

Automatic Stimulus–Response Translation in Dual-Task Performance

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In bottleneck models of overlapping-task performance, stimulus–response translation for secondary tasks is postponed until the primary response is selected. If this is so, then compatibility between the secondary and primary responses, or between the secondary response and the primary stimulus, should not affect primary-task performance. Yet such effects were demonstrated in 5 dual-task experiments combining primary manual and secondary vocal tasks: Pronounced effects of compatibility between the secondary and primary response and between the secondary response and primary stimulus were found on primary-task performance. The latter effect was also found with the lowest level of an extensive stimulus onset asynchrony variation, when the secondary task was not speeded, and even when the 2 tasks were performed on different trials. Findings suggest that secondary responses were activated before primary response selection was completed and thus support an automatic-translation hypothesis holding that, although eventual response *selection* may be serial, stimulus–response *translation* is performed in parallel.

When people perform more than one task at a time, their performance often decreases more or less dramatically, even if the tasks are quite simple. According to an assumption of Welford (1952), this is so because the architecture of the human information-processing system does not allow for the transformation of more than one stimulus into a response at a time: Somewhere on the way from sensory coding to muscle contraction there must be a bottleneck that renders human information processing a single-channel system. Much research has been conducted to test whether this is necessarily so or whether conditions can be found that greatly reduce or eliminate dual-task costs (for overviews, see Meyer et al., 1995; Pashler, 1994a). In fact, it has been argued that most if not all costs may disappear with certain tasks or task combinations (Greenwald & Shulman, 1973) or task instructions (Koch, 1994; Meyer et al., 1995), although unequivocal empirical evidence supporting these claims is still missing. But even if such evidence existed, the limitations that are obviously present in a great variety of tasks and across a broad range of skill levels still call for an explanation. Even if some considerable portion of dual-task interference could be eliminated, or maybe all of it, it would still be interesting to know why and how this kind of interference emerges in other cases.

As a first approximation to a functional model of dual-

task interference, researchers have attempted to localize the performance bottleneck in the stream of information processing from stimulus to response, that is, to determine the processing stage at which two or more tasks interact. Interestingly, considerable dual-task costs emerge even if sensory and motor cross-talk can be excluded, suggesting some form of central bottleneck (e.g., De Jong, 1993; Pashler & Johnston, 1989). Yet, although there is a growing consensus that a central bottleneck really exists—possibly among others, depending on the task—very little is known about which particular processes may be responsible for it and how exactly they bring it about. It is true that, following an early suggestion of Welford (1952), many authors have tended to equate the favored central stage with response selection, but without further specifying how responses are selected and how selection is affected little is gained by that.

Some further first steps toward clarifying the role of the response selection stage under dual-task conditions have been undertaken only recently by Fagot and Pashler (1992) and McCann and Johnston (1992). Fagot and Pashler assumed that each stimulus–response (S-R) mapping relevant for a given task is stored in working memory as a rule, similar to a “production” in the ACT* framework of Anderson (1982). Each rule has a condition, referring to the relevant stimulus information, and an action, corresponding to an abstract code of the required response. This architecture represents a bottleneck because it is assumed that only a single rule can “fire” at the same time. That is, dual-task costs are attributed to a capacity limitation in translating stimulus codes into response codes.

McCann and Johnston (1992) discussed three further possible ways in which response selection processes may produce dual-task costs. First, the number of S-R mapping rules (or sets of rules) that can be held in working memory may be limited to one, so that translating a second stimulus code into the corresponding response code cannot start before the first translation is completed (see De Jong, 1993, for a similar view). Obviously, this possibility is closely

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related to the suggestion of Fagot and Pashler (1992), except that these authors referred to single rules whereas McCann and Johnston seemed to have in mind task-specific sets of rules. Second, rules (or sets of rules) may be held in working memory concurrently, but the number of rules than can be applied or used at the same time may be limited to one. Thus, again, S-R translation may represent the bottleneck. Third, an alternative that is similar to the response-initiation bottleneck to which Keele (1973) and De Jong (1993) referred is that there might be a limitation in the number of motor programs that can be retrieved at the same time. That is, the generation of an abstract response code by applying a translation rule may not be responsible, but rather the translation of this code into a corresponding motor pattern.

As I point out in the General Discussion, these four possibilities are not equally consistent with the available data and, thus, differ in plausibility. Note, however, that at least the first three of them, as well as many other accounts of dual-task performance, localize the critical bottleneck in between stimulus and response stages, hence within the transition from stimulus to response codes. The basic idea is that to activate an associated response code, a stimulus code needs to be translated into the response. Because the S-R mapping will often be arbitrary, some process is needed to make this translation, and it is this process, the database it operates on, or both, that constitutes the bottleneck. If so, secondary stimuli that belong to the less preferred or less important task cannot be translated into their corresponding responses until the translation of the primary stimulus that belongs to the preferred or more important task is completed, that is, until the primary response is selected. An obvious implication of this theoretical sketch, an implication playing a major role in the present article, is that the type of secondary response should not be important for, and thus should not affect, the selection of the primary stimulus or response. As long as the primary response is not selected, no S-R translation operation regarding the secondary task should be performed, so that the secondary response still remains to be identified. Because an unidentified response cannot have specific, identity-related effects, such effects should not be observed before secondary-task translation begins.

In this article, I present evidence from a series of dual-task experiments that is inconsistent with the assumption that secondary responses are not activated before the primary response is selected. These experiments were motivated by an unexpected result of a previous study of mine (Hommel, 1998a), a finding that suggested specific, identity-related effects of the secondary response on primary-task performance. Such an observation suggests that secondary S-R translation is not delayed until primary response selection is completed, but rather that both primary- and secondary-task translations occur concurrently. This again is inconsistent with the hypothesis that S-R translation constitutes a central bottleneck, at least with the simpler versions of this hypothesis. In the following, I first describe the critical findings from the Hommel (1998a) study and propose a rough outline of a theoretical account for it. In particular, I propose an automatic-translation hypothesis holding that, under dual-

task conditions, S-R translation can occur automatically for both tasks at the same time. Next, five experiments are reported that tested several predictions derived from, or suggested by, the automatic-translation hypothesis. In the General Discussion, the theoretical implications of the findings are pointed out and several ways are discussed in which existing bottleneck models of dual-task performance can be extended or made more specific to account for the empirical evidence. My main conclusion is that plausible models must distinguish between two seemingly similar and often equated processes: response activation and response selection.¹

Response Activation and Response Selection: A Two-Process Approach

In investigating the impact of dual-task conditions on the Simon effect (i.e., faster responses to nonspatial stimulus features with spatial S-R correspondence; for reviews, see Lu & Proctor, 1995, and Simon, 1990), Hommel (1998a) had participants perform several combinations of a manual keypressing task and a vocal naming task. The stimuli were the letters X or O, which appeared randomly on the left or right side. In one condition, stimulus location was to be named and letter identity was responded to by pressing a left- versus right-hand key. Task order was not controlled, but the participants were urged to give the vocal task priority. In fact, vocal responses were about 200 ms faster than manual responses, which took about 700–800 ms on average. No doubt, such an outcome is expected from a response-selection bottleneck perspective. Another, also expected, outcome was that the spatial correspondence between stimulus and manual response permitted faster manual responding than noncorrespondence, hence there was a Simon effect. Most surprising, however, correspondence between stimulus and manual (i.e., secondary) response also affected the vocal (i.e., primary) response, even though that was on average performed much earlier than the manual one. Of particular interest, this backward-compatibility effect was replicated in a follow-up experiment in which task order was strictly controlled (minimum interresponse times of 50 ms). This rules out that the effect resulted from those trials on which, contrary to the instruction, the manual response was performed before the vocal.

¹ Here and in the following I share the assumption of network models of information processing (e.g., Cohen, Dunbar, & McClelland, 1990), that the activation level of a response can differ in degrees, with a certain level defined as selection threshold. Accordingly, *response activation* or priming is conceived as a process that increases the activation level of a particular response, whereas *response selection* can be understood as the process that eventually drives a response above its selection threshold. Response activation need not be automatic, nor is response selection necessarily controlled. However, for the sake of simplicity, I assume here that activation due to automatic translation processes is usually insufficient to select a response, so that RT is largely determined by the speed of controlled translation. This assumption may not hold for other tasks and/or other levels of practice than those investigated here.

From a response-selection bottleneck view, this implies that, although the ultimate selection of the manual response may happen only after the vocal response is launched, the manual response must nevertheless be activated before vocal response selection is completed. Yet, if the response was activated, some "manual" S-R translation must have been performed before vocal response selection, which again suggests that, whatever the capacity limitation in dual-task performance may be, S-R translation does not seem to be subject to it. This again strongly contrasts with the picture drawn by Fagot and Pashler (1992) and the first two possibilities discussed by McCann and Johnston (1992), because these all focused on S-R translation as the bottleneck.

One way to account for such backward-compatibility effects without giving up the response-selection view is based on the distinction between automatic response activation and rule-governed response selection, not unlike a similar distinction in Logan's (1988) theory of automatization. Suppose, for instance, an X signaling a left-hand response appears on the right side, thus calling for the vocal response "right." A response-selection bottleneck account suggests that, under vocal priority, both the letter and its position would be identified in parallel, but the manual response will be selected only after vocal response selection is completed. That is, *response selection* is serial and, as it reflects the instructed arbitrary S-R mapping, is rule governed. However, this does not necessarily preclude any *response activation* before, during, or after response selection processes take place.

Consider, for instance, that transient S-R links reflecting the instructed mapping rules are implemented in working memory, as shown in Figure 1A. Even if controlled processes subserving the eventual response selection could use these links only in a serial fashion (as McCann & Johnston's, 1992, second suggestion maintains), automatic response priming might proceed in parallel along the same links long before the controlled processes have started. Consequently, the secondary response could receive some degree of activation before the primary one is selected—a degree high enough to allow the secondary response to exert backward effects, but still below the level required for eventual selection and execution. In the following, I call this version of the two-process approach the *transient-link model*.

