination by nearly 100ms. The critical question was how this manipulation would influence time production in dual-task blocks. If subjects can keep track of time while performing the speeded brightness discrimination, without interference, then their timing performance should not depend much on the difficulty of the brightness discrimination. They should simply produce intervals of about 1.5 seconds (± error) in both the easy and difficulty conditions. But if timing requires central attentional mechanisms, attempts to produce a 1.5-second interval should be strongly biased by the difficulty of the intervening brightness discrimination. The reason is that subjects would not be able start their mental timer until *after* completing the brightness discrimination (see Figure 9.B). Consequently, they should fail to record the extra time taken while performing the difficult version of the concurrent task. It follows that their time productions should be much longer with a difficult brightness discrimination than with an easy discrimination. We refer to this phenomenon as *carryover*. In the extreme, the carryover onto the timing task (i.e. the lengthening of time productions) should be just as large as the effect on the brightness discrimination itself (100% carryover).

The mean produced time interval across single and dual-task blocks was 1481ms (SD = 192ms), which is very close to the target value (1500ms). Subjects received feedback after each time production, which presumably helped them to hone in on the target value. More importantly, carryover was nearly 100%. In dual-task blocks, the brightness manipulation slowed performance on the brightness discrimination by 82ms, and increased time productions by 80ms. The most straightforward explanation is that, as depicted in Fig 9.1B, subjects did not actually begin keeping track of time until after the brightness discrimination was finished (or, at least, until after the stage(s) influenced by our difficulty manipulation). In other words, the data suggest that timing requires the same central attentional mechanisms needed to select a response to Task 1.

This conclusion is supported by the timing variability data. In dual-task blocks, brightness discriminations took about 500ms and had a standard deviation (SD) of 97ms. By comparison, the average SD of the time productions in single-task blocks was 214ms. Assuming that timing variance is proportional to the duration being timed, the SD for a 500-ms interval would be about 124ms. Thus, timing estimates appear to be more variable than brightness discriminations. Hence, if subjects do not keep track of time during the brightness discrimination, time productions will inherit the variability of the approximately 500-ms brightness discrimination, rather than the variability of 500ms of mental timing. This leads to the surprising prediction that timing variability should actually *decrease* in dual-task blocks. Indeed, the SD of time productions was significantly smaller in dual-task blocks (SD = 171ms) than in single-task blocks (SD = 214ms).

One might propose that a failure to keep track of time during the brightness discrimination should lead, overall, to production of an interval much longer than the target interval (e.g. because no counts are made while the brightness discrimination engages central mechanisms is underway). However, this did not happen: mean time productions were 21ms shorter (marginally significant) in the dual-task condition (1471ms) than in the single-task condition (1492ms) and quite close to the target interval (1.5 sec). However, because subjects were given trial-by-trial feedback on the accuracy of their produced time intervals, they presumably learned to compensate for the missed time. In other words, we propose that subjects first performed the brightness judgement (taking about 500ms), then timed out an interval of about 1000ms to produce a total interval of about 1500ms.

In principle, subjects could have learned two different compensations—one for the easy brightness judgement and one for the difficult one—eliminating the carryover onto time productions. Clearly, this did not happen. It seems that people learn to make a single, overall compensation (which can be prepared in advance of each trial), but do not make different compensations for specific conditions (which are mixed together unpredictably and thus cannot be anticipated).

Time reproduction

When the task required time production, the nearly 100% carryover suggests that subjects could not keep track of time while simultaneously performing a speeded brightness discrimination. These findings, however, fall short of demonstrating that mental timing wholly usurps central attentional mechanisms, in general. Subjects might have information about the elapsed time that cannot be used in time production, but can be used when making other types of timing judgements. Moreover, one might suggest that subjects begin timing after completing the brightness discrimination not because they are compelled to do so by basic cognitive architecture, but rather because this strategy simplifies the timing task. Instead of timing out the full 1.5-second interval, they need only time out the period remaining after completing the brightness discrimination (roughly 1 second). As noted earlier, brightness-task response time was relatively consistent from trial to trial, so the amount of error introduced by not timing during that task would probably be less than the error associated with mental timing of the same interval.

