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Original Article

Selection and consolidation of objects and actions

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Abstract Response selection bottleneck models attribute performance costs under dual-task conditions to the human inability to select more than one response at a time. Consistent with this claim Pashler (1991) found that carrying out a speeded manual choice reaction time (RT) task does not impair the unspeeded report of a cued visual target from a masked display. In contrast, Jolicoeur and Dell'Acqua (1999, Experiment 2) observed pronounced interference between a speeded manual choice RT task and the unspeeded report of a small number of visually presented letters, a finding they attributed to resource sharing between response selection and stimulus consolidation. We demonstrate that comparable costs are obtained with the same task combination used by Pashler (1991) if only task order is reversed—a manipulation that is likely to increase the necessity of consolidating the target stimulus into working memory. We also found that these costs are not diminished if the location of the target to be reported is cued in advance (reducing demands on spatial focusing) and that they do not vary with the number of target features to be reported. These findings support a consolidation account of costs in dual-task performance.

Introduction

Human performance is often impaired under multiple-task conditions, that is, when more than one task is carried out at a time. Such impairments are particularly obvious in the so-called Psychological Refractory Period paradigm introduced by Telford (1931). In this paradigm the temporal overlap of two given tasks is systematically varied by presenting the stimuli belonging to them at different points in time (i.e., at different Stimulus Onset Asynchronies or SOAs), and performance is then analyzed as a function of SOA. If this is done, performance in the second task is commonly observed to drop with decreasing SOA, hence, with increasing temporal overlap of the tasks (for an overview, see Pashler, 1994; Jolicoeur, Tombu, Oriet, & Stevanovski, 2002).

According to the currently dominating approach to dual-task performance, overlap costs result from a structural bottleneck at the response selection stage and, thus, reflect the inability of humans to select more than one response at a time (Pashler, 1994; Pashler & Johnston, 1989; Welford, 1952). In line with this assumption, the second of two overlapping tasks has been demonstrated to be postponed to a degree that is linearly related to the SOA. Moreover, manipulations in the second task related to response selection commonly yield additive effects (e.g., Van Selst & Jolicoeur, 1997) whereas perceptual manipulations produce underadditive effects (e.g., Pashler & Johnston, 1989); this can be taken to indicate that the latter, but not the former, affect processes that can be carried out in parallel (Pashler, 1994).

One of the most fundamental implications of response selection bottleneck approaches is that overlap costs in dual-task performance should be bound to the necessity of selecting more than one response at a time, so that no such costs should be observed if in one of two given tasks responding is unspeeded. Indeed, Pashler (1991) found no reliable decrements of dual-task performance under these conditions. His participants carried out a manual choice reaction time (RT) task to a high- or low-pitched tone, while being presented with an unspeeded visual attention task. In the attention task, a brief array of eight masked letters appeared in which the target letter was cued by a bar. The SOA between tone and visual display varied between 50 and 650 ms. Participants made a speeded response to the tone and reported the target letter at the end of the trial at leisure. If the visual task shared a bottleneck with the tone task a decrease in report accuracy as SOA decreases would be expected. However, Pashler (1991) did not observe such a decrease, suggesting that the two tasks did not share a processing bottleneck.

Pashler's (1991) findings are in line with the response selection bottleneck approach to dual-task performance, as this approach would not predict interference between a speeded and an unspeeded task. However, among others, recent observations by Jolicoeur and colleagues raise doubts as to whether this is a general rule. Jolicoeur and Dell'Acqua (1998) had participants encode a small number of letters for later report and carry out a speeded manual response to the pitch of a tone. RT in the secondary, speeded task was found to increase with decreasing SOA, and it increased more the more letters were to be encoded in the primary, unspeeded task. Reliable RT delays were found even with a single letter in the encoding task—a situation that comes close to a replication of Pashler's (1991) task only with task order reversed. Interestingly, the results of Jolicoeur and Dell'Acqua (1999, Experiment 2) suggest that the reversal as such does not seem to explain the discrepancy. They had participants perform the tone task first and the letter report (of five target letters) second and found that, analogously to Jolicoeur and Dell'Acqua (1998), report accuracy decreased with decreasing SOA. Likewise, Jolicoeur, Dell'Acqua, and Crebolder (2000, Experiment 1) found that temporal overlap between the same manual tone task and an unspeeded RSVP (rapid serial visual presentation) task hampered performance in the latter, and that it did more so as response selection in the tone task was made more difficult. According to Jolicoeur et al. (2002), these findings suggest that capacity limitations in dual tasks are not restricted to response selection but may result from the inability to *consolidate* more than one stimulus event or action plan at the same time.

Part of the discrepancy between the absence of dual-task costs in Pashler's (1991) study and the presence of pronounced costs in the experiments of Jolicoeur, Dell'Acqua, and colleagues may be due to the fact that the participants used different strategies. That strategies can play a role in those sorts of task combinations is suggested by the observations of Hommel and Schneider (2002). They employed the same task combination as Pashler (1991), except that the unspeeded visual attention task comprised four instead of eight letters. On the one hand, Hommel and Schneider (2002) demonstrated that overlap costs can be obtained even with this set-up: Accuracy of target report reliably increased with SOA in all four experiments in that study. On the other hand, however, considerable costs occurred only at very short SOAs (50–150 ms) and finer-grained analyses suggested that participants had scheduled the processing in the letter report task depending on the particular range of SOAs used in the particular experiment. For instance, if all SOAs were short (50, 100, and 150 ms) participants seemed to have selected the cued target before selecting the manual response (as suggested by the fact that manual RT was affected by the spatial compatibility between target and manual response), while with a wide SOA range (50–650 ms) they seemed to have maintained some sort of raw representation of the visual display and postponed target selection or consolidation until the manual response selection was completed. As Hommel and Schneider

(2002) discussed, participants may have attempted to avoid the processes subserving response selection and selection (and/or consolidation) of the visual target.

