



Chapter 9

Mental timing and the central attentional bottleneck

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

16 Central bottleneck model

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

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

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



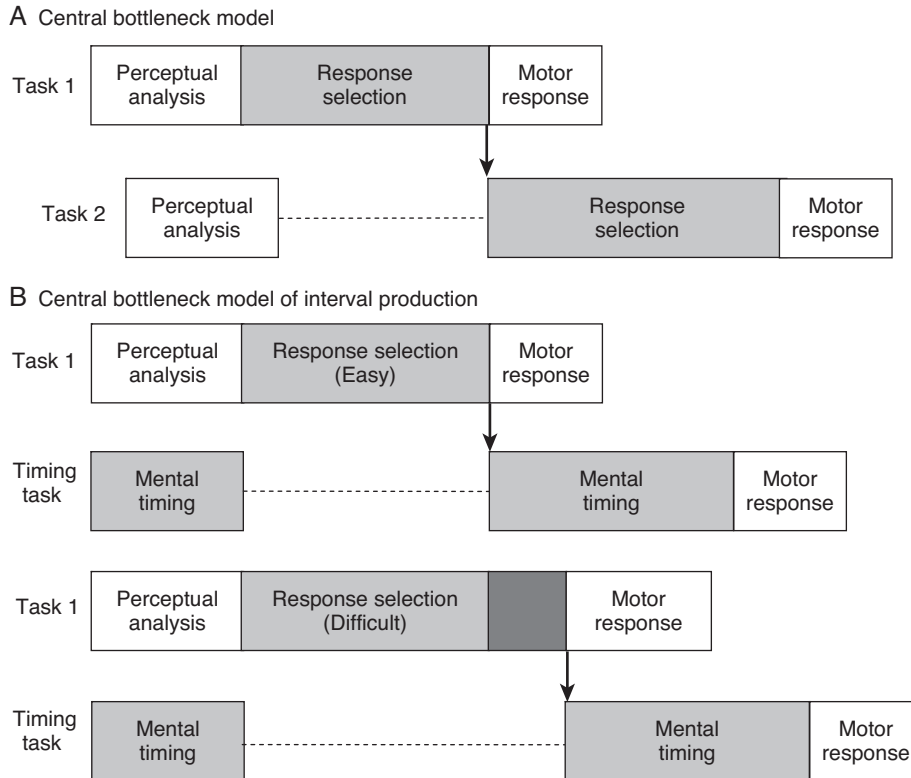


Fig. 9.1 A) The central bottleneck model, as applied to a traditional dual-task experiment. At short stimulus onset asynchronies (SOAs), like the one shown in the figure, the central stage of Task 2 (e.g. response selection) must wait for the central stage of Task 1 to finish. B) The central bottleneck 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.

1 Dual-task interference thus is assumed to result primarily from processing delays (represented by
 2 the dotted line in Figure 9.1A), not from a slowing of mental processes that run concurrently (e.g.
 3 Kahneman, 1973). There is considerable evidence to favour this discrete view (e.g. Pashler, 1984,
 4 1994; McCann and Johnston, 1992; Ruthruff, Pashler, and Hazeltine, 2003; Sigman and Dehaene,
 5 2005), although there continues to be controversy about whether graded sharing of capacity
 6 among central processes can be ruled out (Navon and Miller, 2002; Tombu and Jolicoeur, 2002,
 7 2003; Miller, Ulrich, and Rolke, 2009).

8 One major goal of research on this topic has been to determine the precise processing locus
 9 of the 'central' bottleneck. Studies have demonstrated convincingly that response selection is
 10 subject to the central processing bottleneck (e.g. Pashler, 1984, 1994; Pashler and Johnston, 1989;
 11 McCann and Johnston, 1992), at least relatively early in practice (see Hazeltine, Teague, and Ivry,
 12 2001; Schumacher et al., 2001; Ruthruff et al., 2006; Maquestiaux et al., 2008). Subsequent studies
 13 have associated the bottleneck with a wide range of additional mental processes, including mental
 14 rotation (Ruthruff, Miller, and Lachmann, 1995), encoding into short-term memory (Jolicoeur,
 15 1999; Ruthruff and Pashler, 2001), long-term memory retrieval (Carrier and Pashler, 1995; Byrne

1 and Anderson, 2001), complex stimulus categorizations (Johnston and McCann, 2006), and even
 2 the discrimination of facial expressions (Tomasik et al., 2009). The diversity of mental processes
 3 subject to the processing bottleneck suggests the existence of a single very general-purpose
 4 processing mechanism, perhaps analogous to the CPU (central processing unit) of a computer
 5 (although not necessarily anatomically localized). We refer to this putative mechanism or resource
 6 as the *central mechanism*.