To address this issue, we conducted a series of follow-up experiments with a different kind of timing response. Instead of producing a time interval during the brightness discrimination (interval production), we asked subjects to keep track of the stimulus duration and subsequently reproduce this interval (known as interval reproduction). Thus, as shown in Figure 9.2B, subjects first classified the brightness of a stimulus, and then attempted to reproduce the duration of that stimulus. To make the task challenging, we used a variable stimulus duration of 1.25, 1.5, or 1.75 seconds. The bottleneck model predictions parallel those of the previous experiment with time production, but with an important twist. If subjects can time only after completing the brightness discrimination, then they should perceive a shorter stimulus duration in trials with a difficult brightness discrimination than with an easy discrimination. However, the effect of this estimation bias on time reproductions should be opposite in sign to the effect observed on time productions. Specifically, time reproductions should be *reduced* following the more difficult brightness discrimination, by the same amount that the brightness response is increased (100% carryover).

We found that the mean reproduced time interval was significantly shorter in the difficult condition (1415ms, SD = 209ms) than in the easy condition (1448ms, SD = 200ms). Although this 33-ms carryover effect went in the predicted direction, it was only 22% of the 147-ms lengthening of the brightness judgement itself with difficult discriminations (see Figure 9.3). These results—in contrast to those we obtained with time production—suggest that mental timing is far from being completely subject to a central bottleneck.

One caveat is that, as the stimulus duration increased by 500ms (from 1.25 to 1.75 seconds), interval productions increased by only 194ms. Thus, only 38.8% of the change in stimulus duration was reflected in time productions. Given that the perceived estimate of the stimulus duration on any given trial is noisy, subjects might combine this noisy estimate with a relatively stable estimate of the mean stimulus duration. The result would be regression-to-the-mean in stimulus reproductions. Critically, this regression might also limit the carryover of difficulty effects onto the timing task. Nevertheless, the 22% carryover of difficulty effects is significantly less than the 38.8% of variation in stimulus duration that is reflected in time productions. Put another way, the

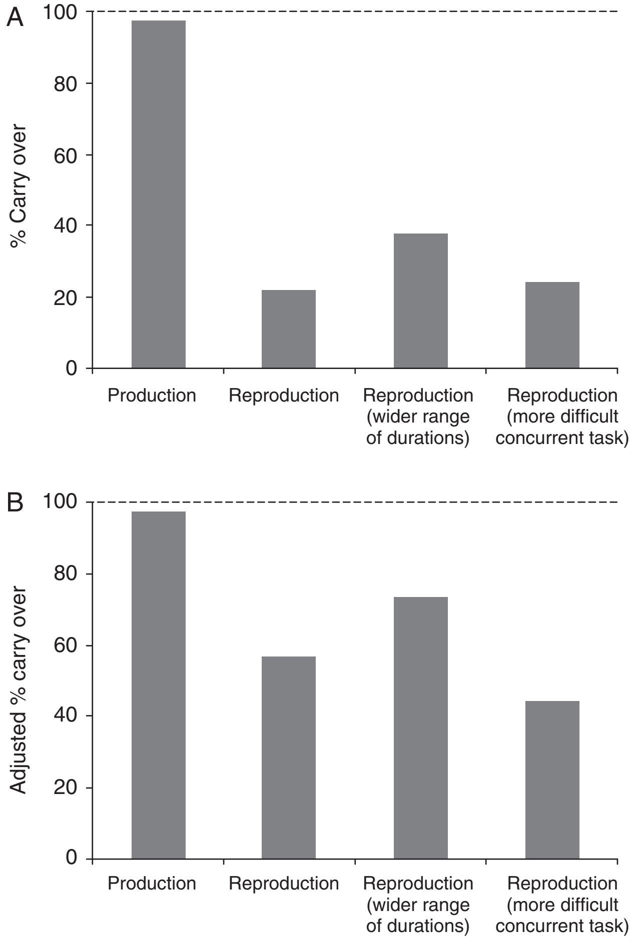

Fig. 9.3 A) Percentage carryover, calculated as the effect of concurrent task difficulty on time productions/reproductions (× 100) divided by its effect on the concurrent task itself. When reproducing intervals, participants might incorporate their estimate of elapsed time on a given trial with their estimate of the mean elapsed time across all trials. This could explain why subjects' reproductions did not increase one-for-one with increases in actual stimulus duration (regression to the mean). To correct for potential regression to the mean (B), we first calculated for each experiment the proportion of the range in actual stimulus durations that was captured by subjects' reproduced durations. Then we divided the percentage carryover (shown in A) by this proportion.