One interpretation of the evidence available thus far is that selecting (or consolidating) a visual target for later report shares a bottleneck with manual response selection (or consolidation), as the approach of Jolicoeur et al. (2002) suggests. To account for Pashler's (1991) failure to find any costs particular scheduling strategies along the lines of Hommel and Schneider (2002) may be considered. Another interpretation might refer to possibly important differences between the unspeeded tasks used by Pashler (1991) on the one hand and by Jolicoeur and colleagues on the other. An obvious difference is that Pashler's task introduces spatial uncertainty and requires the selection of a single, spatially defined target from a larger display, whereas in Jolicoeur and Dell'Acqua's (1998, 1999) task all target stimuli appear in the same location and are not accompanied by distractors. However, if anything, it might be expected that this difference would make dual-task costs more likely in the former than in the latter task, while the empirical findings show the opposite. Moreover, Experiment 2 in the present study, which considered spatial selection as a possible factor (although from a different angle), provides further evidence against a role of spatial uncertainty and location-based selection in dual-task interference—a conclusion that is consistent with the considerations of Pashler (1991). Another difference is that Pashler's stimuli were taken from a very limited four-letter stimulus set whereas Jolicoeur and Dell'Acqua used a rather large 19-letter set. Target identification was thus much easier in the former than in the latter. Jolicoeur and Dell'Acqua (1998) have considered the possibility that not all types of nonspeeded tasks give rise to interference with speeded choice tasks; tasks may fail to do so especially if the display conditions are not perceptually or attentionally demanding. Along these lines it may be speculated that Pashler's (1991) task may have met the conditions for escaping the assumed bottleneck. However, the findings of the present study do not support an interpretation along these lines.

The major aim of the present study was to test whether the task combination employed by Pashler (1991) and Hommel and Schneider (2002) can be demonstrated to show dual-task costs comparable to those obtained by Jolicoeur and colleagues if scheduling strategies as discussed by Hommel and Schneider are prevented (as far as possible). To do so we modified the task design in the following ways.

First of all, we reversed the order of the tasks or, more precisely, of the stimuli and, hopefully, of the cognitive processes operating on them. Participants were first presented with a visual display, from which they were to select one cued target letter for later, unspeeded report, and then with a tone that called for an immediate, speeded binary choice reaction (see Fig. 1). This design seems sufficiently close to that employed by Jolicoeur and Dell'Acqua (1998) to expect a comparable, substantial delay of the second response. A particular advantage of this design is that retaining the visual target information during the following, speeded task does seem to call for some sort of consolidation, which according to Jolicoeur et al. (2002) should be crucial for dual-task costs to occur.

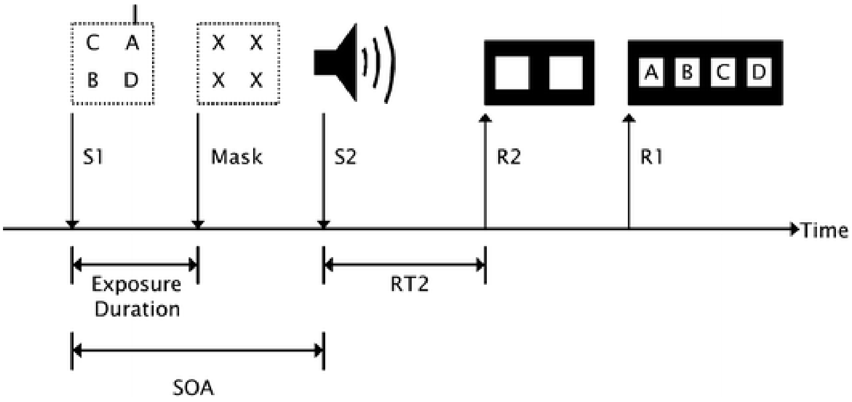

Fig. 1 A schematic illustration of the procedure in Experiment 1. Task 1 required an unspeeded judgment of the marked target of a brief, masked four-letter display. Task 2 required a speeded left–right key-pressing response to the pitch of a tone

A second modification was that we used rather long SOAs and a very wide SOA range. We considered this choice to encourage target consolidation by guaranteeing it a considerable head start even in the worst case, that is, at the shortest SOA. This should prevent participants from postponing target consolidation until the speeded response is selected, a strategy people seem to prefer in cases of SOAs that frequently produce temporal overlap (and/or mutual interruption) of these two processes (Hommel & Schneider, 2002).

Experiment 1

Experiment 1 was a close replication of Hommel and Schneider's (2002) version of Pashler's (1991) set-up. We only reversed the order of the task and employed longer SOAs covering a broader range.

Method

Participants

Sixteen adults were paid to participate in single sessions of about 70 min. They reported having normal or corrected-to-normal vision and audition, and were not familiar with the purpose of the experiment.