Alternatively, even if only one rule or set of rules can be held active at the same time (as assumed by Fagot & Pashler, 1992, or by McCann & Johnston's, 1992, first suggestion), the consistent correlations between stimuli and responses may allow for the development of direct S-R associations that serve as learned shortcuts permitting parallel, automatic activation of response codes (see Figure 1B). Put in the terminology of Logan (1988), although responses are eventually selected by slow algorithmic processing, episodic traces of S-R relationships may be quickly and automatically retrieved at the same time or earlier, so that some response activation may be available before the selection proper proceeds. I call this version of the two-process approach the *direct-link model*.

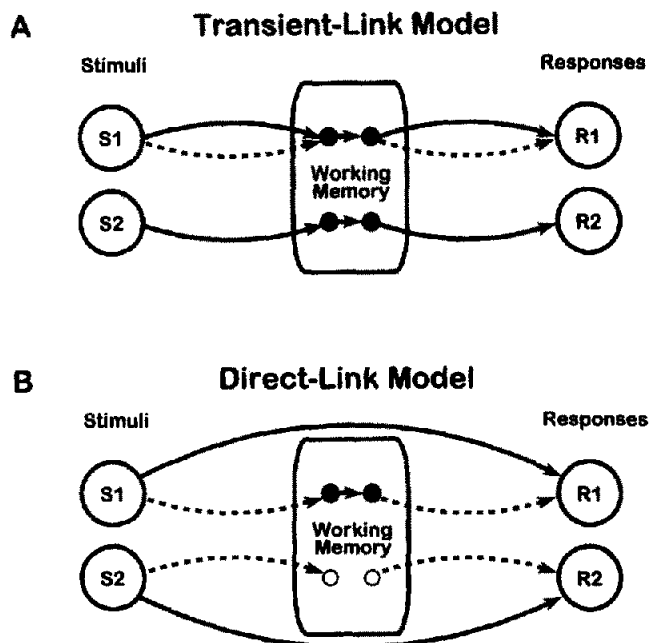


Figure 1. Versions of a two-process account of dual-task performance. A: The transient-link model assumes that several stimulus-response (S-R) mapping rules can be held concurrently active in working memory and used in parallel for automatic S-R translation (represented by straight lines); however, controlled processes (represented by broken lines) can use only one rule at a time. B: The direct-link model assumes that even if only one rule can be active and used by controlled processes at a time, automatic translation runs in parallel via learned, direct S-R associations. Note that multiple rule activation is required for the transient-link model to work, whereas the number of concurrently active rules is irrelevant for the direct-link model.

Whatever the details of the mechanism, the existence of automatic S-R translation would mean that in the Hommel (1998a) study an X may have activated a "left" response code before manual response selection could take place. If so, each stimulus would have produced two spatial codes: one representing the stimulus position and one activated via some kind of link between letter identity and response location. Accordingly, the presentation of a right-side X would have produced a "left" code and a "right" code at about the time of vocal response selection or earlier. This again renders the selection of the proper position name difficult: Because there are two differing spatial codes, the correct one needs to be determined. Note that this is only necessary when the to-be-named relative stimulus position differs from the relative position of the response, hence with manual noncorrespondence, whereas correspondence may fail to affect or even facilitate vocal response selection. Consequently, effects of manual correspondence would be expected to appear in the vocal data. Moreover, such effects would be more likely the later in time vocal response selection takes place, hence the slower primary responding is. This is fully consistent with the reaction time distributions observed in the Hommel (1998a) study.

It is important to emphasize that the automatic-translation hypothesis proposed here does not necessarily contradict (nor depend on) the notion of serial response selection as accepted by most theories of dual-task performance. The ultimate selection, that is, the decision on which of the currently active response codes is to be used for execution, may indeed proceed serially. However, the critical argument is that, although the selection of the secondary response (i.e., rule-governed processing) may be postponed, automatic (association-based) S-R translation need not be, but may produce activation of secondary-response codes long before the postponed response selection actually takes place.

In the following, I report five dual-task experiments conducted to test several implications of the automatic-translation hypothesis. All of these experiments used the same primary task, a manual left-right keypressing response to the color of a red or green stimulus. The secondary task was always vocal, requiring either a "left"- "right" response (in Experiment 1) or a "red"- "green" response to the letter H or S. This introduced compatible or incompatible relationships between the secondary response and either the primary response (with location names as secondary responses) or the primary stimulus (with color names as secondary responses). That is, the vocal response "left" would be compatible with a left-hand keypressing response but incompatible with a right-hand response, and the vocal response "red" would be compatible with identifying the red stimulus in the primary task but incompatible with identifying a green stimulus. The basic idea was that if this kind of compatibility had an effect on the primary task, hence producing a backward-compatibility effect, this would indicate that the secondary response was available at the time the affected process (primary response selection or stimulus identification) took place. If so, the secondary stimulus must have been translated into the secondary response even though primary response selection was not completed, hence translation was automatic.

Experiment 1

Experiment 1 served as a first test of whether the effect observed in the Hommel (1998a) study—an effect of the secondary response on primary task performance—can be generalized to other tasks and another task combination. In the previous study, the critical effect was due to an interaction between a manual Simon task, including spatial S-R correspondence or noncorrespondence, and a location-naming task, hence two location-related tasks. Obviously, the hypothesized automatic-translation process should not depend on these particular types of tasks, nor on the fact that the interaction includes spatial S-R correspondence, so that a similar effect was expected in the (non-Simon) tasks used here. As already mentioned, the critical compatibility relationship was between the secondary vocal response (R2: "left" vs. "right") and the primary manual response (R1: left- vs. right-hand), whereas there was no such relationship between primary and secondary stimulus (S1: red vs. green color; S2: letter *S* vs. *H*) or between stimuli and responses.

If S2-R2 translation is automatic and if it takes place concurrently with S1-R1 translation or R1 selection, R1, the manual response, should be faster if it corresponds to (is compatible with) R2, the vocal response, than if it does not correspond. If so, this backward-compatibility effect should be more pronounced the longer it takes to select R1, hence the longer the manual reaction time (RT). Therefore, compatibility effects should be larger in the upper portions of the RT distribution than in the lower part. Of course, compatibility effects may go both ways, from R2 to R1 as well as from R1 to R2. Thus, R2 may well be faster with R1-R2 compatibility than with incompatibility. However, from a theoretical perspective, such an effect is less interesting than the converse one, because every dual-task account would be consistent with response-response priming effects in a "forward" direction.

Method

Participants. Twelve adults (aged 20–35 years) were paid to participate in a single session of about 30 min. They reported having normal or corrected-to-normal vision and were not familiar with the purpose of the experiment.

Apparatus and stimuli. The experiment was controlled by a Hewlett Packard Vectra RS20 computer, which was interfaced with an A/D card (Data Translation 2821) for sampling of vocal input, attached to an Eizo 9080i monitor via an Eizo MD-B11 graphics adaptor for stimulus presentation, and connected with an additional monitor in an adjacent control room via serial interface. Manual responses were performed by touching, with the left or right hand, respectively, the left or right of two touch-sensitive metal plates mounted on a wooden board.

Participants wore headphones with an integrated microphone (Sennheiser HMD 224), which registered vocal responses. The two vocal response alternatives were "*links*" and "*rechts*," the German words for *left* and *right*. Vocal RTs were measured to the nearest millisecond by sampling the microphone input with a rate of 20 kHz and averaging over 20 consecutive values. A fixed threshold was used as response criterion. The vocal input was also amplified and transmitted to the headphone of the experimenter, who sat in the control room, to allow for on-line identification of incorrect vocal responses.

A white asterisk served as a fixation mark that appeared at the center of the black screen. Stimuli were the uppercase letters H and S, presented in red or green at screen center. From a viewing distance of about 60 cm, each letter measured about 0.3° in width and 0.4° in height.

Design. Within a session, participants worked through two practice blocks and 30 experimental blocks. Each block was composed of two replications of each of the four combinations of letter identity and color, all randomly intermixed. That is, there were 60 experimental trials for each condition overall. Manual responses were assigned to stimulus color, vocal responses to letter identity. This yielded four possible mapping combinations that were counterbalanced across participants.

Procedure. After an intertrial interval of 2,000 ms, the fixation mark appeared for 1,000 ms, followed by a blank interval of 250 ms. Next, the stimulus, a red or green H or S, was presented until both responses were made or until 2,500 ms had passed. Participants made a manual response to stimulus color and a vocal response to the letter. They were required to perform the two responses in strict serial order and an error message was displayed

(and the corresponding responses were counted as incorrect) if the manual response did not lead over the vocal by at least 50 ms.

In case of an order error, a premature (RT < 150 ms) or omitted response (RT > 2,500 ms), an incorrect keypress, or an incorrect vocal response (as determined by the experimenter during the intertrial interval), a brief error message was displayed on the screen, accompanied by a beep. The corresponding trial was recorded and repeated at some random position in the remainder of the block.

Results

Premature responses (mostly due to the microphone picking up some respiratory sounds) accounted for 2.6% of the trials, response omissions for 1.7%, and order errors (vocal before manual response) for 0.5%. These trials were excluded from analyses, as were the trials where a correct response in one mode was accompanied by a choice error in the other (4.5%). From the remaining data, mean RTs and percentages of (choice) errors (PEs) were computed for each response type as a function of compatibility (left-hand key/"left," right-hand key/"right") or incompatibility (left-hand key/"right," right-hand key/"left") between manual and vocal response (see Table 1).

