Parallel response selection in dual-task situations via automatic category-to-response translation

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In contrast to the response selection bottleneck theory of dual-task performance, recent studies have demonstrated compatibility effects between secondary and primary responses on Task 1, suggesting that response information for two tasks may be generated in parallel. In two experiments, we examined the nature of Task 2 response activation in parallel with Task 1, using a psychological refractory period paradigm. Evidence of Task 2 to Task 1 response priming when each Task 2 stimulus was unique indicated that automatic parallel generation of response information occurred for Task 2 via abstract semantic category-to-response translation processes, independent of any direct stimulus–response influences. These findings are discussed in terms of their implications for the traditional response selection bottleneck theory of dual-task performance.

The psychological refractory period (PRP) paradigm (Telford, 1931) has long been used by psychologists as a tool for investigating people's ability to perform two tasks concurrently. In a typical PRP task, participants are presented with two stimuli in close temporal succession and are required to make a speeded response to each. The characteristic result in this paradigm is that the reaction time (RT) for Task 2 increases as the stimulus onset asynchrony (SOA) decreases, whereas the RT for the first task remains relatively unaffected by SOA. One common interpretation of this finding is that there exists a central-processing bottleneck in the stage of response selection, such that the selection of an appropriate response to Task 2 cannot begin until this operation is complete for Task 1 (Pashler, 1984). In this sense, PRP findings demonstrate that for at least the response selection stage of processing, people are strictly unable to do two things at once.

Pashler's (1994) response selection bottleneck (RSB) theory of dual-task performance relies on the locus-of-slack logic, which assumes that tasks can be divided into processing stages that are serial and discrete. Processing stages of the two tasks in a PRP paradigm can run in parallel until the response selection stage; here, there is a bottleneck that permits this processing stage to be completed for only one task at a time. The RSB theory therefore proposes that the response selection stages of the two tasks are serial and discrete with respect to each other, and this has generally accounted well for demonstrations of the PRP effect (for reviews, see Pashler, 1994; Pashler & Johnston, 1998).

Challenges to RSB Theory

More recently, several authors have taken an interest in testing this discreteness assumption. Meyer and Kieras

(1997a, 1997b) proposed the executive-process interactive control (EPIC) architecture, which assumes that parallel processing is, in fact, possible in multiple-task performance and that delays in Task 2 performance at short SOAs in PRP studies are due to strategic response deferment. Tombu and Jolicoeur (2002, 2003) and Navon and Miller (2002) have argued for a central capacity-sharing or divisible resource model, in which PRP effects are due to capacity-limited processes that permit graded capacity sharing across tasks, rather than to a strict all-or-none bottleneck.

Cross-talk effects between tasks have also been examined. Logan and Schulkind (2000) presented four experiments demonstrating retrieval of semantic information about their Task 2 stimuli (S2) occurring in parallel with the processing of Task 1 stimuli (S1). They used a PRP paradigm with letter/digit (Experiment 1), magnitude or parity (Experiment 2), or word/nonword (Experiments 3 and 4) discrimination tasks and found that Task 1 RT was shorter when the category of S2 matched the category of S1 (e.g., both were letters) and Task 1 and Task 2 were the same. This finding suggests that participants were able to retrieve the semantic category of S2 early enough that this information was able to facilitate performance for S1. Logan and Delheimer (2001) demonstrated similar results of parallel retrieval in dual tasks involving episodic memory. Fischer, Miller, and Schubert (2007) found evidence of parallel semantic memory retrieval with nonidentical tasks using locus-of-slack logic, rather than looking at cross-talk effects. They found an underadditive interaction between SOA and Task 2 semantic categorization difficulty, such that the effect was present at long SOAs but, at short SOAs, the difference was, presumably, concealed by the slack period while Task 2 waited for access to the

bottleneck. If memory retrieval for S2 categorical information is assumed to be part of the process of response selection, it would appear that this stage can progress for two tasks simultaneously, violating RSB assumptions. However, it is possible that memory retrieval occurs rapidly prior to the more effortful bottleneck stage, and if this is the case, these findings do not violate the discreteness assumption of the RSB theory. In order to challenge this assumption, it would be necessary to demonstrate that actual response information for Task 2, which should not be available prior to the response selection stage, is generated in parallel with Task 1 response selection.

Hommel (1998) was successful in demonstrating that response compatibility across tasks in a dual-task situation could influence performance in the primary task. In a series of experiments, participants were presented with the letter H or S in either red or green. They first had to make a manual left or right response to the color (R1), followed by a verbal response to the letter identity (R2). In Hommel's Experiment 1, participants responded to the letter identity by saying either "right" or "left" (e.g., "right" for H, "left" for S). Hommel found that RTs to the primary manual task were shorter if the secondary task's vocal response was compatible with the primary task's manual response (e.g., left manual response, then say "left"). In subsequent experiments, Hommel also demonstrated compatibility effects between R2 and S1, suggesting that some Task 2 response information was available when S1 information was influencing R1 selection. This set of results was taken as evidence that R2 information was activated while the primary task response was being selected and led Hommel to propose that S2–R2 translation could occur automatically and in parallel with Task 1 response selection.

A more direct test of the RSB theory's discreteness assumption was conducted by Watter and Logan (2006), who suggested that Hommel's (1998) findings could have been due to more semantic or conceptual Task 2 to Task 1 compatibility relationships (e.g., the emphasis on the spatial codes "left" and "right" as both the response location for Task 1 and the verbal response for Task 2) and might not have been a particularly strong test of parallel response activation. Watter and Logan used magnitude (high/low) and parity (odd/even) tasks with single digit stimuli (1–9, excluding 5) in a standard PRP design, with manual response alternatives for each task mapped to the same two fingers for both tasks. Their design allowed them to dissociate the influence of S2 information on R1, generated via Task 1 relevant S2 semantic information derived under Task 1 category mapping rules (akin to a semantic flanker effect), from the potential influence of R2 information on R1. As an example, consider a participant performing a magnitude task as Task 1 presented with the stimulus "9," the correct response for which is to press a key with the index finger. A Task 2 stimulus "7" is presented at a short SOA, well before a Task 1 response has been made. In this case, S2 (7) might facilitate the categorization of S1 (9) as "high" for Task 1, as compared with an other-category alternative Task 2 stimulus of "3." This trial eventually requires a parity decision for S2 (7) as Task 2, the correct response for

which will eventually also be to press a key with the index finger. In this case, while a participant is attending to and actively performing Task 1, prior to the Task 1 response and with S2 present at a short SOA, Task 1 response selection might be primed from compatible Task 2 response information, if such R2 information is being sufficiently generated in parallel with overt Task 1 response selection processes. Watter and Logan found clear evidence of separable semantic and response priming effects on Task 1 performance from Task 2 at short SOAs, suggesting that Task 2 response information was generated in parallel with attended performance of Task 1 response selection.