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

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

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

42 **Mental timing under divided attention**

43 Most studies examining attentional limitations in mental timing have asked subjects to estimate
 44 time while performing some fairly continuous distracting task (Brown, Chapter 8, this volume).
 45 The mental activities required in these tasks have been quite diverse, ranging from perceptuo-
 46 motor coordination (e.g. mirror drawing) to fine perceptual discriminations (e.g. loudness or

1 brightness) to demanding cognitive operations (e.g. problem-solving). Typically, the subject
 2 reports either a numerical estimate of the duration of some event (*time estimation*), pushes a
 3 button after a specified time interval has elapsed (*interval production*), or reproduces the duration
 4 of some recently experienced event (*interval reproduction*). Sometimes, subjects are asked to judge
 5 durations after the fact (*retrospective timing*), although the present article concerns only cases
 6 where subjects know in advance that they are to record the duration of some interval (*prospective*
 7 *timing*).

8 Overwhelmingly, these studies show that concurrent tasks interfere with prospective
 9 timing (Hicks, Miller, and Kinsbourne, 1976; Zakay, Nitzan, and Glicksohn, 1983; Brown, 1985,
 10 1997; Fortin and Rousseau, 1998; Zakay and Block, 1996, 1997; Mattes and Ulrich, 1998; Zakay,
 11 1998; Rammsayer and Ulrich, 2005). Specifically, performing a concurrent task usually leads to
 12 a foreshortening of perceived time and an increase in the variability of time estimates. These
 13 interference effects typically become more severe as the difficulty of the concurrent task increases
 14 (e.g. Zakay, Nitzan, and Glicksohn, 1983; Brown, 1985, 1997).

15 As an example, Brown (1985, Experiment 1; Brown, Chapter 8, this volume) asked subjects
 16 to perform one of three tasks on a 6-pointed star: (1) attend the star (no response required);
 17 (2) trace the outline of the star; or (3) trace the star using a mirror. After either 16 or 32 seconds
 18 of performing these tasks, the experimenter then asked the subject to verbally report how much
 19 time had elapsed. Half were tested under prospective conditions (they knew in advance they
 20 would be asked to make time judgements) and half under retrospective conditions. Of primary
 21 interest here is the observation that the mean prospective time estimates decreased (by about
 22 27%) as the difficulty of the concurrent task increased.

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

1 prior to the onset of the stimulus whose duration is to be timed. Consequently, it is possible that
 2 the interference reflects not a difficulty in timekeeping per se, but rather a failure to detect the
 3 onset of the interval to be timed (see Lejeune, 1998).

4 Time production

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

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

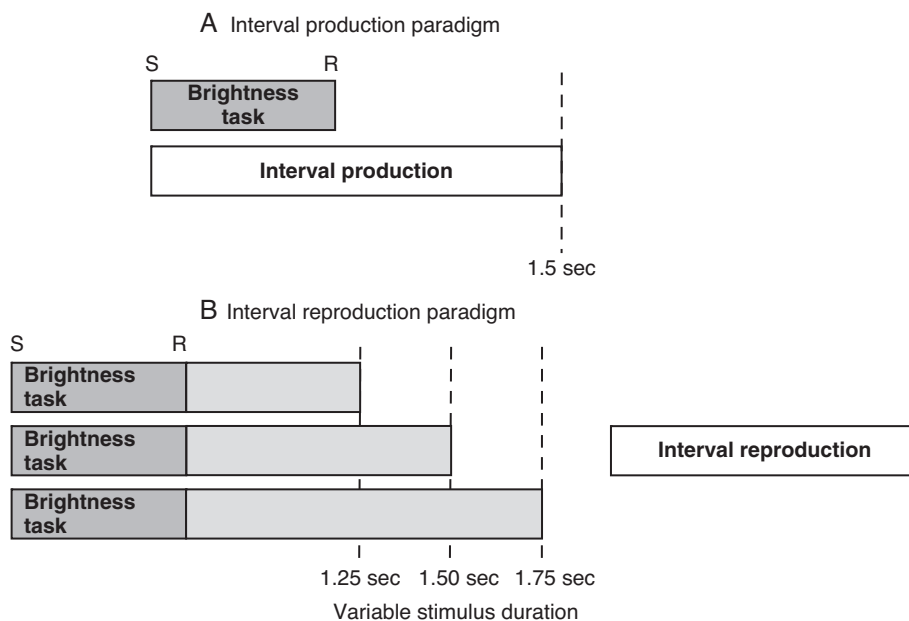


Fig. 9.2 A) Dual-task condition with interval production. Upon stimulus onset, subjects were to perform the brightness discrimination and to begin producing a 1.5-second interval. B) Dual-task condition with interval reproduction. Upon stimulus onset, subjects were to perform the brightness discrimination 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.