An alpha level of .05 was used for all statistical tests. In an omnibus analysis of variance (ANOVA) on RTs with response mode and compatibility as within-subjects factors, all three effects were significant: response mode, $F(1, 11) = 69.56, p < .001$; compatibility, $F(1, 11) = 11.39, p < .01$; and the interaction, $F(1, 11) = 6.05, p < .05$. The PE analysis yielded a very similar picture, with significant main effects of response mode, $F(1, 11) = 6.88, p < .05$; and compatibility, $F(1, 11) = 25.55, p < .001$, and with the interaction approaching significance, $F(1, 11) = 4.31, p < .07$. As shown in Table 1, the RT compatibility effect increased from manual to vocal responses, whereas the PE effect decreased. However, as indicated by separate ANOVAs on manual and vocal data, compatibility effects were significant under all conditions, both in RTs and in PEs.

To gain insight into the temporal dynamics of the compatibility effect, I performed distribution analyses on the RT data. For each participant, response mode, and compatibility condition, quintiles were computed and subjected to a $2 \times 2 \times 5$ ANOVA. Apart from producing a significant (and somewhat trivial) main effect, $F(4, 44) = 128.40, p < .001$,

Table 1
Mean Reaction Time (RT, in Milliseconds) and Percentage of Errors (PEs) for Manual (Primary) and Vocal (Secondary) Responses in Experiment 1 According to Compatibility Between Primary (Manual) and Secondary (Vocal) Responses

Response	Compatible		Incompatible		Δ
	RT	PE	RT	PE	
Manual	645	1.1	720	5.4	75
Vocal	1,101	0.8	1,196	2.8	95

Note. RT compatibility effect sizes are presented in the rightmost column.

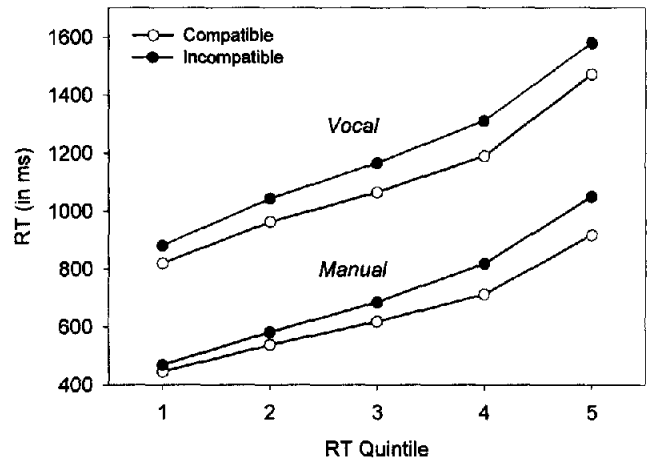


Figure 2. Experiment 1: Mean manual and vocal reaction time (RT) quintiles as a function of compatibility between secondary (vocal) and primary (manual) responses.

the quintile factor participated in interactions with response mode, $F(4, 44) = 33.17, p < .001$, and compatibility, $F(4, 44) = 5.00, p < .005$, as well as in the three-way interaction, $F(4, 44) = 7.46, p < .001$. As is obvious from Figure 2, the compatibility effect increased from lower to higher quintiles, hence from fast to slow responses, in the manual task, but not (or not so much) in the vocal task. Nevertheless, planned comparisons revealed that the compatibility effect was significant for all quintiles in both tasks ($p < .05$, always one-tailed).

For reasons that will become clear in the *Discussion*, I also assessed whether compatibility effects depended on interresponse time (IRT)—hence the temporal lag between the two response onsets. For each participant and compatibility condition, IRT quintiles were determined and the mean manual RT and vocal RT for each quintile were calculated. As can be seen from the group means shown in Figure 3, the manual RT level and the effect of compatibility on manual RTs is about the same for all quintiles. In fact, a two-way ANOVA yielded only a significant compatibility effect, $F(1, 11) = 10.22, p < .01$, whereas the effect of quintile and the interaction term were far from significant ($p > .27$). The vocal RT, not surprisingly, increased with IRT quintile, $F(4, 44) = 115.28, p < .001$, and from compatibility to incompatibility, $F(1, 11) = 12.02, p < .005$. Moreover, the slight decrease of the compatibility effect in the higher quintile apparent from Figure 3 produced an interaction that reached the 10% level.

Discussion

The experiment yielded two important outcomes. First, primary task performance—and, less interestingly so, secondary task performance—was clearly affected by the compatibility relationship between primary and secondary response. This replicates the similar finding of Hommel (1998a) with two different tasks and a different task combination, thus demonstrating that the backward-compatibility

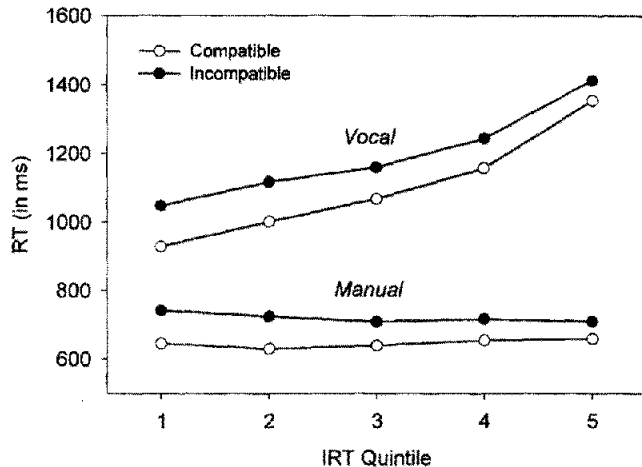


Figure 3. Experiment 1: Mean manual and vocal reaction times (RTs) as a function of interresponse time (IRT) quintile and compatibility between secondary (vocal) and primary (manual) responses. Mean IRT quintiles were 283, 371, 429, 503, and 695 ms with compatibility, and 306, 393, 452, 528, and 703 ms with incompatibility.

effect is quite robust. In particular, the present replication shows that the backward-compatibility effect did not depend on using a Simon task or on some kind of compatibility relationship between S1 and R1 or between S2 and R2.

According to the proposed logic, an effect of R2-R1 compatibility indicates that the secondary response must have been available or at least activated to some degree at the time the primary response was selected. As S2-R2 translation can be assumed to take time, an effect of R2 should be more likely the later in time R1 is selected, hence the higher manual RT. This was in fact observed in the distribution analysis: The manual compatibility effect grew from fast to slow responding. These findings do not suggest that S2-R2 translation underlies capacity limitations. Yet, although there was no single-task control in this experiment (but compare the single-task conditions in Experiment 5), the slow vocal RTs also suggest that secondary responses were considerably delayed by primary-task performance. That is, the result pattern indicates that capacity limitations were not absent altogether, so that the apparent automaticity of S-R translation cannot be attributed to low task difficulty. Nevertheless, whatever processes may be affected by these limitations, S-R translation does not seem to be among them, just as the proposed hypothesis maintains.

The second important outcome of this experiment is that the effect of R2-R1 compatibility did not depend on IRT, hence on the delay between R1 and R2. Why is this important? Note that in this experiment, and in the Hommel (1998a) study as well, the two relevant stimulus attributes, S1 and S2, were part of the same stimulus, and thus always appeared at exactly the same time. Of course, minimizing the temporal delay between S1 and S2 is a necessary precondition for backward-compatibility effects to occur at all, because R2 can affect primary-task performance only if it is activated before the primary response is executed.

Moreover, as dual-task costs have been shown to be about the same whether S1 and S2 belong to the same or to different stimulus objects (Fagot & Pashler, 1992), there was little reason to assume that simultaneous presentation of S1 and S2 would create any problem. However, one may still speculate that presenting only one stimulus on each trial tempts participants to group their responses, hence to withhold the selection of the primary response until both S-R translations are completed. Consequently, the ultimate selection of R1 would follow rather than precede S2-R2 translation, which would account for the present findings without requiring the crucial automatic-translation assumption.

The present data provide two counterarguments to this reasoning. One is that response mode had a huge effect: On average, vocal responses were 466 ms slower than manual. Although this does not exclude the possibility that responses were grouped on some trials, it is hard to believe that the proportion of these trials was big enough to produce a mean manual compatibility effect of 75 ms. But the IRT analysis provides even stronger evidence against a grouping account. Clearly, if responses were grouped, IRT should be short. Thus, if the manual compatibility effect is due to grouping, it should only show up in the shortest, but not in longer IRTs. Obviously, this was not the case: The manual compatibility effect was the same size across all IRT quintiles. So, it can be concluded that in replicating the findings of Hommel (1998a) and demonstrating their generalizability to a task not involving spatial S-R correspondence or a Simon-type manipulation, the present results nicely agree with the automatic-translation hypothesis under test.

As expected, compatibility between R1 and R2 affected not only primary-task performance but S2-R2 processing as well. This is indicated by the observation that the manual compatibility effect was not only propagated to the vocal RTs, which would have yielded additive effects of compatibility and response mode, but increased significantly from manual to vocal responses. The most obvious explanation of this overadditive pattern is that there was some sort of response-response priming across response modes. Although the presence of response-response priming effects as such is not overly surprising (see Kornblum, 1973, for an overview), the demonstration of that kind of effect with responses sharing only very abstract properties (i.e., their meaning) is noteworthy.

Experiment 2

In Experiment 1, the primary manual task was combined with a vocal task that introduced a compatibility relationship between R2 and R1, the vocal and the manual response. In Experiment 2, the location-related vocal responses were replaced by color-related responses. This introduced a compatibility relationship between R2 and S1, that is, between the vocal response and the stimulus (feature) of the manual task. Although the finding of R2-S1 compatibility effects on primary-task performance would greatly increase the generalizability of the backward-compatibility effect, manipulating this relationship admittedly seems odd on first

sight—after all, why should response-related effects “work back” (R2 → S1) in the processing chain? However, there are theoretical reasons for assuming that it may work—reasons going back to Prinz’s (1990) concept of a common coding of stimuli and responses and to verbal-mediation accounts of the manual Stroop effect.