Apparatus and stimuli

We used the same equipment and stimuli as Hommel and Schneider (2002). The experiment was controlled by a PC, attached to a monitor and interfaced with a D/A card for auditory output. The cued letter in the visual attention task was reported by pressing one of four horizontally arranged keys on the computer keyboard (function keys F1–F4, accordingly labeled as A, B, C, and D). Tones were responded to by pressing the left or right of two microswitches mounted side by side on a slightly ascending wooden plate. Participants operated the microswitches with the index and middle finger of their right hand and the computer keys with the four fingers of their left hand.

Visual stimuli, all taken from the standard text mode font, appeared in white on the black screen. A plus sign served as central fixation mark, a vertical line as target cue, the uppercase letters A, B, C, and D as stimuli (S1), and four Xs as masks. From a viewing distance of about 60 cm, letters measured 0.3° × 0.4°. The four stimulus letters, as well as the four Xs replacing them, were centered in the four stimulus positions 0.6° to the left and right and 0.4° above and below the screen's center. The target was indicated by the bar cue, which appeared 0.3° (edge-to-edge) above the (upper) target or below the (lower) target (see Fig. 1). Auditory stimuli (S2) were sinus tones of 200 or 800 Hz, presented simultaneously through two loudspeakers located to the left and right of the monitor.

Design

The experiment consisted of five blocks of 96 randomly ordered trials each, preceded by 40 randomly determined practice trials. The trials in each block resulted from the possible combinations of four letter targets (A, B, C, or D), four target locations (left vs. right in upper vs. lower rows), two tone stimuli or responses (left vs. right key), and three letter-tone SOAs (200, 1,100, or 2,000 ms).

Procedure

The verbal instruction emphasized the unspeeded nature of letter responses and the speeded nature of tone responses. After a blank intertrial interval of 1,300 ms, a trial began with the presentation of the fixation cross for 1,000 ms and another blank interval of 500 ms. Then the letter display appeared, which consisted of the four letters A, B, C, and D, distributed across the four stimulus positions, with the target letter indicated by the bar cue. Identity and location of the target letter was balanced across trials, while the locations of the remaining three nontarget letters were determined randomly in each trial. After a variable exposure duration (see below), the cue was deleted and the letters were replaced by the mask, which stayed on until the letter response was given. The tone was presented for 100 ms after the respective SOA. From tone onset on, the program waited 1,000 ms for the manual response. In cases of missing (RT > 1,000 ms), incorrect, or anticipatory responses (RT < 150 ms), a beep was sounded and the trial was recorded and repeated at some random position in the remainder of the block. In order to discourage speeded letter responses, the program accepted those responses no earlier than 3,000 ms after S1 onset and without any deadline. Exposure duration of the visual display was set to 200 ms during practice trials and the first experimental block. At the end of each block, the duration was individually adjusted according to the overall error rate in the letter task: It was reduced or increased by 42 ms in cases of error rates below 20% or above 30% respectively. After each block, participants received feedback about their accuracy in the letter task and their average RT in the tone task, and they could pause for as long as they wished.

Results and discussion

Trials with missing or anticipatory tone responses accounted for 2.6% and 0.2% of the data respectively. After excluding these trials we computed, for each participant, proportions of errors (PEs) in the letter task, PEs in the tone task, and mean RTs for trials with correct responses in the tone task, as a function of SOA. ANOVAs were run on all three measures with a significance criterion of $p < .05$ and a Greenhouse-Geisser correction wherever applicable.

SOA effects were obtained in the tone task on RTs, $F(1.1, 15.9) = 93.64$, $p < .001$, and PEs, $F(1.4, 20.3) = 14.76$, $p < .001$, but not in the letter task, $F(2, 30) < 1$. As Fig. 2 shows, letter report was constant across SOA while performance in the tone task decreased with decreasing SOA, hence, with increasing temporal overlap of the two tasks. This impression was confirmed by planned *t*-tests, which showed reliable differences for all contrasts in RTs and in PEs, *t*'s

(15) = 3.7–9.9, *p*'s < .005, except for the difference in error rates between the two longest SOAs, *t*(15) < 1.