Miller (2006) provided further evidence of Task 2 response information's exerting an influence on Task 1 performance and extended the findings of previous authors by demonstrating this effect using unrelated tasks. For Task 2 he used a go/no-go task with either auditory (Experiment 1) or visual (Experiment 2) stimuli and found that RTs in the first task were longer when the Task 2 stimulus signaled a no-go response. Similarly, Task 1 RT was lengthened when Task 2 required a complex rather than a simple response. Response information from Task 2 has also been shown to influence the motor output for Task 1, with Miller and Alderton (2006) demonstrating that Task 1 responses were more forceful when a hard, rather than a soft, keypress response was required for Task 2.

Potential Mechanisms of Parallel Response Selection

If Task 2 response information can be generated in parallel with Task 1 response selection in a standard PRP paradigm, the question then arises as to the nature of this R2 information generation. Figure 1 illustrates two general possible mechanisms: Task 2 response activation from specific stimulus representations (stimulus-to-response translation; top panel) and Task 2 response activation from task-relevant semantic category representations (category-to-response translation; bottom panel). The first of these possibilities is equivalent to Hommel's (1998) suggestion of automatic S–R translation. Hommel suggested two potential mechanisms to account for automatic S–R translation. In a *direct-link* model (labeled as path *a* in Figure 1), particular S–R pairs may become associated through experience, with subsequent presentations of S2 giving automatic episodic retrieval of associated R2 information, in parallel with effortful attended performance of Task 1. Hommel equated this with an instance-like account (Logan, 1988), with no need for mapping of S2 to R2 via Task 2 task set rules for this unattended process. In contrast, in a *transient-link* model (labeled as path *b* in Figure 1), stimulus-to-response mapping rules for both Task 1 and Task 2 may be represented concurrently in working memory, with automatic translation of Task 2 stimuli to appropriate responses in parallel with serially limited controlled performance via these mapping rules for Task 1. Hommel suggested that the presence of R2–R1 compatibility effects in early trials in his data, along with a lack of clear practice effects over time, argued against an episodic direct S–R translation account, if not expressly for a transient-link account of automatic S–R translation.

Figure 1. Possible mechanisms of Task 2 response translation in parallel with effortful Task 1 performance in a psychological refractory period dual-task paradigm. Both panels show various routes for generating response information for both tasks, while participants are actively engaged in performing Task 1. The top panel shows relationships between specific stimulus representations and response representations (e.g., for Task 2, a stimulus "tiger" maps to an index finger response); the bottom panel shows relationships between more abstract stimulus category representations and response representations (e.g., for Task 2, a stimulus "tiger" is classified as [living] in an animacy task, and the [living] category maps to an index finger response). Dotted lines represent attended processing in Task 1, to map either a stimulus (top panel) or a category (bottom panel) representation to a response representation via task set rules held online in working memory. Unattended, parallel activation of Task 2 response representations could occur via two possible mechanisms: path *a*, unattended automatic episodic retrieval of response information following association of specific stimulus–response (top panel) or category–response (bottom panel) pairs; or path *b*, unattended automatic translation via task set mapping rules held in working memory, of stimulus (top panel) or category (bottom panel) information to activate response representations. Task 2 response information generated in parallel with overt Task 1 performance might be expected to prime or interfere with response representations of Task 1.

A second general possibility is that Task 2 response information might be automatically activated from semantic category representations of S₂, rather than from specific relationships between S₂ and R₂, illustrated in the lower panel of Figure 1. Such a mechanism would seem to require an additional computational step for an unattended Task 2 stimulus: S₂ would need to activate the appropriate category representation with respect to the Task 2 task set rules (e.g., a stimulus "tiger" would activate a semantic category of "living" in an animacy decision task); and this category representation would need to activate the appropriate response for Task 2. Considering Hommel's (1998) distinction of direct-link versus transient-link S–R processes above, more abstract category-to-response translation might also potentially proceed via episodic learning of specific category–response (C–R) pairs (labeled as

path *a* in Figure 1) or by way of automatic mapping of abstract semantic categories to responses via concurrently represented task set rules (labeled as path *b* in Figure 1).

Some evidence for a role of semantic information in automatic S–R associations has come from a study by Reynvoet, Caessens, and Brysbaert (2002). They obtained response priming for parity judgments on digit stimuli with tachistoscopically presented digit primes, even for primes that were not part of the target set and were, therefore, never associated with a response. Furthermore, this priming persisted when there was no perceptual overlap between the prime and target stimuli, which strongly suggested that the S–R associations were based on the semantic features of the primes. Similarly, in their investigation of the locus of practice effects, Pashler and Baylis (1991) conducted several transfer experiments that demonstrated

that novel items from a learned category benefitted from practice of items learned throughout the experiment. Their results provide evidence for the reinforcement of higher level category-to-response links that may also be detected in dual-task situations.

Although the distinction between episodic accounts of S–R versus C–R response activation seems clear (the same memory processes would be involved, with either specific stimuli or specific category representations acting as retrieval cues), conceptions of automatic category-to-response versus stimulus-to-response translation via working-memory-mediated task-mapping rules may be less distinct. One might generally consider that the mapping of specific stimuli to responses in many situations is achieved via task set rules that map task-salient stimulus features to appropriate response representations; in this situation, mapping of a common feature shared across stimuli to a response might be considered as mapping via a category-like rule, even when these features are primarily perceptual. However, although we might design and describe an experimental task by way of category-mapping rules, a number of different rule representations might actually be used by participants after some experience in performing a task. For example, with a limited number of repeated stimuli, the set of specific S–R mappings for a given task might become individually represented (e.g., for a parity task, 1 = right hand, 2 = left hand, 3 = right hand, etc.), instead of or in addition to a C–R mapping rule (e.g., odd = right hand, even = left hand). In some circumstances, such as with one-to-one mapping of stimuli and responses (as in Hommel, 1998), these relationships would seem to be equivalent, although one might still make a distinction between representations of a specific stimulus versus that stimulus's potential task-relevant category.