observed carryover onto time reproductions was only about 57% of maximum (recall that we found virtually 100% carryover in our earlier experiment on time production).

Increased variation in stimulus duration

To encourage subjects to rely on their perception of the passage of time during each stimulus presentation, rather than the average stimulus duration, we conducted a follow-up experiment with a wider range of stimulus durations (spanning 1 second rather than 0.5 seconds): 1, 1.25, 1.5, 1.75, and 2 sec. This effort appears to have been successful in that the range of time reproductions captured more of the variation in stimulus durations (52.0% versus 38.8%); that is, there appeared to be less regression to the mean.

Another concern regarding our previous experiment is that the difficult brightness discrimination, which produced 15.8% errors, was overly difficult. We therefore increased slightly the brightness difference used in the difficult condition, which brought error rates (3.1%) back into the range typical of most experiments with speeded responses (where the primary dependent measure is response time, not accuracy). Nevertheless, the manipulation still had a substantial effect on response times, as discussed later. A further benefit of a more subtle difficulty manipulation is that it reduces the likelihood that subjects are aware of the different conditions and deliberately compensate for them by adjusting their time estimates away from the perceived duration. To further reduce any such concerns over a deliberate compensation, we also eliminated the trial-by-trial feedback on timing performance. Without this feedback, subjects are less likely to become aware that their time estimates deviate systematically in certain conditions.

Without trial-by-trial feedback, subjects began to more severely underestimate the stimulus duration; the mean reproduced time was 1304ms (SD = 253ms), compared to the actual mean duration of 1500ms. Most critically, however, the difficulty manipulation had a 95-ms effect on brightness judgements, but only a 36-ms effect on time reproductions. Thus, the carryover was only 37.9%. In the preceding section we noted that subjects might integrate perceived time with a stable estimate of the average time; if so, 100% carryover would not occur, even if timing were subject to a central bottleneck. In this experiment, 52% of the variation in actual stimulus duration (from 1 to 2 seconds) was reflected in time reproductions. Even taking possible regression into account, the observed 37.9% carryover effect was only 73% percent of the 'carryover' of actual variation in stimulus duration.

Time reproduction with a more difficult concurrent task

Our initial experiments using time reproductions suggested that subjects could perceive stimulus duration (albeit imperfectly) even while central attentional mechanisms were busy with another task. A potential concern, however, is that the brightness discrimination (even the most difficult version) was not sufficiently demanding to fully engage central attentional mechanisms. In particular, it is possible that the stage sensitive to our difficulty manipulation relies more on perceptual processing mechanisms than central attentional mechanisms.

To address this issue, we used a much more demanding concurrent task that required subjects to map eight alphanumeric stimuli (1, 2, 3, 4, A, B, C, D) onto four response fingers. The mean response time for this task was 873ms, compared to only 481ms for the brightness discrimination. We varied the difficulty of this task via a stimulus–response (S–R) compatibility manipulation (e.g. Van Selst, Ruthruff, and Johnston, 1999; Ruthruff, Pashler and Hazeltine, 2003). The letters were mapped compatibly onto the four fingers and the digits incompatibly, or vice versa (counterbalanced across subjects). Numbers and digits were randomly intermixed within blocks, to avoid confounding difficulty effects with overall task load. Importantly, it seems clear that the manipulated stage (response selection) is central in this case, rather than perceptual. We found that mean response time was 763ms in the compatible condition (per cent error = 1.6%) and 987ms in the incompatible condition (per cent error = 7.3%). Thus, the mean effect size was 224ms.