According to Prinz (1990), to-be-perceived events (i.e., stimuli) and to-be-produced events (i.e., responses) are coded and represented not in different systems or at different stages, but within the same (common-coding) system. Besides having strong implications for an understanding of S-R compatibility effects (see Eimer, Hommel, & Prinz, 1995; Hommel, 1997; Prinz, 1990), the common-coding idea suggests that the activation of response codes may lead to a backward priming of directly associated or conceptually related stimulus codes. Consistent with that, Hommel and Schneider (1998) observed that targets in visual search were in fact detected earlier if their relative position in the search display corresponded to the relative location of an unrelated manual response to be selected during the search. In the present task, R-S backward priming would also be possible from color-word to color-identity codes. If this occurred, it would indicate that automatic translation took place: Only if automatic S2-R2 translation produced activation of a vocal “red” response code can this activation spread to the “red” stimulus code in the manual task, thus yielding an R2-S1 compatibility effect.

Another approach that also suggests compatibility effects with R2-S1 overlap, although for somewhat different reasons, is the verbal-mediation account of the Stroop effect, especially of its manual variant. In the standard Stroop task, participants vocally name the ink of color words, words that may be congruent or incongruent with the to-be-named color. The term *Stroop effect* refers to the robust finding that incongruent words impair vocal performance as compared to neutral or congruent words (see MacLeod, 1991, for an overview). Accounts of the Stroop effect typically focus in some way on the fact that the task-irrelevant aspect, the word, is compatible with the vocal response—more compatible than ink color, the task-relevant stimulus feature; however, Stroop effects can be demonstrated even if the vocal responses are replaced by keypressing (Keele, 1972; Redding & Gerjets, 1977), although the effect is usually smaller then. One way to account for that would be to assume a direct interaction between stimulus codes, hence the color code and the word code (e.g., Hasbroucq & Guiard, 1991; Kornblum, 1994). However, such an assumption is inconsistent with the finding that color-word incongruence does not affect performance with color-search (Flowers & Dutch, 1976) and color-color comparison (Egeth, Blecker, & Kamlet, 1969), although the preconditions for a stimulus-stimulus conflict are still given. Therefore, Morton (1969), Dalrymple-Alford and Azkoul (1972), La Heij (1988), and others have suggested a verbal-coding account. It holds that in manual Stroop tasks the stimulus color code is not directly associated with the manual response but, because the S-R mapping is arbitrary and thus needs to be memorized, is mediated by a verbal code. The conflict is thus not between a color code and a word code, but between two verbal codes:

one corresponding to the irrelevant color word and one mediating the ink-response association.

The design of Experiment 2 shared several features with a manual Stroop task: Not only was there a manual reaction to stimulus color, there was also a verbal color-word code—the one designating the secondary response. If S2-R2 translation is automatic, this verbal code should be available long before R2 selection eventually takes place and, thus, may affect S1 processing—or at least interact with the verbal code mediating S1-R1 translation. If so, manual performance should be better with R2-S1 compatibility than with incompatibility. In turn, the finding of such a compatibility effect would further strengthen the hypothesis of automatic S-R translation.

Method

Participants. Twelve adults (aged 21–28 years) were paid to participate. They fulfilled the same criteria as in Experiment 1.

Apparatus, stimuli, design, and procedure. These were the same as in Experiment 1, except that the vocal responses were “rot” and “grün,” the German words for *red* and *green*. That is, a red or green H or S was presented in each trial, and participants responded first to the color by pressing a left or right key, then to the letter by saying “rot” or “grün.” The four possible combinations of two color-key mappings (red → left and green → right, or green → left and red → right) and two letter-word mappings (H → “rot” and S → “grün,” or S → “rot” and H → “grün”) were balanced across participants.

Results

After excluding trials with premature (0.2%) and omitted responses (1.3%), as well as trials with order errors (0.2%) and concomitant errors (i.e., correct responses in one mode accompanied by a choice error in the other; 2.1%), I computed mean RTs and PEs for each response type as a function of compatibility between the vocal response and the stimulus in the manual task (see Table 2 for group means). The RT analysis yielded significant main effects of response mode, $F(1, 11) = 111.40, p < .001$, and compatibility, $F(1, 11) = 28.94, p < .001$, and a significant interaction, $F(1, 11) = 22.87, p < .001$, whereas the PE analysis produced only a compatibility main effect, $F(1, 11) = 25.24, p < .001$. That is, whereas the RT compatibility effect was

Table 2
Mean Reaction Time (RT, in Milliseconds) and Percentage of Errors (PEs) for Manual and Vocal Responses in Experiment 2 According to Compatibility Between Secondary (Vocal) Response and Primary (Manual-Task) Stimulus

Response	Compatible		Incompatible		Δ
	RT	PE	RT	PE	
Manual	635	1.2	739	5.7	104
Vocal	1,081	0.5	1,242	4.8	161

Note. RT compatibility-effect sizes are presented in the rightmost column.

once again larger for the vocal than the manual responses, the error rates were the same for both response modes. As in Experiment 1, separate analyses showed that compatibility effects were significant for both measures under all conditions.

In the analysis of the RT distributions (i.e., Response Mode \times Compatibility \times Quintile; see Figure 4), the quintile factor not only produced a main effect, $F(4, 44) = 290.21$, $p < .001$, but also was involved in two-way interactions with response mode, $F(4, 44) = 52.87$, $p < .001$, and compatibility, $F(4, 44) = 10.12$, $p < .001$. The latter indicated that, as in Experiment 1, the compatibility effect increased from fast to slow responses, although planned comparisons confirmed significant effects for all quintiles. However, in contrast to Experiment 1, the three-way term was not significant ($p > .39$). That is, this time, the superadditivity of compatibility and quintile in the primary manual task fully propagated to the secondary vocal task.

As Figure 5 makes apparent, the compatibility effect on manual RTs did not depend on IRT, which was substantiated by the finding that the compatibility main effect, $F(1, 11) = 22.53$, $p < .001$, was not modified by an interaction with IRT quintile ($p > .3$). In contrast to Experiment 1, there was a slight positive relationship between the general RT level and IRT, which produced a main effect of quintile, $F(4, 44) = 4.56$, $p < .005$. The results were the same for the vocal data, where the significant main effects of compatibility, $F(1, 11) = 32.19$, $p < .001$, and quintile, $F(4, 44) = 130.41$, $p < .001$, were accompanied by a far-from-significant interaction ($p > .7$).

Discussion

As expected, the compatibility relationship between the secondary response and the primary stimulus had a strong impact on primary-task performance. Again, this impact increased with increasing RT in the primary task; most likely

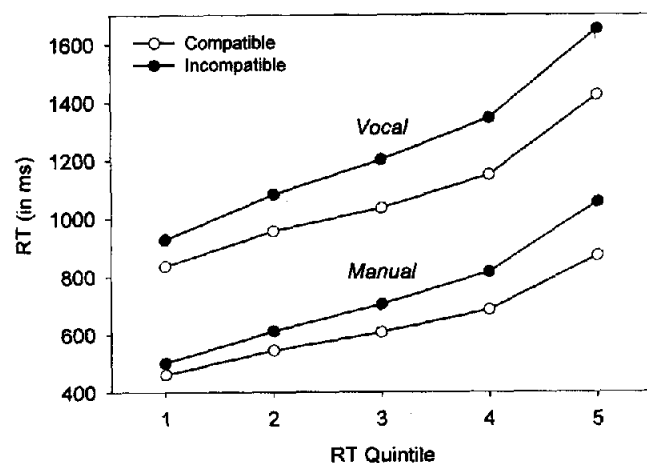


Figure 4. Experiment 2: Mean manual and vocal reaction time (RT) quintiles as a function of compatibility between secondary (vocal) response and primary (manual-task) stimulus.

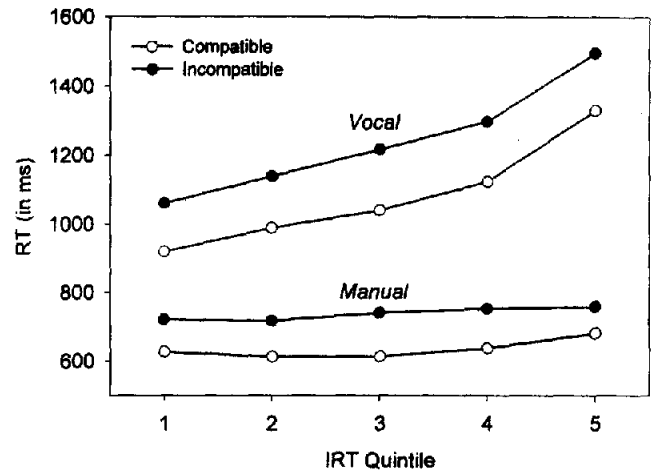


Figure 5. Experiment 2: Mean manual and vocal reaction times (RTs) as a function of interresponse time (IRT) quintile and compatibility between secondary (vocal) response and primary (manual-task) stimulus. Mean IRT quintiles were 292, 376, 426, 487, and 649 ms with compatibility, and 338, 422, 475, 545, and 736 ms with incompatibility.

because S2-R2 translation takes time and, thus, can affect S1 processing only if this is not completed before R2 is activated to a certain degree. The observation that R2-S1 compatibility had an effect at all is consistent with Prinz's (1990) general assumption that response codes may have backward effects on stimulus processing and the verbal-mediation account of manual Stroop effects—even though here the interfering verbal code was made available by S-R translation, not due to its correspondence to a stimulus aspect. Most important, however, the present findings further extend the available evidence for automatic S-R translation and, thus, strongly support the two-process approach.