The Present Study: Testing Parallel Category-to-Response Translation

In considering these potential mechanisms, it appears that there has been no good test of category-to-response translation in mediating Task 2 to Task 1 response-priming effects. Previous work by Hommel (1998), Miller (2006), and Miller and Alderton (2006) studied these effects with simple S–R mapping tasks in which small sets of stimuli were repeated frequently throughout experiments and did not meaningfully consider potential category-to-response mechanisms. Although Watter and Logan (2006) described the response generation processes for both tasks in terms of stimulus-to-category and then category-to-response activations and empirically distinguished semantic-category- from response-related Task 2 to Task 1 priming effects, two issues prevent meaningful conclusions about potential category-to-response mechanisms. First, frequent stimulus repetition within each task could have led to the development of automatic S–R translation processes (either episodic or via specific S–R rules) independent of mediation via more abstract categories. Second, the use of the same stimuli for Task 1 and Task 2, although orthogonally mapped to different tasks, still resulted in a subset of stimuli being consistently mapped to the same

response for both Task 1 and Task 2. (For example, if a magnitude Task 1 mapped high stimuli to the index finger and a parity Task 2 mapped odd stimuli to the index finger, the stimulus “9” would always require an index finger response for both Task 1 and Task 2, despite different task-mapping rules.) If the immediate S–R relationships (either episodic or rule based) for these consistently mapped stimuli were more strongly learned or represented than for other continually remapped stimuli, this could represent a different potential source of Task 1 response facilitation effects: Although S–R translation for S2 might still occur in parallel with Task 1 response selection, the development of these S–R relationships could occur substantially through experience in Task 1, diluting Watter and Logan's claims about the parallel operation of Task 2 response generation processes.

The goal of the present study was to examine the nature of Task 2 response activation processes occurring in parallel with Task 1 in dual-task situations. As a first step, we sought to more stringently determine whether R2-to-R1 priming could be observed when reliable R2 information could be generated only from stimuli presented exclusively in Task 2. Experiment 1 replicated the cross-task priming PRP design of Watter and Logan (2006), using stimuli that did not overlap between tasks, where response information derived for S2 could only be the result of mapping that stimulus to a response using the Task 2 task set mapping rules.

As a more direct test of specific stimulus-to-response versus category-mediated translation accounts of parallel response activation, Experiment 2 examined whether Task 2 response information could be generated only from semantic category information in parallel with Task 1 response selection, in the absence of any potential direct S–R episodic or specific S–R rule-based translation effects for Task 2. To achieve this, we presented a unique stimulus for S2 on every trial, in addition to having no stimulus overlap between tasks. Task 2 to Task 1 response-priming effects in this situation cannot be attributed to any kind of direct or specific S–R translation, since each S2 stimulus is presented only once; instead, this would be evidence for automatic activation of R2 information from more abstract semantic category information, in parallel with attended performance of Task 1 response selection.

EXPERIMENT 1

In Experiment 1, participants performed a typical PRP task using word stimuli. Task 1 was a size discrimination task; participants were to determine whether a given noun (S1) represented something that was larger or smaller than a computer monitor. For Task 2, they were to judge whether or not S2 represented something that was living or nonliving. The stimulus set for each task consisted of a small number of nouns unique to each task that were repeated within task throughout the experiment.

Method

Participants. Thirty-one undergraduate students from McMaster University (23 females) participated in the experiment in exchange

for partial course credit. All the participants had normal or corrected-to-normal vision, and 28 were right-handed.

Apparatus and Stimuli. The stimuli were 16 five-letter nouns, presented in white on a black background using a ViewSonic Professional series P95f+ monitor that was controlled by a Dell Dimension 4600 computer. Two stimuli were presented on each trial, one above the other in the center of the screen. The participants were seated at a viewing distance of approximately 50 cm, and from this distance, each word stimulus subtended approximately 1° of visual angle in height and 3.5° in width. The vertical separation between the near edges of the two stimuli was approximately 1.5°. The two stimuli were separated in time by an SOA of 0, 200, or 800 msec, and the participants made a response to each stimulus by pressing the “1” or “2” button on the number pad of a standard computer keyboard with either the index or the middle finger of the right hand, respectively.

The participants performed a separate task for each stimulus. As Task 1, they were required to identify whether the top stimulus word (S1) represented a large thing or a small thing (size task). “Large” items were described as being larger than the computer monitor, and “small” items were those smaller than the computer monitor. For Task 2, they judged whether the bottom stimulus word (S2) was alive or not (animacy task). All the stimuli for both Task 1 and Task 2 were unambiguously classifiable under both size and animacy task rules. Importantly, the same 8 of our total of 16 words were always presented only in Task 1, and the other 8 words were always presented only in Task 2. There were an equal number of items in each task category (large vs. small, living vs. nonliving), and these were divided evenly across tasks such that there were 2 words from each of the four dual-category combinations (large/living, large/nonliving, small/living, small/nonliving) in the stimulus set for each task. A one-way ANOVA conducted on the Kučera and Francis (1967) written word frequencies for our stimuli revealed no significant differences among categories [$F(3,12) = 0.70$, $MS_e = 59.15$, $p = .57$].

Procedure. The experiment consisted of 512 trials, made up of eight iterations of the factorial combination of the eight stimuli for Task 1 and the eight stimuli for Task 2, with SOA randomly determined for each trial. Trials were presented in randomized order in 16 blocks of 32 trials each, and the participants were given the opportunity to rest before initiating the beginning of each block. Prior to the experimental trials, the participants completed a practice block of 16 trials that were not included in the analysis. On every trial, a fixation screen was first presented for 500 msec. This display consisted of two rows of two dashes centered on the screen, separated laterally by approximately 5° of visual angle within each row, flanking the locations where S1 and S2 would appear. On 0-msec SOA trials, this display was replaced with a display of S1 and S2 for 1,000 msec, followed by a blank screen for 2,000 msec. Otherwise, the fixation screen was replaced with S1 alone, with S2 accompanying it after the SOA duration. Both stimuli were presented together for 1,000 msec, followed by a blank screen for 2,000 msec. Response mapping for each task was counterbalanced between participants across the index and middle fingers of the right hand.