The mean reproduced interval (1373ms; SD = 301ms) was again shorter than the actual mean stimulus duration of 1500ms. The key finding, however, is that only 24.1% of the difficulty effect on the S–R compatibility task carried over onto time reproductions. In contrast, 54.8% of the actual variation in stimulus duration was reflected in the time reproductions; as the actual duration increased from 1 to 2 seconds, the reproduced duration increased from 1093ms to 1641ms. Thus, the observed 24.1% carryover of difficulty effects represents only 44% of the 'carryover' from actual variation in stimulus duration. Even though the difficult S–R compatibility task clearly requires central mechanisms for an extended period of time, it appears that subjects were simultaneously able to keep track of the elapsed time (albeit imperfectly).

Conclusions

In this chapter, we posed the question of whether mental timing mechanisms can operate even while central attention is occupied with a demanding concurrent task. As we described earlier, previous literature seems generally inconclusive on this issue. Recent investigations in our lab suggest that when subjects actually *produce* time intervals in parallel with a concurrent task, timing mechanisms are subject to a central processing bottleneck. On the other hand, when subjects merely note stimulus duration in order to *reproduce* it shortly afterwards, mental timing is affected only to a rather modest degree by a concurrent speeded task. These results therefore refute the suggestion that timing is wholly subject to the same discrete central bottleneck as other types of effortful mental processes (such as response selection, memory encoding, and mental rotation). To put it simply, there must exist some mechanism(s) capable of perceiving time that are not completely disabled while central mechanisms are devoted to a concurrent task. It is an open question whether such mechanisms are functionally dedicated to timing or have other functions (see Ivry and Schlerf, 2008).

Models of time perception

A widely cited model of time perception proposes the existence of an autonomous pacemaker and an accumulator that counts the ticks (see, e.g. Gibbon, Church, and Meck, 1984; Ulrich, Nitschke, and Rammsayer, 2006). It is often suggested that, under dual-task conditions, attention must be divided between the concurrent task and the counting. The result is that many counts are missed and perceived time is foreshortened. Such a model potentially explains the present findings with time reproductions (i.e. mild disruption of timing during a concurrent task) if one adds the proviso that the accumulator benefits from central attention but is not entirely disabled without it. To account for the bottleneck in timing performance we found with time productions, one could add the plausible assumption that people can strategically disable this counting mechanism when it suits them. That is, perhaps the demanding nature of the time production paradigm encourages people to break performance down into two phases: performance of the concurrent task, followed by time production of the remaining time interval. Time reproduction, meanwhile, is easier because it merely requires online recording of an estimate of the elapsed time (actual reproduction of the estimated time can be delayed until well after the concurrent task has finished).

The present results could also be reconciled by proposing a combination of explicit and implicit time perception mechanisms. Suppose that the explicit timing mechanism—the one that is subject to bottleneck-type interference—is the most accurate timing mechanism. However, the implicit timing mechanism—which is not subject to the central bottleneck—can also provide useful temporal information, albeit with a lower resolution. People might be able to utilize the latter, less-precise mechanism when central attention is occupied by a concurrent task and thus not lose track of time completely.

References

Bratzke, D., Ulrich, R., Rolke, B., and Schröter, H. (2008). Motor limitation in dual-task processing with different effectors, *Quarterly Journal of Experimental Psychology,* **61**, 1385–99.

Brown, S. W. (1985). Time perception and attention: the effects of prospective versus retrospective paradigms and task demands on perceived duration. *Perception & Psychophysics*, **38**, 115–24.

Brown, S. W. (1997). Attentional resources in timing: interference effects in concurrent temporal and nontemporal working memory tasks. *Perception & Psychophysics*, **59**, 1118–40.

Byrne, M. D. and Anderson, J. R. (2001). Serial modules in parallel: the psychological refractory period and perfect time-sharing. *Psychological Review*, **108**, 847–69.

Champagne, J. and Fortin, C. (2008). Attention sharing during timing: modulation by processing demands of an expected stimulus. *Perception & Psychophysics,* **70**, 630–9.