Experiment 3

In Experiments 1 and 2, and in the Hommel (1998a) study as well, participants were presented with integral stimuli, that is, with single objects comprising both critical stimulus features. Although one may consider this choice to foster response grouping strategies, a grouping account is not consistent with the present findings: The observed large response mode effects do not suggest that responses were grouped very often and the independence of manual compatibility effects from IRTs clearly rules out that compatibility effects were confined to trials where grouping was likely. Nevertheless, if S-R translation is really as automatic as proposed here, it should be possible to demonstrate that compatibility effects occur with temporally nonintegral stimuli as well and, thus, do not depend on integral stimulus presentation. Therefore, in Experiment 3, the basic design of Experiment 2 was combined with a manipulation of the temporal relationship between S1 and S2 presentation, that is, the stimulus onset asynchrony (SOA) variation typically used in studies on the psychological refractory period (PRP). Of course, the longer the SOA is, the less likely S2-R2

translation will be completed, so that a decrease of the manual compatibility effect with increasing SOA is to be expected. Nevertheless, a substantial effect at the shortest SOA (50 ms) was clearly predicted. If compatibility effects are demonstrable even with variable SOAs—a condition that is commonly assumed to work against strategies to group or synchronize responses—this would provide further evidence for the generalizability of the present findings.

Method

Participants. Twenty-four volunteers (aged 15–40 years) were paid to participate in a single session of about 40 min. They fulfilled the same criteria as in Experiment 1.

Apparatus, stimuli, design, and procedure. These were the same as in Experiment 2, with the following exceptions: Stimulus presentation always started with a red or green rectangle the same size as the letters. After an SOA of 50, 150, or 650 ms, the rectangle was replaced by a stimulus letter (either S or H) of the same color. Participants responded to the color by pressing a left or right key and to the letter by saying "rot" or "grün." The instruction emphasized that the manual task was the primary one and the vocal task was secondary, but there was no strict control of response order and no corresponding error messages.

As a result of the SOA manipulation, block size increased to 24 (2×2 S-R combinations \times 3 SOAs \times 2 replications). There were two practice and 15 experimental blocks, resulting in 30 experimental trials for each cell of the design.

Results

After excluding trials with premature responses (1.0%), response omissions (0.7%), or concomitant errors (1.8%), I computed mean RTs and PEs for each response type as a function of manual stimulus–vocal response compatibility and manual stimulus–vocal SOA (see Figure 6 for RT means).

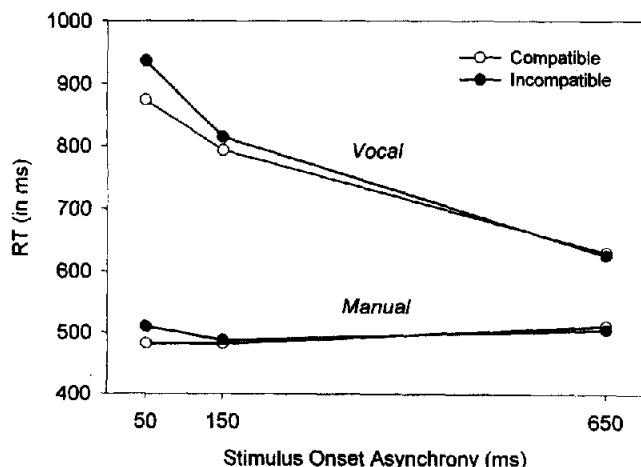


Figure 6. Experiment 3: Mean reaction times (RTs) for manual and vocal responses as a function of stimulus onset asynchrony and compatibility between secondary (vocal) response and primary (manual-task) stimulus.

In the omnibus RT analysis, the main effects of response mode, $F(1, 23) = 184.18, p < .001$, compatibility, $F(1, 23) = 8.04, p < .01$, and SOA, $F(2, 64) = 41.94, p < .001$, the interactions of mode and compatibility, $F(1, 23) = 7.74, p < .05$, mode and SOA, $F(2, 64) = 157.34, p < .001$, and compatibility and SOA, $F(2, 64) = 8.06, p < .001$, as well as the three-way interaction, $F(2, 46) = 9.35, p < .001$, were all significant. Separate analyses showed that with manual responses, only the Compatibility \times SOA interaction produced a significant effect, $F(2, 46) = 3.63, p < .05$, whereas both compatibility ($p > .17$) and SOA ($p > .5$) did not. In vocal responses, however, all three effects were significant: compatibility, $F(1, 23) = 12.53, p < .005$; SOA, $F(2, 64) = 254.39, p < .001$; and the interaction, $F(2, 46) = 11.90, p < .001$. Planned comparisons indicated that the manual compatibility effect was significant with an SOA of 50 ms, but not with 150 or 650 ms. The vocal compatibility effect was significant with 50 and 150 ms, but not with 650 ms.

In an attempt to match the most common PRP design closely, response order was not controlled during the experiment. To test whether this may have played a role, I carried out an additional analysis on only those trials from the critical 50-ms SOA condition where the manual response led the vocal by at least 100 ms. The results were virtually identical to the original outcome: The effects of response mode, $F(1, 23) = 458.39, p < .001$, and compatibility, $F(1, 23) = 14.15, p < .001$, and the interaction, $F(1, 23) = 16.17, p < .001$, were all significant. Of particular importance, the compatibility effect was significant in both manual responses (481 vs. 509 ms) and vocal responses (880 vs. 943 ms; p s $< .05$, respectively).

The error analysis yielded three effects: Errors were lower on compatible than on incompatible trials (1.6% vs. 2.2%), $F(1, 23) = 5.04, p < .05$, and with long than with short SOAs (3.1%, 1.4%, and 1.1%, respectively), $F(2, 46) = 6.41, p < .005$. A further interaction of these two variables, $F(2, 46) = 11.96, p < .001$, was due to the compatibility effect's being present with the shortest SOA (2.0% vs. 4.2%), absent with the intermediate SOA (1.5% vs. 1.4%), and slightly inverted with the longest SOA (1.4% vs. 0.9%).

Discussion

The results show very clearly that the R2-S1 compatibility effect demonstrated in Experiment 2 did not depend on the temporally integral presentation of S1 and S2. Although a standard PRP design with an extensive variation of SOA was used here, a substantial effect was again observed in both tasks.

Yet, there is one fly in the ointment: The compatibility effects, and especially the critical manual one, were much smaller than in Experiment 2, which might suggest at least a moderating effect of temporal integrality. However, a closer look at the RT level and a consideration of the SOAs used reveals why the two experiments produced quantitatively different outcomes. (A further possible factor is discussed in Experiment 4.) If one compares the 50-ms SOA condition in Experiment 3 with Experiment 2, it is obvious that the manual RTs were about 200 ms faster in the present

experiment. The underlying reason is not obvious, but it may well be that presenting S1 and S2 in succession already indicates the required task order and thus reduces or eliminates the serial-order problem integral stimuli (or stimuli whose order is uncertain) pose on participants (Koch, 1994).

Whatever the reason for faster responding might be, it is apparent from the distribution analyses in Experiments 1 and 2 that fast manual responses were associated with smaller compatibility effects, presumably because the faster the manual response the less likely it can be affected by the product of the time-consuming S2-R2 translation. That is, the fast manual RTs in Experiment 3 must necessarily result in a decreased manual compatibility effect. Figure 7 shows the manual compatibility effects from Experiment 2 (cf. Figure 4) and from the 50-ms condition of Experiment 3 plotted against RT quintiles. It can be seen that if the RT level is considered, the compatibility effects are not very different, at least not as different as a comparison of the means suggests. Moreover, in Experiment 3, S1 always preceded S2, even at the smallest SOA, which means some delay of S2 processing and, thus, some delay of the point in time at which R2 is available. Delaying the availability of R2 decreases the likelihood that it affects primary-task performance, the more so if the primary reactions are fast. Thus, other things being equal, to have been affected by R2 with the same likelihood as in Experiment 2, manual RTs in the 50-ms condition of Experiment 3 must have been 50 ms longer. Considering this further complication, a fair between-experiments comparison of the graphs in Figure 7 would require shifting the curves for Experiment 3 about 50 ms downward before compatibility effects for corresponding RT levels are compared. With this in mind, the results match quite nicely, which suggests that the compatibility-size difference between Experiments 2 and 3 does not represent a real problem for the present approach—actually, the auto-

matic-translation hypothesis offers a coherent account of the rather complex data patterns.

Experiment 4

Over and above the evidence already available from the analyses of Experiment 2, Experiment 3 provides further evidence against the assumption that the manual R2-S1 compatibility effect is an artifact of temporally integral stimulation. Even if the temporal relationship between S1 and S2 varies extensively, manual compatibility effects occur. This suggests automatic S2-R2 translation. However, there may be other than stimulus-related conditions of (or limitations to) automatic translation. In standard dual-task or PRP paradigms, both (or all) of the tasks are speeded, whether a particular task order is required or not. Even if response grouping in the most basic sense (i.e., full preparation of all responses before emission of the first) could be excluded, speeding both tasks would still suggest some way of temporally coordinating the tasks or the processes underlying them. Possibly, this coordination somehow allows for, or even requires, automatic translation processes, suggesting that backward-compatibility effects such as observed here depend on the particular experimental conditions and, thus, may disappear if the task context is changed.

Although the mere demonstration that backward effects are context-sensitive would not rule out an automatic-translation account, it would certainly limit its scope in theoretically interesting ways. Consequently, I asked what would happen if, in a design such as that used in Experiment 2, the temporal constraints for the secondary task were relaxed. There would then be not the slightest advantage for preparing the secondary task concurrently, or temporally overlapping with the primary task. If S2-R2 translation was fully automatic, as the hypothesis under test at least suggests, some degree of R2 activation may be present even if R2 performance is much later in time. If, however, automatic translation depended on some kind of task coordination necessary to meet the temporal constraints of dual-task situations, automatic translation may be absent and, thus, may not produce manual R2-S1 compatibility effects.

Method

Participants. Sixteen adults (aged 20–34 years) were paid to participate in a single session of about 30 min. They fulfilled the same criteria as in Experiment 1.