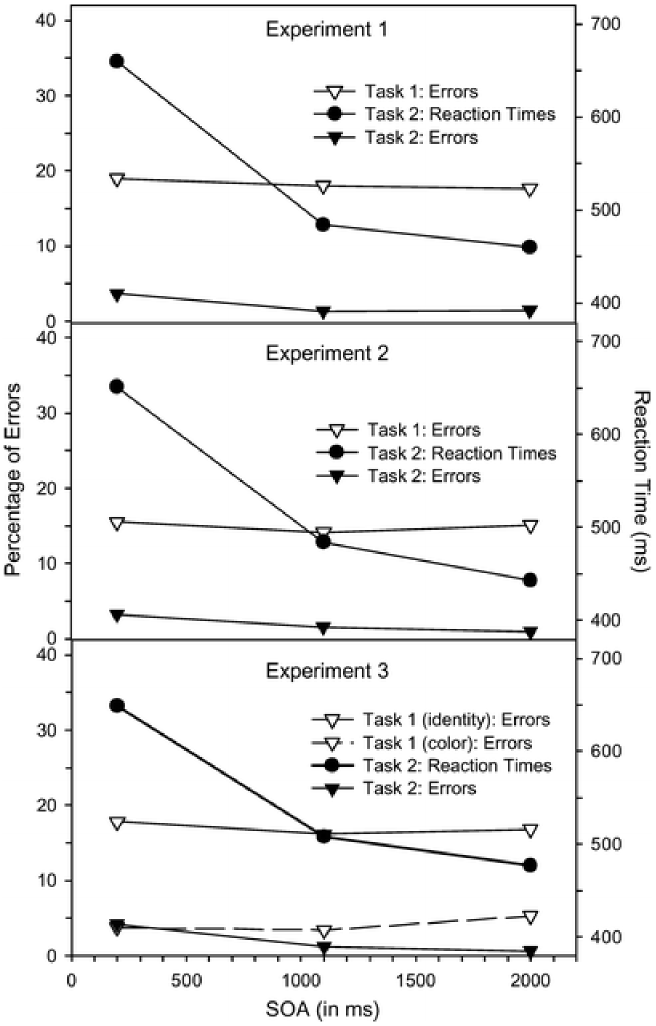

Fig. 2 Proportions of errors in Task 1 and proportions of errors and reaction times in Task 2 as a function of stimulus onset asynchrony (SOA)

The outcome provides unequivocal evidence that selecting a visual target (and consolidating it for later report) impairs the performance of a speeded binary-choice response to a substantial degree. This observation is in striking contrast to the lack of substantial interference between the very same component tasks in the study of Pashler (1991) in particular and predictions from response selection bottleneck accounts in general. However, the observation fits Jolicoeur et al.'s (2002) assumption that consolidating a stimulus for later use shares processing resources with response selection: If the SOA is short, the visual target is not yet fully consolidated in short-term memory (STM), so that the selection of the speeded manual response is delayed. The fact that after an SOA of 200 ms the delay was still more than 100 ms suggests that consolidation is a relatively slow process, which again is in agreement with Jolicoeur and Dell'Acqua's (1999, Experiment 2) and Jolicoeur et al.'s (2000, Experiment 1) demonstrations of substantial costs at SOAs of 400 ms or longer.

Experiment 2

The consolidation approach of Jolicoeur et al. (2002) provides a tenable account of our findings. And yet we have no direct evidence that it was target consolidation that interfered with the speeded task in Experiment 1. In fact, the visual task is likely to comprise at least two more processes that may have been responsible. One is target selection. Even though Pashler (1991) and others (e.g., Johnston, McCann, & Remington, 1995) have argued that target selection necessarily precedes STM processes this need not be the case. For instance, participants may first store parts of or even the whole visual display and only later select the part of it that is required for target report (Hommel & Schneider, 2002). Another candidate process is memory maintenance, that is, processes that keep the activation of needed memory codes at an activation level that is sufficient for later recall.

Proponents of the response selection bottleneck accounts have claimed that all three processes—target selection, consolidation, and maintenance— do not share central resources with response selection (e.g., Johnston et al., 1995; Pashler, 1991; for an overview, see Pashler, 1998, chapter 7). Accordingly, such accounts would not predict any SOA-specific dual-task costs from any of those processes, which apart from the question of which process is responsible conflicts with our findings anyway. Jolicoeur and colleagues, on the other hand, favor consolidation to account for their own findings, and there are indeed some indications that this is the most likely candidate in the present case as well.

With regard to memory maintenance, quite a number of studies have gathered evidence that maintaining information in STM does have a negative impact on the general performance level but does not selectively impair response selection or related processes (for overviews, see Logan, 1980; Pashler, 1994). For instance, varying the number of items held in STM has been found to interact with some variables related to response selection (e.g., number of S-R alternatives: Logan, 1979) but not with others (e.g., S-R translation: Hommel & Eglau, 2002; or S-R compatibility: Logan, 1978). Failures to interact with STM load have also been reported for variables related to encoding (e.g., visual noise: Logan, 1978), comparison (e.g., stimulus discriminability: Egeth, 1977; Woodman, Vogel, & Luck, 2001), consolidation (e.g., attentional blink: Akyürek & Hommel, 2003), and response type (e.g., yes vs. no: Logan, 1978), suggesting that maintaining information in STM has a rather nonspecific effect on task preparation (Logan, 1980; Pashler, 1994; Woodman et al., 2001).

With regard to target selection, our present Experiment 1 produced results comparable to those of Jolicoeur and Dell'Acqua (1998), even though the demands on attentional selection were very different: A single target was to be picked from a four-item display in the former while all presented stimuli were to be reported in the latter. Hence, selection processes are not an obvious alternative either. Nevertheless, we wanted to provide converging evidence against target selection if possible. We did so in Experiment 2 by virtually eliminating the attentional selection component of the visual task by cuing the target location long before the visual display was presented. If this eliminated or at least reduced the effect of task overlap we would have an indication that target selection does make a contribution to dual-task costs; if it did not, we would at least have some indirect support for a consolidation account.

Method

Twenty-four adults were paid to participate. They fulfilled the same criteria as in Experiment 1. The method was as in Experiment 1 with one exception. Instead of presenting the target cue together with the letter display it now appeared 1,000 ms earlier, right after the offset of the fixation cross.

Results and discussion

Trials with missing tone responses (2.4%) and anticipations (0.01%) were excluded from the analyses. The remaining data were treated as in Experiment 1. SOA affected RTs, $F(1.1, 25.6) = 264.04$, $p < .001$, and PEs, $F(1.5, 35.4) = 13.70$, $p < .001$, in the tone task, whereas the effect was unreliable in the letter task, $F(2, 46) = 2.73$, $p > .07$. As Fig. 2 shows, performance in the visual task hardly varied with SOA; even the unreliable tendency toward significance does not indicate the standard SOA function but a 1% increase in performance at the middle SOA. In contrast, tone performance was progressively more impaired as the two tasks overlapped more, as was observed in Experiment 1.