1 The key manipulation was the difficulty of the brightness judgement. In the easy condition
2 the brightness difference was large, whereas in the difficult condition the brightness difference
3 was much more subtle. These conditions were randomly intermixed within dual-task blocks, so
4 that difficulty would not be confounded with load (i.e. the number of pending tasks to be pre-
5 pared was the same). In single-task blocks, decreasing the difference in brightness increased the
6 time to complete the brightness discrimination by nearly 100ms. The critical question was how
7 this manipulation would influence time production in dual-task blocks. If subjects can keep track
8 of time while performing the speeded brightness discrimination, without interference, then their
9 timing performance should not depend much on the difficulty of the brightness discrimination.
10 They should simply produce intervals of about 1.5 seconds (\pm error) in both the easy and diffi-
11 culty conditions. But if timing requires central attentional mechanisms, attempts to produce a
12 1.5-second interval should be strongly biased by the difficulty of the intervening brightness
13 discrimination. The reason is that subjects would not be able start their mental timer until *after*
14 completing the brightness discrimination (see Figure 9.B). Consequently, they should fail
15 to record the extra time taken while performing the difficult version of the concurrent task.
16 It follows that their time productions should be much longer with a difficult brightness discrimi-
17 nation than with an easy discrimination. We refer to this phenomenon as *carryover*. In the
18 extreme, the carryover onto the timing task (i.e. the lengthening of time productions) should be
19 just as large as the effect on the brightness discrimination itself (100% carryover).

20 The mean produced time interval across single and dual-task blocks was 1481ms (SD =
21 192ms), which is very close to the target value (1500ms). Subjects received feedback after each time
22 production, which presumably helped them to hone in on the target value. More importantly,
23 carryover was nearly 100%. In dual-task blocks, the brightness manipulation slowed performance
24 on the brightness discrimination by 82ms, and increased time productions by 80ms. The most
25 straightforward explanation is that, as depicted in Fig 9.1B, subjects did not actually begin keeping
26 track of time until after the brightness discrimination was finished (or, at least, until after the
27 stage(s) influenced by our difficulty manipulation). In other words, the data suggest that timing
28 requires the same central attentional mechanisms needed to select a response to Task 1.

29 This conclusion is supported by the timing variability data. In dual-task blocks, brightness
30 discriminations took about 500ms and had a standard deviation (SD) of 97ms. By comparison,
31 the average SD of the time productions in single-task blocks was 214ms. Assuming that timing
32 variance is proportional to the duration being timed, the SD for a 500-ms interval would be about
33 124ms. Thus, timing estimates appear to be more variable than brightness discriminations.
34 Hence, if subjects do not keep track of time during the brightness discrimination, time produc-
35 tions will inherit the variability of the approximately 500-ms brightness discrimination, rather
36 than the variability of 500ms of mental timing. This leads to the surprising prediction that timing
37 variability should actually *decrease* in dual-task blocks. Indeed, the SD of time productions was
38 significantly smaller in dual-task blocks (SD = 171ms) than in single-task blocks (SD = 214ms).

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

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

7 Time reproduction

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

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

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

39 One caveat is that, as the stimulus duration increased by 500ms (from 1.25 to 1.75 seconds),
 40 interval productions increased by only 194ms. Thus, only 38.8% of the change in stimulus dura-
 41 tion was reflected in time productions. Given that the perceived estimate of the stimulus duration
 42 on any given trial is noisy, subjects might combine this noisy estimate with a relatively stable
 43 estimate of the mean stimulus duration. The result would be regression-to-the-mean in stimulus
 44 reproductions. Critically, this regression might also limit the carryover of difficulty effects onto
 45 the timing task. Nevertheless, the 22% carryover of difficulty effects is significantly less than the
 46 38.8% of variation in stimulus duration that is reflected in time productions. Put another way, the