Apparatus, stimuli, design, and procedure. These were the same as in Experiment 2, except that the vocal response was to be made at leisure without any time pressure. That is, a red or green H or S was presented in each trial, and participants responded first to the color by pressing a left or right key, then to the letter by saying "rot" or "grün." Participants were discouraged from quick vocal responding in the following way: After the manual response the program paused for 1,500 ms and then the stimulus disappeared, which was the signal for vocal responding. RTs for vocal responses were not stored, but the experimenter monitored these responses on-line and reminded the participant to take time in cases of repeated premature responding. As in the previous experiments, the trial was counted as an error trial if either the manual or the vocal response (or both) were incorrect.

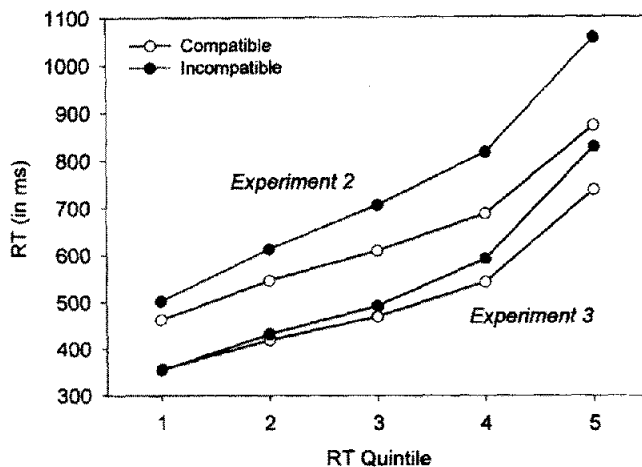


Figure 7. Mean manual reaction time (RT) quintiles for Experiments 2 and 3 (50-ms stimulus onset asynchrony condition) as a function of compatibility between secondary (vocal) response and primary (manual-task) stimulus.

Results

After excluding trials with premature responses (0.1%), manual response omissions (0.1%), and incorrect vocal responses (1.0%), I computed mean manual RTs and PEs as a function of compatibility between the vocal response and the stimulus in the manual task. A significant compatibility effect was observed in the RTs, $F(1, 15) = 5.20, p < .05$, with compatible trials yielding faster responses than incompatible trials (632 vs. 661 ms). However, in errors, the two compatibility conditions were very similar (1.7% vs. 1.9%; $p > .8$). Again, the RT compatibility effect varied with relative response speed, increasing linearly from 7 ms with the first to 53 ms with the fifth quintile.

Discussion

The outcome of Experiment 4 shows that automatic S2-R2 translation, as indexed by the manual compatibility effect, does not require that R2 be performed in close temporal proximity to R1.² This suggests a high degree of automaticity that does not (fully) depend on particular strategies or task-coordinating activities. However, a look at the size of the compatibility effect also shows that relaxing the temporal constraints for the secondary task was not without any effect: As compared to Experiment 2, the effect was reduced to less than one third (29 ms vs. 104 ms). In contrast to Experiment 3, this reduction cannot be explained with reference to the RT level, because manual responses were not much quicker in Experiment 4 (647 ms) than in Experiment 2 (687 ms). So, what could have happened here?

One possibility is that the critical manipulation of delaying the secondary response had an impact on the activation level of the set of S-R mapping rules belonging to the secondary task. Consider the transient-link model depicted in Figure 1A. According to that, stimulus and response codes are connected through memorized S-R mapping rules only, which serve for both controlled and automatic S-R translation. Consequently, the occurrence and efficiency of automatic translation depends on whether the respective rule is held active in working memory, and on how actively it is maintained. Under the severe time pressure that characterizes typical dual-task conditions, people will tend to hold both primary- and secondary-task rules in a state of maximum readiness—and the backward-compatibility effects obtained in this study show that they can. Accordingly, automatic S-R translation processes can access and use those rules in parallel, with the result that both R1 and R2 become activated to some degree. However, given that the content of working memory is likely to be subject to spontaneous decay, the activation level of rules should depend on when and how often these rules are “refreshed” by memory-maintenance processes. Assume now that, under the relaxed time constraints in the present experiment, participants first refreshed the primary rule set only, made their primary response, and only then refreshed the secondary set. If so, at stimulus presentation and during primary-task performance the secondary set of rules was much less activated than under the tight temporal constraints in Experiment 2 or 3.

Accordingly, if we assume that the amount or rate of automatic S-R translation is limited by the degree of rule activation in working memory, a reduced backward compatibility effect is, in fact, to be expected.

There is another, not necessarily alternative, possibility that would be consistent with both the transient- and the direct-link version of the two-process approach. According to that, automatic translation took place in the present experiment as it did in the previous ones, but participants attempted to cope with it differently. That is, secondary responses were automatically activated upon stimulus presentation, whether directly or mediated by memorized rules, but given the long delay of R2 and the relaxed time constraints, participants might have actively suppressed the automatically activated response. If, for instance, a red H called for a left-hand keypress and the vocal response “red,” the “red” response would have been inhibited and—because of the feature overlap of stimulus and secondary response—processing the red color would have also been hampered. The consequence would be a negative backward-compatibility effect, especially with long manual RTs.

Negative effects were, in fact, observed: Of the 16 participants, 5 had negative compatibility effects of substantial size (−7, −22, −28, −42, and −79, always with the by-far-strongest contribution from the slowest RT quintile), whereas the remaining 11 had pronounced positive effects ranging between 21 and 102 ms. Interestingly, a reanalysis of the data from Experiment 3 showed a similar tendency: Nine of the 24 participants exhibited negative compatibility effects in the 50-ms SOA condition (in five cases greater than −10 ms), and 10 participants had negative effects with the 150-ms SOA (nine greater than −10 ms). Even in Experiment 2, where only 1 of 12 participants showed an overall negative effect, 5 people showed effects between −29 and −259 ms in the first trials (see the General Discussion). Thus, there is evidence that at least some of the participants did actively and efficiently counteract their automatic-translation processes, thereby reducing the mean backward-compatibility effect.

Experiment 5

The outcome of Experiment 4 shows that S2-R2 translation did not depend on R2 being performed as quickly as possible—the secondary response may actually occur long after the primary one. This is consistent with the basic tenet of the automatic-translation hypothesis holding that, given

² Note that this finding does not stand in contradiction to the absence of backward-compatibility effects with longer SOAs observed in Experiment 3. In Experiment 3, R1 was made about 500 ms after S1 onset and, thus, preceded the onset of S2 by about 150 ms on average. S2-R2 translation must have occurred even later, so that S1 processing could not be affected by the identity of R2 for trivial temporal reasons. However, in Experiment 4 (as well as in Experiments 1, 2, and 5), the SOA was zero, so that S2-R2 translation could start early enough to allow for an impact of R2 on S1. Thus, whereas Experiment 3 demonstrated that substantially delaying S2 to S1 eliminated the effect of backward compatibility, Experiment 4 showed that delaying R2 to R1 did not.

the respective stimulus information, the associated response is activated along a learned or transient S-R connection. However, if the time by which the secondary response is performed is not important, one may ask whether it must be performed at all. Possibly, automatic translation would occur even if it is not, provided that the S2-R2 rule is not completely deactivated, or simply forgotten. To test this consideration, in Experiment 5, I used a single-task situation that nevertheless required the participants to hold two S-R mappings in memory. This was achieved by using the same tasks as in Experiment 2, but by precuing only one of the tasks in advance of each trial. The crucial question was whether performing the manual response would be affected by compatibility between the present stimulus color and that vocal color-word response the stimulus would require if vocal responding had been precued. Given the outcome of Experiment 4 and the possibility that increasing the temporal distance between two responses leads to differential activation of S-R mapping rules, or even to active response suppression, we of course cannot expect intertask-compatibility effects to reach the same size as under standard dual-task conditions. However, even in Experiment 4 a significant overall effect was obtained, so that at least some indication of automatic translation might be found in the present experiment, too.

Method

Participants. Twenty-four adults (aged 19–34 years) were paid to participate in a single session of about 30 min. They fulfilled the same criteria as in Experiment 1.

Apparatus, stimuli, design, and procedure. These were the same as in Experiment 2, with the following exceptions: Instead of two responses only one response, a manual or a vocal response, was to be made on each trial. Because the number of trials was the same as in Experiment 2, this reduced the number of replications in each condition from 60 to 30. Which response to make was signaled before each trial: After the intertrial interval, the fixation mark was presented for 2,000 ms with the word *Tasten* (“keypressing”) or *Sprechen* (“speaking”) above it. Both fixation mark and message were then deleted and followed by a 500-ms blank interval before the stimulus appeared. The stimulus was always a red or green H or S. After the “keypressing” cue, participants responded to the color by pressing a left or right key; after the “speaking” cue, they responded to the letter by saying “rot” or “grün.”

Results

Trials with premature responses (1.6%), response omissions (0.1%), or response mode confusions (0.2%) were excluded. The remaining data were treated as in Experiment 2 (see Table 3 for means). In the omnibus RT analysis, the main effects of response mode, $F(1, 23) = 68.29, p < .001$, and compatibility, $F(1, 23) = 14.10, p < .001$, were significant, but the interaction only approached significance, $F(1, 23) = 3.63, p < .07$. Although the compatibility effect tended to be larger with vocal responses, separate analyses indicated that it was significant with manual responses, $F(1, 23) = 5.00, p < .05$, and vocal responses, $F(1, 23) = 19.81, p < .001$. Again, both compatibility effects increased as response speed decreased in a linear fashion, the manual

Table 3

Mean Reaction Time (RT, in Milliseconds) and Percentage of Errors (PEs) for Manual and Vocal Responses in Experiment 5 According to Compatibility Between Vocal Response and Manual-Task Stimulus

Response	Compatible		Incompatible		Δ
	RT	PE	RT	PE	
Manual	470	1.6	492	5.8	22
Vocal	600	1.1	639	2.7	39

Note. RT compatibility-effect sizes are presented in the rightmost column.

effect ranging from 1 ms in the first quintile to 43 ms in the fifth.