The results are very clear in showing a result pattern that is virtually identical to that obtained in Experiment 1. In fact, ANOVAs across Experiments 1 and 2 did not reveal any hint of a main effect of experiment or an interaction involving this factor for the two measures from the manual task. In contrast, a main effect of experiment on target reports, $F(1, 30) = 7.35$, $p < .01$, confirmed that the spatial attentional demands were diminished in Experiment 2 compared with Experiment 1.

Thus, we can safely exclude target selection as a source of overlap-specific dual-task costs—a conclusion shared by, and supporting the claims of, Johnston et al. (1995) and Pashler (1991).

Experiment 3

Given the available evidence against a role of memory maintenance and the strong evidence against a selection account provided by our Experiment 2 we are left with STM consolidation, the candidate favored by Jolicoeur and colleagues (2002). According to these authors STM consists of a number of modality-specific subsystems, such as a verbal, visual, and tactile store. If so, memory consolidation can refer to different types of codes and, hence, may work according to different characteristics (e.g., with integration windows of different widths) depending on the modality and format of the codes. First of all, therefore, we wanted to gather preliminary evidence regarding the type of code whose consolidation was apparently responsible for the interference with manual response selection observed in Experiments 1 and 2.

The most obvious assumption would be that participants consolidated codes taken from the visual search display into visual short-term memory (VSTM), and that this process interfered with response selection in the tone task. However, the visual targets were letters, which could also have motivated participants to recode the target verbally and then consolidate that verbal trace. How can these two possibilities be experimentally distinguished? Experiment 3 was motivated by the fact that verbal stimuli commonly unfold over time whereas visual stimuli allow parallel access to their features. As a consequence, consolidating a verbally coded stimulus or stimulus feature may operate with a longer integration window than consolidating a visually coded stimulus or stimulus feature and, thus, delay overlapping response selection processes longer than consolidating visually coded information. Indeed, results from studies on the Attentional Blink (AB) provide evidence of different integration windows. The AB describes the observation that if people monitor a stream of stimuli for two targets (T1 and T2), they often miss T2 if it falls into an interval of about 100–500 ms after T1 had appeared (e.g., Raymond, Shapiro, & Arnell, 1992). Despite minor differences in detail, most available AB accounts attribute the effect to the attentionally demanding consolidation of T1 that blocks out higher level T2 processing until completed (for an overview, see Shapiro, Arnell, & Raymond, 1997). Accordingly, variations in the time T2 is blocked out—hence, variations in the duration of the AB—can be taken to reflect variations in the time it takes to consolidate T1. In other words, AB duration indicates the effective integration window related to T1.

With a visual T1 increasing the number of features to be reported does not increase the size or duration of the AB. For instance, both Jolicoeur (1999) and Ward, Duncan, and Shapiro (1996) varied the size and the identity of T1 and had participants report either one of these features or both. An AB was obtained in all conditions in both studies and there was no indication of any impact of the number of features reported on its size or duration. This suggests that increasing the number of features to be consolidated does not affect integration time, at least not with these (visual) stimuli. Such observations fit reports that VSTM-based performance is insensitive to the number of features of visual objects to be consolidated (Luck & Vogel, 1997) and support the idea that the consolidation of visual information operates on object-specific feature conjunctions (Jiang, Olson, & Chun, 2000; Luck & Vogel, 1997). Interestingly, there is evidence that the AB does increase as a function of T1-related features if T1 is verbally coded. Olson, Chun, and Anderson (2001) presented pseudowords and anagrams as T1, and varied the visual length (number of letters) and phonemic length (number of syllables) of these stimuli in an orthogonal fashion. Whereas visual length had hardly any effect, phonologically long T1s produced a deeper and longer AB than phonologically short T1s. Olson et al. suggest that verbal codes are consolidated into verbal STM, which in contrast to VSTM is suspected to be sensitive to phonological word length (e.g., Baddeley, Thomson, & Buchanan, 1975).

To summarize, AB studies suggest that the time it takes to consolidate visual stimuli does not vary with the number of features to be reported if they are coded visually, but that it increases with the number of features if they are coded verbally. Therefore, in Experiment 3 we doubled the number of features to be reported of the stimulus in the visual attention task to see whether this would change the outcome. In particular, we presented the four letters of the visual display in four different colors and then asked participants, in an unpredictable fashion, to report either the identity or the color of the cued target. In cases of visual coding, this should not change the outcome, as both features belong to the same stimulus event and, thus, should be integrated into the same object trace without prolonging integration time (Jiang et al., 2000; Luck & Vogel, 1997). However, if people recoded the visual information verbally this should lead to a substantial increase in the information to be consolidated, as participants would now need to maintain verbal codes for both target identity and color. This should increase integration time and, thus, further delay the selection of the speeded manual response at short SOAs. Accordingly, we considered a steeper SOA function in the manual RTs as an indication of verbal coding in the visual attention task.