The participants were told that the experiment was a test of their concentration, to see how quickly and accurately they could perform successive simple tasks. They were told that the size task (Task 1) was most important and was always to be completed first, and it was explicitly stated that they should not wait until the second stimulus appeared before responding to S1. They were instructed to respond as quickly and as accurately as they could to the first (top) stimulus and that only once they had completed their response to this task were they to turn their attention to performing the animacy task. A card attached to the bottom of the computer display served to remind the participants of the response mapping for the tasks. At the end of every block, the participants were informed of their average accuracy and RT for Task 1.

Data analysis. Mean RTs were computed for trials on which both Task 1 and Task 2 were correct. Trials with RTs less than 200 msec

were excluded from analysis, as well as trials with Task 1 RTs over 2,000 msec or Task 2 RTs over 2,500 msec. The data analysis aimed to determine the potential semantic- and response-priming effects of each task on the other. For Task 1, on each trial, we assessed whether S2 was of the same or a different category as S1 with respect to the Task 1 task set rules (i.e., large or small)—a category-level compatibility relationship akin to a semantic flanker effect—and whether the response to Task 2 (R2) was the same as or different from the response to Task 1 (R1). For Task 2, we evaluated the same relationships, now with S1 and S2 compatibility based on their classification under Task 2 task set rules (i.e., living or nonliving), plus the compatibility of R1 and R2. Note that the semantic compatibility relationships may differ between tasks on a single trial (S1 and S2 may be compatible under the Task 1 rules, but not according to the Task 2 rules, and vice versa), but response compatibility is necessarily consistent across tasks on a given trial. Task 1 and Task 2 semantic and response compatibility relationships were evaluated across all SOAs. Mean RTs for Task 1 and Task 2 were submitted to separate 2 (semantic compatibility) $\times$ 2 (response compatibility) $\times$ 3 (SOA) repeated measures ANOVAs, with all variables treated as within-subjects factors.

Although the participants were instructed to give priority to completing Task 1 prior to performing Task 2, it is possible that, on at least some trials, the participants may have withheld responding and considered their responses to both tasks prior to making their response to Task 1. In this situation, priming of a Task 1 response from Task 2 response information would not require any degree of parallel response activation. To test for this possibility, we examined mean Task 1 RTs for our shorter SOA conditions (0 and 200 msec), separated by interresponse interval (IRI) quintile. Separate 2 (semantic compatibility) $\times$ 2 (response compatibility) $\times$ 5 (IRI) repeated measures ANOVAs were conducted, with all variables treated as within-subjects factors.

Error rate data represent participants' combined performance on both tasks. Errors were coded according to the Task 1 categories of semantic and response compatibility for each trial, given our primary focus on Task 1 performance under the influence of Task 2 information. Coding errors according to the Task 2 conditions reallocate half of the trials in the semantic categories but do not affect the response classification, since response compatibility is consistent across tasks. Evaluating accuracy on the basis of the Task 2 conditions did not alter our results, so we report only the accuracy data coded via Task 1 conditions here. The participants' combined error rate data were submitted to three-way repeated measures ANOVAs identical to those used for primary RT analyses.

Results

Data from 5 participants were excluded from analysis due to overall error rates greater than 30%. An additional participant was excluded for having overall RTs that were more than three standard deviations longer than the average for the participant group. RT trimming for the remaining 25 participants removed an average of 2.9% of the trials from each participant's data set.

Mean RTs for trials on which responses to both tasks were correct are presented for Task 1 and Task 2 in Figure 2. A PRP effect was observed, with RTs decreasing with increasing SOA in Task 2; Task 1 RTs were relatively flat across SOAs, although some speeding of RT with longer SOAs was also observed here. For Task 1, response compatibility effects were apparent at 0- and 200-msec SOAs, with response-compatible trials faster than response-incompatible trials, although this effect appeared less distinct at the 800-msec SOA. These observations were supported by a main effect of response compatibility [$F(1,24) = 7.54$, $MS_e = 2,160.94$, $p < .05$]. The

Figure 2. Reaction time (RT) data for Experiment 1. The left panel shows mean RT data for Task 1 and Task 2, and Task 1 data are presented at a larger scale in the right panel. Data are separated by combinations of semantic-compatible (Sem^+) and -incompatible (Sem^-) and response-compatible (Resp^+) and -incompatible (Resp^-) conditions. Error bars represent standard errors and are representative of the standard errors in all the conditions within a given task. Critical Task 2 to Task 1 response compatibility effects are demonstrated in Task 1 data, with response-compatible trials (Resp^+ , solid lines) faster than response-incompatible trials (Resp^- , dashed lines), most evident at 0- and 200-msec stimulus onset asynchronies.

pattern of response compatibility relationships appeared to interact with semantic compatibility, although this effect was marginal [$F(1,24) = 3.92$, $MS_e = 3,674.89$, $p = .059$]. There was no main effect of semantic compatibility, nor other interactions involving this factor. Observed variability in overall RT across SOAs also produced a significant main effect of SOA [$F(2,48) = 4.36$, $MS_e = 19,740.83$, $p < .05$].

Similar results were observed for Task 2. An expected strong main effect of SOA was observed [$F(2,48) = 807.93$, $MS_e = 8,026.45$, $p < .001$]. In addition to a main effect of response compatibility [$F(1,24) = 4.43$, $MS_e = 4,329.26$, $p < .05$], the interaction between response compatibility and semantic compatibility was also significant [$F(1,24) = 35.62$, $MS_e = 5,322.77$, $p < .001$], reflecting faster performance for all-compatible (semantic- and response-compatible) and all-incompatible (semantic- and response-incompatible) trials, as compared with mixed-compatibility trials across SOAs.

Mean RT data for Task 1, separated by IRI quintile, are presented in Figure 3. There was little evidence of Task 1 response compatibility effects being due to withholding of Task 1 responses while Task 2 responses were considered. The response compatibility effect and interactions of response and semantic compatibility were observed across IRI quintiles, with little overall RT difference observed across quintiles. At the 0-msec SOA, these observations were supported by significant interactions of semantic and response compatibility [$F(1,24) = 4.59$, $MS_e = 10,474.16$, $p < .05$] and of response compatibility and IRI quintile [$F(4,96) = 2.49$, $MS_e = 8,755.67$, $p < .05$], both modifying a marginal main effect of response compatibility [$F(1,24) = 2.96$, $MS_e = 8,619.90$, $p = .099$]. At the 200-msec SOA, there was a main effect of response compatibility [$F(1,24) = 10.28$, $MS_e = 5,139.60$, $p < .01$], with an interaction of semantic compatibility and IRI quintile [$F(4,96) = 2.89$, $MS_e = 10,010.36$, $p < .05$].