In the omnibus PE analysis, the main effects of response mode, $F(1, 23) = 6.28, p < .05$, and compatibility, $F(1, 23) = 32.09, p < .001$, and the interaction, $F(1, 23) = 6.69, p < .05$, were all significant. As shown in Table 3, the compatibility effect was larger for manual than vocal responses. However, separate analyses indicated that the effect was significant with both manual, $F(1, 23) = 26.28, p < .001$, and vocal responses, $F(1, 23) = 7.82, p < .01$.

Discussion

These results indicate that the vocal response was activated automatically even in manual-only trials. Although participants knew that only stimulus color was relevant and was to be translated into a left- or right-hand keypressing response, they could not help but prepare the vocal color-word response as well, at least to a certain degree. That is, as expected, the automatic-translation processes indicated by the compatibility effect do not critically depend on dual-task conditions as long as the task context ensures that the participants do not deactivate or forget the S-R mapping rules.

However, the effect was in the same range as in Experiment 4, that is, again much smaller than in Experiment 2. Along the lines of my previous considerations, this reduction may have been due to participants reacting to the task cue by refreshing the task-relevant, but not the irrelevant, set of rules. For instance, presenting a manual cue might have resulted in a refresh of the manual, but not the vocal, set. Consequently, the vocal set was in a substantially less-activated state than in Experiments 1–3, where the vocal response was to be given immediately after the manual one. Under the assumption that the rate of automatic S-R translation varies with the degree of rule activation, the reduced compatibility effect with single responses comes as no surprise.

Alternatively, or in addition to that, participants might have attempted to counteract automatic-translation processes in ways similar to those seen in Experiments 3 and 4. Indeed, although 13 of the 24 participants showed pronounced positive compatibility effects ranging from 6 to 128 ms, the remaining 11 participants exhibited negative effects, 8 of them in the range of –11 to –52 ms. So again, there is

evidence that removing two responses in time leads at least some people to actively suppress the S-R mapping rules belonging to the currently not-needed responses.

General Discussion

The main purpose of the present study was to test the hypothesis that even when two tasks are performed (more or less) serially, the secondary response is activated before the primary response is selected. The reported experiments followed a straightforward logic: If and only if the secondary response is available before primary response selection should the compatibility between the secondary and the primary response, or between the secondary response and the primary stimulus, matter for primary-task performance. In line with this reasoning, pronounced effects of R2-R1 compatibility and of R2-S1 compatibility were observed in Experiments 1 and 2, respectively. As expected, these effects were stronger the slower the primary response was, hence the more likely that S2-R2 translation had already begun. Results also show that automatic translation as indicated by R2-S1 compatibility effects did not depend on very specific task conditions, such as the temporal integrality of S1 and S2 (Experiment 3) or the temporal demands of the secondary task (Experiment 4). As evidenced by Experiment 5, translation even occurred if its outcome was not needed at all on the respective trial. Thus, it can safely be concluded that automatic translation takes place under a considerable variety of conditions and task contexts.³

However, it has also been shown that the effects of backward or intertask compatibility were not immune to task variations. Whereas Experiment 2 produced large effects of more than 100 ms, removing the two responses in time, as was done in Experiments 4 and 5, reduced the effect to about one fifth. Two possible, not necessarily alternative, explanations for this reduction were discussed, one in terms of memory decay and refresh, the other in terms of response suppression. Some direct support for the response-suppression explanation is provided by the observation of negative effects in a substantial number of participants in Experiments 3–5. However, although a single hypothesis seems sufficient to account for the reduction of compatibility-effect sizes with longer delays between R1 and R2, there is no reason to rule out the decay–refresh hypothesis on grounds of the present data. In fact, it may well be that longer delays lead to both rule decay and suppression strategies.

Whatever the limiting conditions for automatic translation may be, it is clear by now that under standard dual-task conditions secondary responses are activated during or even before primary-response selection. This finding is not in agreement with the idea that the bottleneck responsible for dual-task interference prevents concurrent S-R translation. Other findings are much in line with the standard response-selection bottleneck view, though. For instance, the same vocal response that could be made after about 620 ms on average under the single-response condition of Experiment 5 took 542 ms longer to be initiated under the dual-task condition of Experiment 2. It is true that the presence of a delay in Experiment 2 as such is a trivial finding; after all, a

vocal response was counted as incorrect if it was not delayed by at least 50 ms. However, people should be able to perform successive responses with less than 500 ms in between, so that the task instruction is unlikely to account for the huge size of the effect. Likewise, the additional perceptual analysis necessary for the manual task does not explain why the delay was that big. Accordingly, it does not seem unreasonable to attribute the increase in vocal RT under dual-task conditions to some kind of response-selection bottleneck. Moreover, Experiment 3 yielded a result pattern that is very typical for PRP experiments and commonly taken to support bottleneck models: Although primary-task RTs were constant across SOAs, secondary-task RTs produced a function with a slope approaching -1 . In other words, the greater the temporal overlap between the two tasks, the more the second task was delayed—an observation that fits very well with the assumption of a processing bottleneck (e.g., Pashler, 1994a). But however this bottleneck might work, it does not seem to preclude responses from being activated as soon as the associated stimulus is available and analyzed.

As already pointed out in the introduction, one way to deal with the seeming contradiction between backward-compatibility effects indicating parallel processing and huge dual-task interference indicating serial processing is to distinguish carefully between the processes responsible for the activation of responses or response codes and the processes subserving the ultimate selection of responses. Although more research is necessary to elaborate this distinction in sufficient detail, the present results do allow some conclusions as to both response activation and response selection.

Response Activation

In most dual-task or PRP approaches, response selection and response activation are thought to be one and the same

³ Apart from the issue of automatic S-R translation, it should be noted that the observation of backward-compatibility effects provides considerable support for the cross-talk model proposed by Navon and Miller (1987). This model holds that if some perceptual or response-related process in one task activates or produces a code or output that is similar to an output of a concurrent task, this may facilitate performance as compared with code or output dissimilarity. In fact, the present data demonstrate that both primary- and secondary-task performance can be affected by “outputs, throughputs, or side effects” (Navon & Miller, 1987, p. 435) of the respective other task. But more than that, this study’s outcome also demonstrates how important similarity and cross-talk between tasks can be in determining the degree of dual-task interference. Actually, instead of between-task compatibility one may also speak of between-task similarity, inasmuch as compatibility renders the manual and the vocal task more similar to each other than does incompatibility. Although it is clear that this similarity manipulation was not responsible for the huge response-mode effects obtained in the dual-task conditions of Experiments 1–4, it does account for substantial contributions to the overall interference of still up to 161 ms. This suggests that the similarity between tasks may play a much greater role than commonly assumed (e.g., Pashler, 1994a).

thing: Responses are assumed to be selected by activating (the codes representing) them. Yet, there is ample evidence that activated responses need not be executed. For instance, irrelevant stimuli can be shown to activate incorrect responses associated with them enough to produce lateralized readiness potentials (e.g., Coles, Gratton, Bashore, Eriksen, & Donchin, 1985; De Jong, Liang, & Lauber, 1994), electromyographical activity (Eriksen, Coles, Morris, & O'Hara, 1985; Zachay, 1991), or overt, subliminal response tendencies (St. James, 1990; Zachay, 1991), even on trials where the correct response is eventually selected and executed. If response activation is thought to be the result of S-R translation, this implies that S-R translation and response selection are not (necessarily) identical: Although the former is responsible for whether or not response codes are activated, the latter deals with the outcome of all the translations, hence the resulting response-activation pattern. As I have argued, selection may well rely on translation, but this does not mean that all translation processes subserve selection.

According to the two-process approach to dual-task performance proposed in the introduction, response activation does not wait until selection starts but begins right after stimulus identification. As activation is assumed to proceed in parallel, both primary and secondary responses will be activated rather soon, independent of when they are executed. Indeed, although the present results point to some moderating role of temporal factors (i.e., timepoint of rule-memory refresh, response suppression with long R2-R1 delays, or both), the repeated observation of backward and between-task compatibility strongly supports the assumption of immediate, parallel response activation. But how is this parallel activation accomplished?

Two model versions were presented that both would allow S1 and S2 to be translated into their corresponding responses at the same time. The transient-link model assumes that automatic processes use the same memorized rules that guide controlled response selection, but whereas selection is done serially, activation spreads in parallel. The direct-link model assumes two different routes for activation and selection. Whereas controlled translation and selection uses the rules stored in working memory, automatic activation spreads along learned, direct S-R associations. It should be noted that the two versions do not necessarily exclude each other. On the one hand, the transient-link model requires multiple rules to be activated and accessible concurrently, something that is not needed by the direct-link model. On the other hand, however, it may well be that direct S-R associations are formed even though automatic processes can access stored rules in parallel, so that responses receive both direct and rule-mediated activation.

Although the present data do not allow for one or the other model version to be rejected completely, finer grained analyses of practice effects revealed some preliminary evidence against the direct-link model. An important implication of this model is that compatibility effects should increase over practice, because the strength of a direct link between stimulus and response should grow with the number of repetitions of the respective S-R combination.