Method

Sixteen adults were paid to participate. They fulfilled the same criteria as in Experiment 1. The method was as in Experiment 1 with one exception. The four letters no longer appeared in white but each had a different color: Red, green, blue, or yellow. The mapping of colors to letters and locations varied randomly from trial to trial. In 50% of the trials participants were asked to indicate the identity of the cued letter, just as in Experiments 1 and 2. In the other 50% of the trials, they were to indicate the color of the cued target by using four additional, color-labeled keys of the computer keyboard (function keys F5–F8, accordingly labeled with colored stickers). The feature to be reported was signaled no earlier than at the end of the trial, that is, after S2 had disappeared and R1 was carried out. Participants were presented with the relevant feature dimension and the four possible response alternatives ("form (A, B, C, D)" or "color (red, green, blue, yellow)", in German). The two judgment dimensions (identity vs. color) were balanced across all cells of the design, so that experimental blocks were composed by crossing the four letter targets, four target locations, two tone stimuli, and three SOAs with the two judgment dimensions. As this doubled the block length we reduced the number of replications from five to three, that is, participants worked through a total of 576 experimental trials. Within the balancing constraints the sequence of judgment dimensions was randomly determined. Thus, participants could not anticipate which dimension would be relevant in a given trial and they were instructed to always pay attention to both of them.

Results and discussion

Trials with missing tone responses (1.9%) and anticipations (0.01%) were excluded from the analyses. The remaining data were treated as in Experiment 1, except that the factor "dimension" (identity vs. color) was added to the ANOVA on the data from the visual task. Results revealed that reporting the color of the visual target was easier than reporting its identity, $F(1, 15) = 61.14$, $p < .001$, but the reported dimension did not interact with SOA, $F(2, 30) < 1.3$. The middle SOA was again associated with a small, unreliable 1% increase in report accuracy, $F(2, 30) = 3.06$, $p > .06$, but the data did not show any further, systematic impact from task overlap. In contrast, tone performance was impaired more the greater the temporal overlap between the two tasks, which was again true for both RTs, $F(1.5, 22.2) = 113.29$, $p < .001$, and PEs, $F(1.3, 19.3) = 22.72$, $p < .001$.

Again, the outcome is very clear in showing an effect pattern that is virtually identical to that obtained in Experiment 1—as confirmed by the absence of any effect involving experiment in joint ANOVAs on all three measures from Experiments 1 and 3. This suggests that increasing the number of object-specific features to be consolidated did not change the time demands on consolidation, which again implies that consolidation processes operated on visual but not verbal codes.

General discussion

Response selection bottleneck approaches attribute dual-task costs to the inability of the human processing system to select more than one response at a time. Accordingly, no such costs (in particular, costs that vary with SOA) should be observed with combinations of speeded and unspeeded tasks, hence, if response selection processes do not overlap. The study of Pashler (1991) provided support for this prediction, inasmuch as reporting a cued target from a search display was not affected by the temporal overlap with a binary-choice RT task. In contrast, Jolicoeur and Dell'Acqua (1999, Experiment 2) and Jolicoeur et al. (2000, Experiment 1) found substantial deficits in a delayed letter report task if it overlapped with a manual response choice task. The results of the present study rule out the possibility that this discrepancy is linked to the particular tasks that were used. In fact, we find that merely reversing the order of the same two tasks that in previous studies showed no (Pashler, 1991) or little (Hommel & Schneider, 2002) evidence of overlap costs produced a substantial delay in RTs in the secondary task—costs that, if anything, were even more pronounced than those reported by Jolicoeur and colleagues. Thus, there is no reason to believe that the partial-report component of the task compound employed by Pashler (1991) is any less difficult or less resource demanding than the whole-report variant used by Jolicoeur and co-workers. Performing it properly apparently draws on resources that are shared with response selection processes of another task, which therefore suffers from temporal task overlap. Hence, the null effects reported by Pashler (1991) are unlikely to reflect the lack of capacity sharing with the particular task combination. Instead, ordering these tasks in a particular fashion seems to provide participants with an opportunity to schedule capacity-demanding processes in such a way that overall performance is independent from SOA (Hommel & Schneider, 2002). Eliminating this opportunity by reversing task order reveals that capacity is shared between these tasks, which supports the arguments of Jolicoeur and Dell'Acqua (1998, 1999).

One way to save a response selection bottleneck account of our findings would be to assume that our participants may for some reason have treated the nominally unspeeded visual attention task as a speeded task, that is, upon presentation of the visual display they may not only have selected the cued target but may have immediately translated it into the corresponding response. If so, the overlap of the two tasks would have been in terms of response selection processes, which according to the response selection bottleneck account is expected to result in a delay in the second response. However, even though this is a logical possibility, it is not supported by the data. First of all, the response selection account predicts that increasing the duration of the bottleneck stage of the first task should also slow down performance in the second task at short SOAs (e.g., Pashler, 1994). Indeed, this pattern has been demonstrated for the number of response alternatives (Karlin & Kestenbaum, 1968; Smith, 1969)—a variable that is assumed to affect response selection difficulty (Pashler, 1998). On this account, and under the assumption that in our visual attention task responses were immediately selected, doubling the number of response alternatives from four to eight in the present Experiment 3 should have increased RTs in Task 2. Yet the results for the speeded manual response were virtually identical to what we saw in the other two experiments. Secondly, on a response selection account it would be hard to see why making response selection twice as difficult would fail to show any impact on Task 1 performance in Experiment 3. Thirdly, if it had been responses rather than stimuli that were maintained until the overt response in Task 1, the design of Experiment 3 should have doubled the memory load from one to two—after all, participants did not know the relevant dimension until being asked at the end of the trial and, hence, would have needed to maintain the responses to both possible questions. If so, it is difficult to see why neither Task 1 nor Task 2 shows any evidence of an overall decrement compared with the (from this point of view much easier) task combination in Experiments 1 and 2. Thus, overall, we doubt that a response selection account of our data is tenable.