Figure 3. Task 1 reaction time (RT) data for Experiment 1, separated by interresponse interval (IRI) quintile. Mean RT is plotted over IRI quintiles for each stimulus onset asynchrony (SOA) separately, for combinations of semantic-compatible (Sem^+) and -incompatible (Sem^-) and response-compatible (Resp^+) and -incompatible (Resp^-) conditions. At shorter SOAs (0 and 200 msec), RTs for response-compatible conditions at smaller IRI quintiles were equivalent to or shorter than RTs at larger IRI quintiles, suggesting that critical Task 2 to Task 1 response compatibility effects were not due to strategic delaying or grouping of Task 1 responses.

Table 1
Mean Dual-Task Error Rates (% Error) and Standard Errors of
the Means (SEMs) for Experiments 1 and 2

SOA	Sem ⁺				Sem ⁻			
	Resp ⁺		Resp ⁻		Resp ⁺		Resp ⁻	
	% Error	SEM	% Error	SEM	% Error	SEM	% Error	SEM
Experiment 1								
0	7.60	0.02	9.41	0.02	14.83	0.03	4.28	0.01
200	5.56	0.02	7.69	0.01	14.38	0.02	3.44	0.01
800	5.03	0.01	6.66	0.01	12.85	0.02	2.82	0.01
Experiment 2								
0	14.92	0.02	11.21	0.01	18.69	0.02	6.54	0.01
200	11.77	0.01	8.78	0.01	15.79	0.02	7.97	0.01
800	10.36	0.01	7.98	0.01	14.90	0.02	5.74	0.01

Note—Data are divided by semantic-compatible (Sem⁺) or -incompatible (Sem⁻) and response-compatible (Resp⁺) or -incompatible (Resp⁻) trials and by stimulus onset asynchrony (SOA). Error rates reflect errors on either Task 1 or Task 2 of a particular trial; most errors were committed on overt Task 2 performance.

.05], modifying a marginal main effect of IRI quintile [$F(4,96) = 2.01$, $MS_e = 22,599.54$, $p = .099$].

Mean combined Task 1 and Task 2 error rate data are summarized in Table 1. Although error rates were determined on a trial-wide basis including both tasks, more than 75% of the errors were observed to arise from overt performance of Task 2. In general, accuracy of performance was consistent with the RT data. Main effects of response compatibility [$F(1,24) = 17.70$, $MS_e = 0.001$, $p < .001$] and semantic compatibility [$F(1,24) = 17.26$, $MS_e = 0.008$, $p < .001$] were modified by an interaction between these two factors [$F(1,24) = 24.99$, $MS_e = 0.011$, $p < .001$]. All-compatible and all-incompatible trials were more accurate than mixed-compatibility trials across SOAs. Accuracy also increased with SOA, as demonstrated by a main effect of SOA [$F(2,48) = 3.29$, $MS_e = 0.004$, $p < .05$].

Discussion

Task 1 to Task 2 priming was expected and unsurprising here, since explicit Task 2 performance was deliberately constrained to follow Task 1 performance in series. Our primary focus was on whether Task 2 response information was being generated early enough and in parallel with overt Task 1 performance to influence Task 1 response selection. The results from Experiment 1 replicated those of Watter and Logan (2006), who demonstrated the influence of Task 2 response information on Task 1 responses at early SOAs. Importantly, our present data replicated their findings using separate stimulus sets for each task, suggesting that this critical R2-to-R1 priming effect is not driven by stimuli with identical S–R mappings across tasks. These findings support the notion that Task 2 response information can be generated from S2 in parallel with overt performance of Task 1 response selection and that this can occur when S2–R2 relationships can be derived only under Task 2 task set rules.

Analysis of Task 1 RT over IRI quintiles did not support the possibility that the Task 1 response compatibility effects were due to delaying or withholding of Task 1 responses. Mean RTs for response-compatible trials at

smaller IRI quintiles were observed to be equivalent to or shorter than RTs at larger IRI quintiles, with response-incompatible trials at earlier quintiles markedly slower. If our Task 1 compatibility effects were due to delaying of Task 1 responding and grouping of Task 1 and Task 2 responses, one would expect to observe response compatibility effects at short IRIs with a marked increase in overall Task 1 RT, relative to trials at longer IRIs. We observed no evidence of such Task 1 delaying or response grouping in this experiment, strengthening our claims of parallel response activation.

Although error rates were somewhat higher than in some more traditional PRP studies, they were extremely comparable to those in other PRP studies, such as Watter and Logan (2006), using stimuli and tasks with similarly high degrees of potential cross-task priming and interference. Errors were much more frequently observed in mixed-compatibility conditions, with a large majority of these committed on overt Task 2 performance. This pattern of data suggests that the participants were focusing on Task 1 and achieving relatively accurate overall Task 1 performance, with interference arising from semantic and response compatibility relationships plus the overt Task 1 response manifesting as more errorful responses on Task 2.

What is not clear from this experiment is whether this unattended parallel S2-to-R2 generation process is a result of learning and subsequent automatic retrieval of particular S–R pairs from a given S2 (akin to Hommel's [1998] direct-link model of automatic S–R translation), whether R2 is being automatically generated via specific S–R mapping rules in working memory (akin to Hommel's [1998] transient-link model of automatic S–R translation), or whether more abstract category-to-response versions of these episodic or rule-based mechanisms might be involved. Since there were only eight Task 2 stimuli in this experiment, the participants encountered each S2 word 64 times over the experimental session. It would not be surprising if the participants were capable of learning specific S–R associations for each Task 2 stimulus within the course of this experiment (as in Watter & Logan,

2006), with unattended retrieval and activation of R2 directly from S2 in parallel with overt Task 1 performance; similarly, this situation could be conducive to developing specific S–R mapping rules.

It would be potentially more interesting if participants could generate R2 information from S2 in parallel with Task 1 response selection without any influence of previously acquired S–R learning or specific S–R task rule development for Task 2. Such a finding would suggest that Task 2 response information was being generated from semantic category information from S2—possibly as a more abstract episodic form of automatic translation of C–R associations or as an unattended implementation of category-to-response mapping rules.