Fortin, C., and Rousseau, R. (1998). Interference from short-term memory processing on encoding and reproducing brief durations. *Psychological Research,* **61**, 269–76.

Gibbon, J., Church, R. M., and Meck, W. H., (1984). Scalar timing in memory. *Annals of the New York Academy of Sciences,* **423**, 52–77.

Gottsdanker, R. (1979). A psychological refractory period or an unprepared period? *Journal of Experimental Psychology: Human Perception and Performance,* **5**, 208–15.

Green, C., Johnston, J. C., and Ruthruff, E. (2007). Recognition of pictures may not require central attentional resources. *Proceedings of the 29th Annual Cognitive Science Society*, pp.317–22. Austin, TX: Cognitive Science Society.

Hazeltine, E., Teague, D., and Ivry, R. B. (2002). Simultaneous dual-task performance reveals parallel response selection. *Journal of Experimental Psychology: Human Perception and Performance,* **28**, 527–45.

Hicks, R. E., Miller, G. W., and Kinsbourne, M. (1976). Prospective and retrospective judgments of time as a function of amount of information processed. *American Journal of Psychology*, **89**, 719–30.

Jolicoeur, P. (1999). Concurrent response selection demands modulate the attentional blink. *Journal of Experimental Psychology: Human Perception and Performance*, **25**, 1097–113.

Kahneman, D. (1973). *Attention and effort*. Englewood Cliffs, NJ: Prentice-Hall.

Ivry, R. B. and Shlerf, J. E. (2008). Dedicated and intrinsic models of time perception. *Trends in Cognitive Sciences*, **12**, 273–80.

Lejeune, H. (1998). Switching or gating? The attentional challenge in cognitive models of psychological time. *Behavioural Processes*, **44**, 127–45.

Lien, M.-C., and Proctor, R. W. (2002). Stimulus-response compatibility and psychological refractory period effects: Implications for response selection. *Psychonomic Bulletin and Review,* **9**, 212–38.

Lien, M.-C., Ruthruff, E., Hsieh, S.-L., and Yu, Y.-T. (2007). Parallel central processing between tasks: Evidence from lateralized readiness potentials. *Psychonomic Bulletin and Review,* **14**, 133–41.

Luck, S. J. (1998). Sources of dual-task interference: Evidence from human electrophysiology. *Psychological Science,* **9**, 223–7.

Maquestiaux, F., Laguë-Beauvais, M., Ruthruff, E., and Bherer, L. (2008). Bypassing the central bottleneck after single-task practice in the psychological refractory period paradigm: evidence for task automatization and greedy resource recruitment. *Memory & Cognition,* **36**, 1262–82.

Mattes, S. and Ulrich, R. (1998). Directed attention prolongs the perceived duration of a brief stimulus. *Perception and Psychophysics*, **60**, 1305–17.

McCann, R. S. and Johnston, J. C. (1992). Locus of the single-channel bottleneck in dual-task interference. *Journal of Experimental Psychology: Human Perception and Performance,* **18**, 471–84.

Miller, J., Ulrich, R., and Rolke, B. (2009). On the optimality of serial and parallel processing in the psychological refractory period paradigm: effects of the distribution of stimulus onset asynchronies. *Cognitive Psychology* **58**, 273–310.

Navon, D. and Miller, J. (2002). Queuing or sharing? A critical evaluation of the single-bottleneck notion. *Cognitive Psychology,* **44**, 193–251.

Pashler, H. (1984). Processing stages in overlapping tasks: evidence for a central bottleneck. *Journal of Experimental Psychology: Human Perception and Performance,* **10**, 358–77.

Pashler, H. (1994). Dual-task interference in simple tasks: data and theory. *Psychological Bulletin,* **116**, 220–44.

Pashler, H. and Christian, C.L. (1994). Bottlenecks in planning and producing vocal, manual and foot responses (Center for Human Information Processing Technical Report). La Jolla, CA: University of California, San Diego, Center for Human Information Processing. (Available from http://www.pashler.com/manuscripts.html)

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

Pashler, H. and Johnston, J. C. (1998). Attentional limitations in dual-task performance. In H. Pashler (Ed.) *Attention*, pp.155–89. Hove: Psychology Press/Erlbaum (UK) Taylor & Francis.