We have already considered three further processes that may be responsible for the delay in the secondary task: Target selection, target consolidation, and target maintenance. If target selection were responsible, or at least a substantial contributor, we would have expected that trivializing the task's selection component in Experiment 2 reduced or even eliminated dual-task costs. Yet a look at Fig. 2 confirms that there was no evidence of any reduction, which rules out target selection as a candidate. As pointed out already, this conclusion is consistent with the claims of Johnston et al. (1995) and Pashler (1991) that input selection and response selection can proceed in parallel.

Target maintenance is also an unlikely factor. This is not only implied by the substantial amount of studies discussed above but also suggested by our own observations. As the letter display preceded the tone by 200 ms or more manual RTs must have been affected by maintenance processes at all times but, if anything, more so the longer the SOA. Yet the results show a sharp decrease in dual-task costs as SOA increases, which is exactly the opposite pattern. Thus, at most, the need to maintain a target's representation until report may have elevated the overall level of RTs in the tone task, i.e., independently of SOA. Unfortunately, we have no single-task control condition to check for this possibility. However, given that in all three experiments RTs at long SOAs were comparable to those in the Hommel and Schneider (2002) study, where the tone task was carried out first, we are skeptical, even with respect to a nonspecific impact of memory maintenance processes on the task employed.

By exclusion, this leaves us with the remaining candidate process, target consolidation. On the one hand, there is no reason to believe that target consolidation should be affected by manipulations of selection difficulty. Thus, the failure to find an effect of this manipulation in Experiment 2 fits in nicely. On the other hand, consolidating a target should take a limited amount of time, so that concurrent resource-sharing tasks should be impaired only if the SOA is short. Again, this fits well with our observation that dual-task costs increase with decreasing SOA. Experiment 3 revealed further indications that point to a role of consolidation processes. According to Luck and Vogel (1997) the units consolidated into VSTM are not features but objects, suggesting that it should not matter how many features the items to be stored consist of. Two observations from Experiment 3 are consistent with this expectation: Even though participants had to encode twice as many target features in that experiment than in Experiments 1 and 2, the error rate was comparable to that in Experiment 1 (where target location was cued the same way) and the dual-task costs were not any larger.

The emerging picture is sketched in Fig. 3. Apparently, neither target selection nor target maintenance in the primary task (i.e., S1) impairs processing the stimulus (S2) or the response (R2) of an overlapping secondary task. However, consolidating a visual S1 into (V)STM does delay the selection of R2, which leads to an elevation of RT2 at short SOAs. This finding supports the claim of Jolicoeur and colleagues (Jolicoeur & Dell'Acqua, 1998; Jolicoeur et al., 2002) that stimulus consolidation and response selection are processes that draw on the same resources. The question of how these resources can be further characterized cannot be answered on the basis of our findings, nor were we able to find detailed ideas about this issue in the available literature. A possibility would be to link the common bottleneck to the integration of feature codes (Hommel, Müsseler, Aschersleben, & Prinz, 2001; Jolicoeur et al., 2002; Stoet & Hommel, 1999). Regarding stimulus information, consolidating an event into STM may involve the build-up of an integrative physiological state that coordinates the firing patterns of cells coding the features of the respective event (Luck & Beach, 1998; Luck & Vogel, 1997). To include all features, which are likely to be coded in different brain maps in different cortical sites, such an integrative state needs to somehow exclude or suppress other activities in quite a number of coding domains—a process that, if successful, would need to create a functional processing bottleneck. Making an action plan may also involve the integration of all those codes that represent the relevant features of the intended action (Stoet & Hommel, 1999, 2002), which would also imply the creation of a relatively global processing bottleneck (Hommel, 1998). Consolidating a stimulus event may thus interfere with both concurrently consolidating another stimulus event into STM and creating a coherent action plan at the same time.

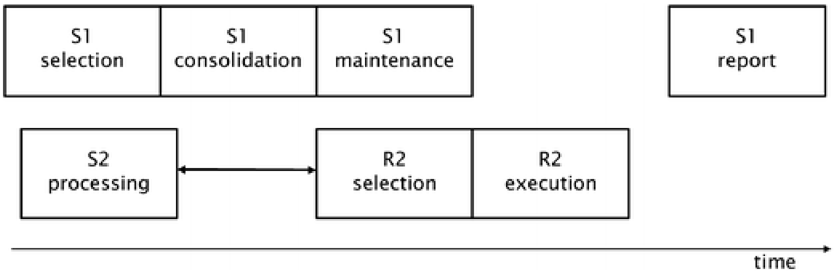

Fig. 3 Schematic representation of the relevant cognitive processes in Tasks 1 and 2. Note that consolidating the stimulus (S1) in Task 1 and selecting the response (R2) in Task 2 are the only processes that are assumed to interfere with each other

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References

Akyürek, E. G., & Hommel, B. (2003). Short-term memory and the Attentional Blink: Capacity versus content. Manuscript submitted for publication.

Baddeley, A., Thomson, N., & Buchanan, M. (1975). Word length and the structure of short-term memory. *Journal of Verbal Learning and Verbal Behavior*, *14*, 575–589.

Egeth, H. (1977). Attention and preattention. In G. H. Bower (Ed.), *The psychology of learning and motivation* (pp. 277–320). New York: Academic Press.