EXPERIMENT 2

Experiment 2 explicitly examined whether Task 2 response information could be generated from S2 in the absence of any previously experienced S–R pairs. We employed a very large Task 2 stimulus set, again separate from Task 1 stimuli as in Experiment 1, with the same strict cross-task semantic- and response-priming PRP method. Participants encountered each S2 only once throughout the experiment. As such, any Task 2 to Task 1 response priming observed must be due to participants' ability to activate R2 information from the semantic category of a unique S2 stimulus, in parallel with overt performance of Task 1. Such a finding would go beyond prior S–R accounts (e.g., Hommel, 1998) and would suggest that parallel automatic response activation is substantially mediated via semantic category representations.

Method

Participants. Forty-eight undergraduate students (26 females) participated in the experiment in exchange for partial course credit. All the participants had normal or corrected-to-normal vision, and 33 were right-handed.

Apparatus and Stimuli. The computer apparatus and tasks performed by the participants were the same as those in Experiment 1. The stimuli were 240 nouns, which included the 16 words making up the stimulus set for the previous experiment. The same 8 words were used for Task 1, and the stimulus set for Task 2 was made up of the remaining 232 words. Again, all the words were distinctly classifiable under the task set rules for each task. There were an equal number of words in each task set category (large/small, living/nonliving), as well as an equal number of dual-category combinations in both Task 1 and Task 2. Two separate one-way ANOVAs revealed no significant differences in word length [$F(3,236) = 1.56$, $MS_e = 3.91$, $p = .20$] or Kučera and Francis (1967) written word frequency among categories [$F(3,236) = 2.20$, $MS_e = 437.18$, $p = .09$].

Procedure. The experiment consisted of 232 trials, divided into seven blocks of 30 trials and a final block of 22. Each Task 2 item was presented only once and in random order; the eight Task 1 stimuli were iterated 29 times to create a complete stimulus set and then were presented in random order over the 232 trials. Before the experiment began, the participants were informed of the two tasks and completed a practice block of 24 trials. The Task 1 stimuli for the practice block were the same as those used throughout the experiment, and the stimuli for Task 2 were an additional 24 unique words not used in the experimental trials. All other aspects of stimulus presentation and response mapping were identical to those in Experiment 1. The priority of Task 1, as well as strict serial performance of the two tasks, was again emphasized to the participants at length. RT and error rate data were analyzed as in Experiment 1.

Results

Mean RTs were computed for trials on which both Task 1 and Task 2 were correct. Data from 7 participants were excluded from analysis due to overall error rates of more than 30%. Data from an additional participant were excluded because of RTs that were more than three standard deviations longer than the average for the group. RT trimming removed an average of 2.4% of the trials from each of the remaining 40 participants.

Mean RT data for Task 1 and Task 2 are presented in Figure 4. Once again, a PRP effect was observed, with RTs decreasing with increasing SOA in Task 2; Task 1 RTs were relatively flat across SOAs, although some speed-

Figure 4. Reaction time (RT) data for Experiment 2. The left panel shows mean RT data for Task 1 and Task 2, and Task 1 data are presented at a larger scale in the right panel. Data are separated by combinations of semantic-compatible (Sem+) and -incompatible (Sem-) and response-compatible (Resp+) and -incompatible (Resp-) conditions. Error bars represent standard errors and are representative of the standard errors in all the conditions within a given task. Critical Task 2 to Task 1 response compatibility effects are demonstrated in Task 1 data, with response-compatible trials (Resp+, solid lines) faster than response-incompatible trials (Resp-, dashed lines), most evident at the 200-msec stimulus onset asynchrony.

ing of RT with longer SOAs was also observed here. For Task 1, response compatibility effects were clearly observed at the 200-msec SOA, with response-compatible trials faster than response-incompatible trials. This pattern appeared to be numerically present at the 0- and 800-msec SOAs but was much less distinct. These observations were confirmed by a significant main effect of response compatibility [$F(1,39) = 9.92$, $MS_e = 4,598.74$, $p < .01$], with a significant interaction of response compatibility with SOA [$F(2,78) = 3.17$, $MS_e = 3,763.96$, $p < .05$]. The main effect of SOA was significant [$F(2,78) = 14.36$, $MS_e = 31,505.34$, $p < .001$], with no significant main effect or interactions of semantic compatibility ($F_s < 1$).

Task 2 RT data revealed an expected strong main effect of SOA [$F(2,78) = 917.22$, $MS_e = 11,795.59$, $p < .001$]. Evidence of both semantic and response compatibility relationships was observed. As in Experiment 1, all-compatible and all-incompatible trials were faster than trials with mixed semantic and response compatibility, supported by interactions of semantic and response compatibility [$F(1,39) = 33.89$, $MS_e = 7,081.21$, $p < .001$] and of response compatibility and SOA [$F(2,78) = 5.49$, $MS_e = 5,880.60$, $p < .01$], with a marginal three-way interaction [$F(2,78) = 2.63$, $MS_e = 5,214.51$, $p = .079$].

Mean RT data for Task 1, separated by IRI quintile, are presented in Figure 5. Mean RTs appeared to vary systematically with IRI, with an approximate 100-msec increase in mean RT over the longest to shortest IRI quintiles for most conditions at the 0- and 200-msec SOAs. Task 1 compatibility effects were not limited to short IRI quintiles: For the 0-msec SOA, patterns of semantic and response compatibility effects were most evident at the third and fourth IRI quintile; for the 200-msec SOA, a strong response compatibility effect was present over all quintiles. These observations were supported at the 0-msec SOA by a main effect of IRI quintile [$F(4,152) = 7.49$, $MS_e = 20,855.83$, $p < .001$] and a significant three-way interaction of semantic compatibility, response compatibility, and IRI quintile [$F(4,152) = 2.63$, $MS_e = 18,224.25$, $p < .05$]. At the 200-msec SOA, there was a main effect of IRI quintile [$F(4,152) = 9.15$, $MS_e = 27,706.97$, $p < .001$] and a main effect of response compatibility [$F(1,38) = 18.09$, $MS_e = 20,020.11$, $p < .001$]. There was no interaction of response compatibility and IRI quintile [$F(4,152) = 0.28$] and no other effects or interactions (all $F_s < 1.5$).