Rammsayer, T. and Ulrich, R. (2005). No evidence for qualitative differences in the processing of short and long temporal intervals. *Acta Psychologica,* **120**, 141–71.

Rogers, R. D. and Monsell, S. (1995). Costs of a predictable switch between simple cognitive tasks. *Journal of Experimental Psychology: General,* **124***,* 207–31.

Ruthruff, E. and Pashler, H. (2001). Central and peripheral interference in RSVP displays. In K. Shapiro (Ed.), *The Limits of Attention: Temporal Constraints on Human Information Processing*, pp.100–23. New York: Oxford University Press.

Ruthruff, E. and Pashler, H. (2008). Does mental timing require central attention? Unpublished manuscript.

Ruthruff, E., Pashler, H., and Hazeltine, E. (2003). Dual-task interference with equal task emphasis: graded capacity-sharing or central postponement? *Perception and Psychophysics*, **65**, 801–16.

Ruthruff, E., Van Selst, M., Johnston, J. C., and Remington, R. W. (2006). How does practice reduce dual-task interference: Integration, automatization, or simply stage-shortening? *Psychological Research*, **70**, 125–42.

Schumacher, E. H., Seymour, T. L., Glass, J. M., Fencsik, D., Lauber, E., Kieras, D. E., et al. (2001). Virtually perfect time sharing in dual-task performance: Uncorking the central attentional bottleneck. *Psychological Science*, **12**, 101–8.

Sigman, M. and DeHaene, S. (2005). Parsing a cognitive task: a characterization of the mind's bottleneck. *PLoS Biology*, **3**, e37.

Tomasik, D., Ruthruff, E., Allen, P. A., and Lien, M.-C. (2009). Non-automatic emotion perception in a dual-task situation. *Psychonomic Bulletin & Review,* **16**, 282–8.

Tombu, M. and Jolicoeur, P. (2002). All-or-none bottleneck versus capacity sharing accounts of the psychological refractory period phenomenon. *Psychological Research*, **66**, 274–86.

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

Ulrich, R., Ruiz Fernández, S., Jentzsch, I., Rolke, B., Schröter, H., and Leuthold, H. (2006). Motor limitation in dual-task processing under ballistic movement conditions. *Psychological Science,* **17**, 788–93.

Ulrich, R., Nitschke, J., and Rammsayer, T. (2006). Crossmodal temporal discrimination: assessing the predictions of a general pacemaker–counter model. *Perception and Psychophysics*, **68**, 1140-52.

Van Selst, M. V., Ruthruff, E., and Johnston, J. C. (1999). Can practice eliminate the psychological refractory period effect? *Journal of Experimental Psychology: Human Perception and Performance*, **25**, 1268–83.

Welford, A. T. (1952). The "psychological refractory period" and the timing of high-speed performance: a review and a theory. *British Journal of Psychology,* **43**, 2–19.

Zakay, D. (1998). Attention allocation policy influences prospective timing. *Psychonomic Bulletin & Review,* **5**, 114–18.

Zakay, D. and Block, R. A. (1996). The role of attention in time estimation processes. In M. A. Pastor and J. Artieda (Eds.) *Time, internal clocks and movement*, pp.143–64. Amsterdam: Elsevier.

Zakay, D. and Block, R. A. (1997). Temporal cognition. *Current Directions in Psychological Science*, **6**, 12–16.

Zakay, D., Nitzan, D., and Glicksohn, J. (1983). The influence of task difficulty and external tempo on subjective time estimation. *Perception & Psychophysics,* **34**, 451–6.

Acknowledgements

This work was supported by grants from the National Institute of Mental Health (R01-MH45584, H. Pashler, PI, and P50 MH066286, Keith Nuechterlein, PI) and the National Science Foundation (Grant BCS-0720375, H. Pashler, PI; Grant SBE-0542013, G. Cottrell, PI).