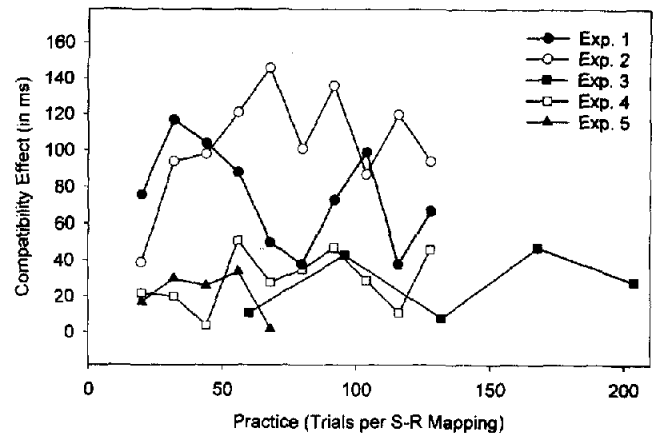


Figure 8. R2-R1 compatibility effects in Experiment (Exp.) 1 and R2-S1 compatibility effects in Experiments 2, 3 (50-ms stimulus onset asynchrony condition), 4, and 5 for the manual task as a function of practice (number of valid trials with each stimulus-response [S-R] mapping). Practice increases in steps of 12 trials per condition, except in Experiment 3, where step size is 36. Abscissa offsets for each curve of 8 or 24 (for Experiment 3) trials reflect practice during the pre-experimental warm-up trials.

Figure 8 shows the relationship between R2-R1 or R2-S1 compatibility and practice. True, all compatibility effects numerically increased from the first to the second data point except in Experiment 4. However, it is also clear that this does not reflect a continuous growth of compatibility effects with practice—in fact, it is only in Experiment 2 that the compatibility effect had its minimum in the very first trials. Moreover, all of these numerical variations were unreliable: ANOVAs run on the individual compatibility effects with practice as a within-subject variable, separately for each experiment, did not reveal any effect ($.15 < p < .88$).

A closer look at the data shows that the lack of practice effects was due to a large degree of interindividual variability, especially in the first trials. Take, for instance, the considerable growth of effect size across the first two data points in Experiment 2. Far from reflecting a general increase of the compatibility effects' magnitudes (a pattern that occurred in 2 participants only, whereas 5 exhibited marked decreases), this growth was due to 4 of 5 participants with pronounced negative effects in the first trials (ranging from -29 to -259 ms) showing positive effects in the following block. As already discussed, negative effects may indicate some kind of response-suppression strategy, which in Experiment 2 could have been confined to the very first trials for some reason. For instance, it might be that in the beginning the secondary response was often activated before the primary one, so that suppressing the secondary response would have helped participants concentrate on the primary task first.

However, even though the issue of individual strategies in dual-task performance clearly deserves further investigation, the mere presence of pronounced compatibility effects in the first trials—be they positive or negative—suggests that S-R rules were used for fast, automatic S-R translation

from the beginning. As similar result patterns were observed in the other experiments, it seems safe to conclude that there is no support for the prediction of the direct-link model that backward-compatibility effects depend on, and increase with, the repetition of S-R combinations. This does not directly confirm the transient-link model but, in the absence of theoretical alternatives, lends some plausibility to it.

Taken together, the present demonstration of between-task compatibility effects strongly suggests that, as proposed in the introduction, translation processes do not represent a bottleneck per se. Of course, this does not imply that people can learn innumerable translation rules at once, but it does suggest that at least two sets of two rules each, the number of rules commonly used in dual-task or PRP experiments, can be held in working memory and used for S-R translation concurrently.

Response Selection

The main characteristic of bottleneck models of dual-task performance consists of the assumption that somewhere in the human information-processing system, there must be a stage or process that can handle only one task at a time. The greater the temporal overlap between the tasks, the more likely this limitation will result in a delay: If the respective stage or process is already occupied by one task, the other comes to a halt. Although several stages and processes have been assessed to see whether they exhibit the sought-after bottleneck-like characteristics, unequivocal evidence for effective serial processing has been found with response-related processes only. Consequently, bottleneck accounts tend to locate the major problems occurring with multiple tasks at what they call the response-selection stage (e.g., Pashler & Johnston, 1989; Welford, 1952).

Although the observations of backward- and between-task-compatibility effects are inconsistent with the standard bottleneck approach to dual-task performance, other aspects of the present data are much more in line with the idea of a bottleneck. The huge delays of the secondary task in Experiment 1 and 2 or the negative relationship between dual-task interference and SOA in Experiment 3 strongly suggest that, even if several S-R rules can be used in parallel for rule-governed response activation, there seems to be a further, serially working mechanism that comes into play before eventual response execution. What kind of mechanism could that be?

The present findings help rule out most of the hitherto proposed alternatives. First, one can reject the assumption of Fagot and Pashler (1992) or McCann and Johnston (1992, first alternative) that the bottleneck may occur because only one S-R rule can be followed at a time: Although the results do suggest huge dual-task interference, translating the secondary stimulus into its corresponding response was certainly not delayed until the primary response was selected. This finding also contrasts with McCann and Johnston's second alternative, holding that only one set of rules can be held in memory at a time. An obvious attempt to save the single-set hypothesis is the argument that the participants in the present study may have effectively transformed the

two sets of rules into one comprising four S-R mapping rules. Although this is difficult to exclude, the implications of such an assumption raise more questions than answers. If participants can integrate different types of rules into a single set that can be held continuously in memory, how should the strong dependency of secondary RT on SOA as observed in Experiment 3 be explained? And why then was the delay of the vocal response in Experiment 2 as compared to Experiment 5 so big? Evidently, the single-set hypothesis cannot account for both dual-task interference and between-task compatibility effects: Either dual-task costs are attributable to the inability to hold in mind the rules for more than one task at a time—then the compatibility effects provide a theoretical problem, or the integration of rules from several tasks must be allowed—then the presence of dual-task interference becomes hard to understand.

Convergent evidence against a (strict) limitation in the number of rules or rule sets comes from the studies of Triggs (1968/1969) and Duncan (1979, Experiment 2). Both had participants respond to two stimuli by performing, with different hands, spatially compatible or incompatible responses. The S-R mapping for the primary and the secondary task varied orthogonally, so that it could be the same for the two tasks (both compatible or incompatible) or differ between tasks (compatible in one, incompatible in the other). Of particular importance, rule consistency had a pronounced effect, hence both primary and secondary responses were faster if the rule was the same for the two tasks than if the rules were different. Moreover, Duncan observed that with inconsistent rules, transformational errors were especially frequent. That is, participants often applied the right rules in the wrong order. These interactions between the two sets of rules suggest that the S-R mapping rules for the secondary task were not retrieved only after primary-task translation was completed, but both sets were held active in working memory at the same time.

Having stricken three items from the four-bottleneck list drawn up in the introduction, we are left with Keele's (1973) hypothesis of a response-initiation bottleneck, and there is nothing in the present results that would stand in opposition to it. However, even proponents of a response-initiation bottleneck have conceded that as a sole account of dual-task interference effects, an initiation model would not work (e.g., De Jong, 1993; Logan & Burkell, 1986). Among other things, such a model would predict underadditive interactions between SOA and factors related to response decision, and the elimination of PRP effects if the primary task does not require an overt response; but what is found is additivity of SOA and decisional factors (e.g., McCann & Johnston, 1992; Pashler & Johnston, 1989) and a slowing of the secondary response even in the no-go conditions of a primary go/no-go task (Bertelson & Tisseyre, 1969; Smith, 1967). Thus, there is reason to assume that the major problem in dual-task performance is not so much with the retrieval of motor programs but rather with some more central process concerned with response selection, which brings us back to where we started.

Because the main concern of the present study was automatic processes—hence, the lack, not the presence, of

seriality—it is hardly surprising that the outcome provides much stronger evidence for where the hypothesized serial bottleneck in multiple-task performance is not than for where it actually is. However, the present findings do help put things in perspective. Most prominent, in view of the hints of a large degree of parallelism in S-R translation and response activation, hence of a rich flow of information, it is noteworthy and perhaps questionable that a common theme of bottleneck approaches to dual-task interference is lack or scarcity: just a single channel between perceptual and response domains, too little working-memory capacity for rule storage, or a slow serial selection mechanism. What if serial processing is not the problem—as the idea of a bottleneck suggests—but the solution, as Neumann (1984) and Van der Heijden (1981) have considered? In fact, the main problem with multiple tasks may not be too little of something, but rather too much, namely too much response information. If translation and response activation are really as automatic as the present results suggest, there often will be more than one response active at a time. This again may pose several kinds of difficulties for response selection, two of which seem to be of special interest for a deeper understanding of multiple-task interference.

First, if people intend to execute responses in a particular order—because they are told to do so or for strategic reasons—multiple response activation creates a decision problem: Which response should be executed first? As both (or, with multiple tasks, all) activated responses are fully valid alternatives in the task, the identity of the response by no means represents a criterion for this decision; what needs to be known is the information responsible for the activation, that is, the stimulus.

Second, multiple response activation may cause a problem for what one may call response-feature integration (see Pashler, 1993, 1994a, for related considerations). As discussed by Hommel (1997, 1998b), responses are likely to be cognitively represented by codes of their perceivable features or effects, so that a response representation may be thought of as a network of response-feature codes. If so, activating a response would mean priming not a single, unitary structure, but rather a number of codes that represent different response features. When two responses are activated at the same time, this means that feature codes belonging to different responses are concurrently active, which creates a problem of response discrimination: How does the action-planning system know which features go together? Again, solving this problem requires information about the source of activation, hence the stimulus.

Both the order and the integration problem—as well as their possible solutions—imply that the processes responsible for response selection cannot be located exclusively in the response system but must be capable of relating stimulus information to response activation. One obvious way to do this is to increase the activation of the correct response by continuously sampling and translating the primary stimulus information (i.e., the information indicating the first response) into response activation until the activation level of one response (most likely the correct one, but not necessarily so) exceeds the activation of its competitors by a certain

amount (Van der Heijden, 1981). This would render response selection a serial process and produce the kind of bottleneck I am looking for. It is important to note, though, that response selection would be serial not because S-R translation provides a processing bottleneck, but because it does not.

⁴ Order-decision problems might occur even when no explicit order instruction is given (as in the present Experiment 3, or in Pashler, 1994b), because SOA variations involving long delays of the second stimulus may tempt participants to respond in the order of the response-associated stimuli (see Koch, 1994, and Meyer et al., 1995, for similar lines of thought).

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