Error rate data representing the combined errors for both tasks are displayed in Table 1. These data were once again coded according to the Task 1 categories of semantic and response compatibility. As in Experiment 1, although errors on either task excluded a whole trial as errorful, more than 70% of the errors were observed to arise from overt performance of Task 2. Analysis revealed a main effect of response compatibility [$F(1,39) = 30.93$, $MS_e = 0.016$, $p < .001$], with response-compatible trials less accurate, overall, than response-incompatible trials. This effect was modified by an interaction with semantic compatibility [$F(1,39) = 15.75$, $MS_e = 0.008$, $p < .01$], indicating that for a given level of response compatibility, the participants were less errorful when semantic compat-

Figure 5. Task 1 reaction time (RT) data for Experiment 2, separated by interresponse interval (IRI) quintile. Mean RT is plotted over IRI quintiles for each stimulus onset asynchrony (SOA) separately, for combinations of semantic-compatible (Sem⁺) and -incompatible (Sem⁻) and response-compatible (Resp⁺) and -incompatible (Resp⁻) conditions. Critical Task 2 to Task 1 response compatibility effects at the 200-msec SOA were observed across all IRI quintiles, with overall RTs comparable to those in Experiment 1, suggesting that these effects were not due to strategic delaying or grouping of Task 1 responses.

ibility was similarly compatible or incompatible, as compared with mixed-compatibility conditions. Consistent with Experiment 1, accuracy also improved across SOA [$F(2,78) = 8.01$, $MS_e = 0.005$, $p < .01$].

Discussion

The purpose of Experiment 2 was to investigate whether the Task 2 to Task 1 response priming effects observed in Experiment 1 and in Watter and Logan (2006)—and perhaps also in other studies (e.g., Hommel, 1998; Miller, 2006; Miller & Alderton, 2006)—were caused solely by effects of specific S–R associations (either episodic or task set mediated) for Task 2 stimuli, or whether R2 information might be generated in parallel via more abstract category-to-response processes. In Experiment 2, the participants were presented with a novel S2 on every trial, which eliminated any opportunity for direct S–R episodic or specific S–R mapping effects for Task 2. In our RT data, Task 2 to Task 1 response-priming effects were still evident, as demonstrated by faster performance in Task 1 on response-compatible trials than on response-incompatible trials, primarily at the 200-msec SOA. Analysis of Task 1

RT data over IRI quintiles again suggested that our findings of response priming from Task 2 to Task 1 were not the result of participants' withholding their response to Task 1 until they had calculated a response to Task 2, with the primary R2-to-R1 compatibility effects at the 200-msec SOA observed consistently across all IRI quintiles, with mean RTs comparable to those in Experiment 1. Overall, our RT data suggest that the participants were able to extract semantic information regarding the animacy of a novel S2 and have the resulting category representation (living or nonliving) activate the appropriate Task 2 response, while they were simultaneously engaged in actively performing Task 1 response selection.

Although our error results suggested a different pattern of interaction between semantic and response compatibility than in Experiment 1, these data were composed mostly of errors committed on Task 2 and, as such, likely reflect cross-task priming and interference from Task 1 information on Task 2 performance with novel stimuli. The slightly higher observed error rate for Experiment 2 may reflect the additional difficulty of responding to all novel Task 2 stimuli; this said, these error rates are comparable to those observed by Watter and Logan (2006) using PRP designs with similarly high degrees of semantic and response overlap between tasks.

Several possible mechanisms might be considered for the parallel generation of Task 2 response information from S2 semantic information. One possibility is that category-to-response relationships in Task 2 could be learned and, subsequently, automatically recalled in parallel with overt Task 1 response selection, akin to the specific stimulus-to-response learning suggested by Hommel (1998) as the basis of his direct-link translation model of parallel response activation, comparable to an instance-like account (e.g., Logan, 1988). In this case, stimulus category representations (e.g., living or nonliving in our present Task 2) would need to become sufficiently and consistently activated from a succession of unique S2 stimuli, so that particular C–R pairings could be encoded sufficiently well. Subsequent presentations of new S2 stimuli would need to generate appropriate and sufficient semantic category representations, which could act as retrieval cues for associated response information. The retrieval mechanism here is no different from the episodic description offered by Hommel for his direct-link account of automatic S–R translation. Our present situation would require the additional abstraction of semantic category information from individual stimuli and the learning of an association of this more abstract representation and a response, and would require that this more abstract representation be able to be activated and then act as a retrieval cue from a succession of novel stimuli, all while participants are effortfully attending to and performing a different, separate task.

An alternative to this account is consistent with a more comprehensive version of Hommel's (1998) transient-link model, where task sets of both tasks are maintained in working memory, with unattended and automatic stimulus to response translation via these mapping rules in parallel with controlled Task 1 performance. Importantly, task set

representations would have to allow translation of response information from abstract semantic category representations, without any need for direct or specific S–R mediation. This kind of account could be more fully aligned with alternative models of dual-task performance, such as Navon and Miller's (2002) resource model, Tombu and Jolicoeur's (2002, 2003) central capacity-sharing model, Meyer and Kieras's (1997a, 1997b) strategic response deferment model, or Logan and Gordon's (2001) executive control of theory of visual attention model, all of which allow true parallel computation of responses for two concurrent tasks to some degree. All of these possibilities, including an automatic category-to-response (C–R) adaptation of Hommel's episodic direct-link model, have potential implications for the traditional RSB model and for our conception of *response selection* in general and are considered further in the General Discussion section below.

Although Experiment 2 most importantly demonstrated the critical effect of Task 2 to Task 1 response compatibility, several differences were noted, as compared with the data from Experiment 1. Although semantic compatibility effects from S1 were observed in Task 2 RTs, no semantic compatibility effects of S2 were observed on Task 1 performance in Experiment 2. In our Experiment 1 and in Watter and Logan (2006), this S2-to-R1 effect reflects the ability of Task 1 related semantic category information from S2 to contribute to Task 1 categorization of S1, on the basis of Task 1 task set rules. The lack of S2-to-R1 influence in Experiment 2 is not surprising, considering that every S2 stimulus was unique; in Experiment 1 and Watter and Logan, repetition of a small set of S2 stimuli may have increased the degree to which Task 1 related semantic information was extracted from S2 during attended performance of Task 1. The continued presence of semantic compatibility effects from S1 on R2 in Experiment 2 with repeated S1 stimuli is consistent with this interpretation.