Hommel, B. (1998). Automatic stimulus-response translation in dual-task performance. *Journal of Experimental Psychology: Human Perception and Performance*, *24*, 1368–1384.

Hommel, B., & Eglau, B. (2002). Control of stimulus-response translation in dual-task performance. *Psychological Research*, *66*, 260–273.

Hommel, B., & Schneider, W.X. (2002). Visual attention and manual response selection: Distinct mechanisms operating on the same codes. *Visual Cognition*, *9*, 392–420.

Hommel, B., Müsseler, J., Aschersleben, G., & Prinz, W. (2001). The theory of event coding (TEC): A framework for perception and action planning. *Behavioral and Brain Sciences*, *24*, 849–878.

Jiang, Y., Olson, I. R., & Chun, M. M. (2000). Organization of visual-short term memory. *Journal of Experimental Psychology: Learning, Memory, & Cognition*, *26*, 683–702.

Johnston, J. C., McCann, R. S., & Remington, R. W. (1995). Chronometric dissociation of input attention and central attention in human information processing. *Psychological Science*, *6*, 365–369.

Jolicoeur, P. (1999). Dual-task interference and visual encoding. *Journal of Experimental Psychology: Human Perception and Performance*, *25*, 596–616.

Jolicoeur, P., & Dell'Acqua, R. (1998). The demonstration of short-term consolidation. *Cognitive Psychology*, *36*, 138–202.

Jolicoeur, P., & Dell'Acqua, R. (1999). Attentional and structural constraints on visual encoding. *Psychological Research*, *62*, 154–164.

Jolicoeur, P., Dell'Acqua, R., & Crebolder, J. (2000). Multitasking performance deficits: Forging some links between the attentional blink and the psychological refractory period. In S. Monsell & J. Driver (eds.), *Control of cognitive processes: Attention & performance XVIII* (pp. 309–330). Cambridge, MA: MIT Press.

Jolicoeur, P., Tombu, M., Oriet, C., & Stevanovski, B. (2002). From perception to action: Making the connection. In W. Prinz & B. Hommel (Eds.), *Common mechanisms in perception and action: Attention & performance XIX* (pp. 558–586). Oxford: Oxford University Press.

Karlin, L., & Kestenbaum, R. (1968). Effect of number of alternative on the psychological refractory period. *Quarterly Journal of Experimental Psychology*, *20*, 167–178.

Logan, G. D. (1978). Attention in character-classification tasks: Evidence for the automaticity of component stages. *Journal of Experimental Psychology: General*, *107*, 32–63.

Logan, G. D. (1979). On the use of the concurrent memory load to measure attention and automaticity. *Journal of Experimental Psychology: Human Perception and Performance*, *5*, 189–207.

Logan, G. D. (1980). Short-term memory demands of reaction-time tasks that differ in complexity. *Journal of Experimental Psychology: Human Perception and Performance*, *6*, 375–389.

Luck, S. J., & Beach, N. J. (1998). Visual attention and the binding problem: A neurophysiological perspective. In R. D. Wright (Ed.), *Visual attention* (pp. 455–478). New York: Oxford University Press.

Luck, S. J., & Vogel, E. K. (1997). The capacity of visual working memory for features and conjunctions. *Nature*, *390*, 279–281.

Olson, I. R., Chun, M. M., & Anderson, A. K. (2001). Effects of phonological length on the attentional blink. *Journal of Experimental Psychology: Human Perception and Performance*, *27*, 1116–1123.

Pashler, H. (1991). Shifting visual attention and selecting motor responses: Distinct attentional mechanisms. *Journal of Experimental Psychology: Human Perception and Performance*, *17*, 1023–1040.

Pashler, H. (1994). Dual-task interference in simple tasks: Data and theory. *Psychological Bulletin*, *116*, 220–244.

Pashler, H. (1998). *The psychology of attention*. Cambridge, MA: MIT Press.

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

Raymond, J. E., Shapiro, K. L., & Arnell, K. M. (1992). Temporary suppression of visual processing in an RSVP task: An attentional blink? *Journal of Experimental Psychology: Human Perception and Performance*, *18*, 849–860.

Shapiro, K. L., Arnell, K. M., & Raymond, J. E. (1997). The attentional blink: A view on attention and glimpse on consciousness. *Trends in Cognitive Science*, *1*, 291–296.

Smith, M. C. (1969). The effect of varying information on the psychological refractory period. *Acta Psychologica*, *30*, 220–231.

Stoet, G., & Hommel, B. (1999). Action planning and the temporal binding of response codes. *Journal of Experimental Psychology: Human Perception and Performance*, *25*, 1625–1640.

Stoet, G., & Hommel, B. (2002). Interaction between feature binding in perception and action. In W. Prinz & B. Hommel (Eds.), *Common mechanisms in perception and action: Attention & performance XIX* (pp. 538–552). Oxford: Oxford University Press.

Telford, C. W. (1931). The refractory phase of voluntary and associative responses. *Journal of Experimental Psychology*, *14*, 1–36.

Van Selst, M., & Jolicoeur, P. (1997). Decision and response. *Cognitive Psychology*, *33*, 266–307.

Ward, R., Duncan, J., & Shapiro, K. (1996). The slow time-course of visual attention. *Cognitive Psychology*, *30*, 79–109.

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.

Woodman, G. F., Vogel, E. K., & Luck, S. J. (2001). Visual search remains efficient when visual working memory is full. *Psychological Science*, *12*, 219–224.