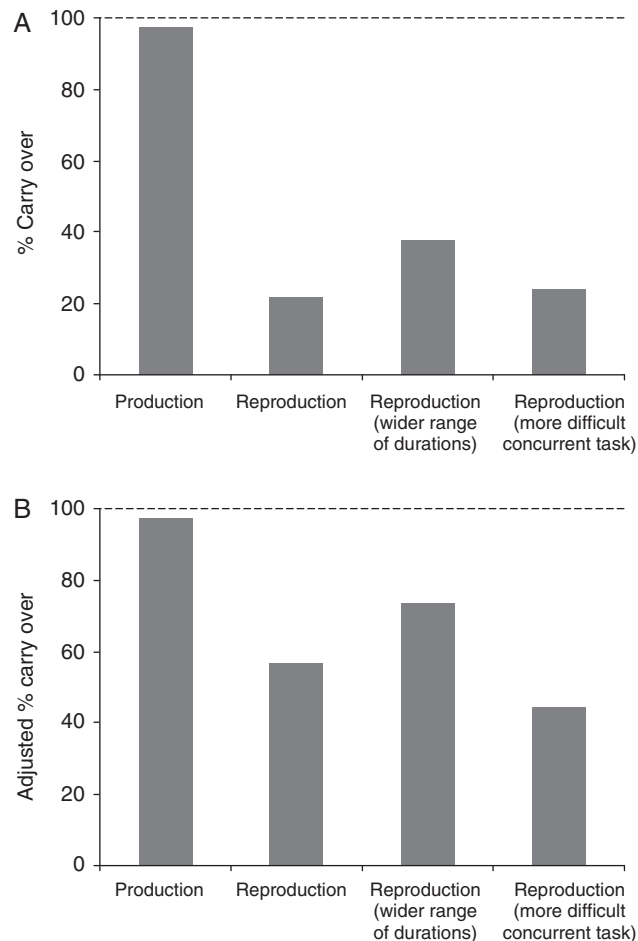


Fig. 9.3 A) Percentage carryover, calculated as the effect of concurrent task difficulty on time productions/reproductions ($\times 100$) divided by its effect on the concurrent task itself. When reproducing intervals, participants might incorporate their estimate of elapsed time on a given trial with 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.

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

3 Increased variation in stimulus duration

- 4 To encourage subjects to rely on their perception of the passage of time during each stimulus
- 5 presentation, rather than the average stimulus duration, we conducted a follow-up experiment
- 6 with a wider range of stimulus durations (spanning 1 second rather than 0.5 seconds): 1, 1.25, 1.5,
- 7 1.75, and 2 sec. This effort appears to have been successful in that the range of time reproductions

1 captured more of the variation in stimulus durations (52.0% versus 38.8%); that is, there appeared
2 to be less regression to the mean.

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

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

24 Time reproduction with a more difficult concurrent task

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

31 To address this issue, we used a much more demanding concurrent task that required
32 subjects to map eight alphanumeric stimuli (1, 2, 3, 4, A, B, C, D) onto four response fingers. The
33 mean response time for this task was 873ms, compared to only 481ms for the brightness
34 discrimination. We varied the difficulty of this task via a stimulus–response (S–R) compatibility
35 manipulation (e.g. Van Selst, Ruthruff, and Johnston, 1999; Ruthruff, Pashler and Hazeltine,
36 2003). The letters were mapped compatibly onto the four fingers and the digits incompatibly, or
37 vice versa (counterbalanced across subjects). Numbers and digits were randomly intermixed
38 within blocks, to avoid confounding difficulty effects with overall task load. Importantly, it seems
39 clear that the manipulated stage (response selection) is central in this case, rather than perceptual.
40 We found that mean response time was 763ms in the compatible condition (per cent error =
41 1.6%) and 987ms in the incompatible condition (per cent error = 7.3%). Thus, the mean effect
42 size was 224ms.

43 The mean reproduced interval (1373ms; SD = 301ms) was again shorter than the actual
44 mean stimulus duration of 1500ms. The key finding, however, is that only 24.1% of the difficulty
45 effect on the S–R compatibility task carried over onto time reproductions. In contrast, 54.8% of
46 the actual variation in stimulus duration was reflected in the time reproductions; as the actual
47 duration increased from 1 to 2 seconds, the reproduced duration increased from 1093ms

1 to 1641ms. Thus, the observed 24.1% carryover of difficulty effects represents only 44% of the
 2 'carryover' from actual variation in stimulus duration. Even though the difficult S–R compatibil-
 3 ity task clearly requires central mechanisms for an extended period of time, it appears that
 4 subjects were simultaneously able to keep track of the elapsed time (albeit imperfectly).

5 **Conclusions**

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

19 **Models of time perception**

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

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

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