As a second contrast, our critical Task 2 to Task 1 response compatibility effects were observed convincingly only at the 200-msec SOA in Experiment 2, as compared with both earlier SOAs in Experiment 1. Considering that the same tasks were used in both experiments, with comparable Task 1 RTs across experiments, the unique versus repeated nature of our Task 2 stimuli would appear to be responsible for this difference in time course. To more closely examine this issue, we conducted an additional ANOVA on Task 1 RT data from both Experiments 1 and 2, with experiment as a between-subjects variable. There were strong main effects of both response compatibility [$F(1,63) = 14.45$, $MS_e = 3,710.18$, $p < .001$] and SOA [$F(2,126) = 15.20$, $MS_e = 27,005.75$, $p < .001$]. Semantic and response compatibility factors interacted [$F(1,63) = 3.98$, $MS_e = 4,316.27$, $p < .05$], and the interaction of response compatibility with SOA was marginal [$F(2,126) = 2.53$, $MS_e = 3,098.26$, $p = .084$]. No significant effects or interactions involving the experiment factor were observed (all $F_s < 1$), aside from the nonsignificant interaction of experiment, semantic compatibility, and SOA [$F(2,126) = 1.87$, $MS_e = 3,736.28$, $p = .158$].

These results suggest that the pattern of Task 2 to Task 1 response priming across SOAs and the effect of semantic priming were not significantly different in the two experiments. This analysis also has potential implications for the role of the repeated stimuli used in Experiment 1. Presumably, since every Task 2 stimulus was repeated several times throughout Experiment 1, automatic response activation for Task 2 may have occurred via either direct S–R translation (whether episodic or rule based) or more abstract semantic-category-mediated translation (again, either through learned, episodic C–R links or concurrently represented task rules). In Experiment 2, using all novel stimuli, automatic generation of Task 2 response information was possible only through category-mediated representations. Since the nature of the response compatibility effect did not appear to differ across experiments, we cannot comment specifically on the influence of specific S–R translation in Experiment 1. It is possible that even with repeating stimuli and the opportunity to learn direct S–R links via episodic or rule-based translation, participants in fact make use of more abstract category-to-response translation.

GENERAL DISCUSSION

The goal of the present study was to investigate the nature of R2 information generated in parallel with Task 1 response selection in dual-task situations. Experiment 1 ruled out the possibility that R2-to-R1 compatibility effects demonstrated previously by Watter and Logan (2006) were caused by strong S–R representations that developed primarily through experience in Task 1. By employing a unique stimulus set for each task, we were able to demonstrate R2-to-R1 priming when R2 information could be reliably generated only on the basis of the identity of S2 on any given trial, independent of any S1-to-R1 learning or Task 1 mapping rules. Experiment 2 more directly examined the nature of this unattended generation of R2 information from S2, demonstrating R2-to-R1 compatibility effects when a unique S2 stimulus word was presented on every trial. This suggests that R2 information must have been generated from more abstract semantic category information from S2 on every trial, in the absence of any opportunity for direct S–R episodic or specific S–R rule-based influences.

As was outlined in the discussion of Experiment 2 above, several potential mechanisms might be considered to account for the unattended generation of R2 information from S2 category information in parallel with Task 1 response selection—namely, an episodic C–R learning process, akin to Hommel's (1998) direct-link framework for automatic S–R translation, versus a more rule-based, nonepisodic but still automatic mapping of activated category representations to appropriate responses. This second account could be conceived of as a more general interpretation of Hommel's transient-link model of automatic S–R translation, where R2 information is generated from the semantic category of S2, rather than mapping directly from S2 to R2. Although our present study cannot readily distinguish between these possible alternatives,

both possibilities raise interesting questions regarding the nature of dual-task-processing architectures.

An automatic C–R translation account, with episodic category-to-response associations akin to Hommel's (1998) direct-link model, would seem to be more alignable with a traditional RSB account of dual-task performance (Pashler, 1994; Pashler & Johnston, 1998). To make a case to best preserve RSB theory, one might argue that Task 2 response information derived via an episodic process from S2, in parallel with controlled performance of Task 1 response selection, would not meaningfully violate any assumptions of the RSB model. In such a case, the process of mapping stimulus information onto an appropriate response would still be serial and discrete between tasks, with the observed R2-to-R1 compatibility effects considered as an interesting but separate and independent mechanism to response selection.

As was discussed by Hommel (1998) and Watter and Logan (2006), the traditional response selection process might be better conceived as a succession of separate response activation and subsequent response selection processes, the latter of which might still be considered as serial and discrete. Hommel suggested that in this situation, response activation potentially begins as soon as stimulus information is available and proceeds in parallel for both tasks in a dual-task situation. Hommel discussed this parallel response activation primarily within the context of specific S–R translations, but the results of our Experiment 2 demonstrate this same parallel response activation with R2 information generated via abstract semantic category-to-response processes. If these rapid automatic C–R translations are the result of multiple task set mappings being held active in working memory and leading to the activation of multiple responses in parallel, our results may be considerably more disruptive to the traditional RSB theory.

The latter possibility would seem to reduce both the extent and scope of what it is that a classical notion of response selection is required to do. As was discussed by both Hommel (1998) and Watter and Logan (2006), if response information is typically generated for both tasks in parallel, response selection may be more a process of response gating than an obligatory and heavily computational process. These authors and others (e.g., Logan & Gordon, 2001; Meyer & Kieras, 1997a, 1997b) have also discussed a number of methods by which variably selective serial performance typified by overt bottleneck-like dual-task performance might be a functional solution to inherently parallel dual-task response computation, by allowing a mechanism for resolving cross-task interference, preventing collision of incompatible peripheral actions, and by providing a mechanism for S–R binding with multiple concurrent tasks.

The present study suggests that beyond the repeated-stimulus parallel response priming of Watter and Logan (2006), and beyond the specific S–R accounts of parallel response activation of Hommel (1998), Miller (2006), and Miller and Alderton (2006), parallel generation of response information in dual tasks is substantially mediated via abstract semantic-category-to-response relation-

ships. These findings extend other evidence for automatic semantic-to-response mediation of S–R priming effects (Reynvoet et al., 2002) in dual-task situations, operating in parallel in the unattended task. These findings provide interesting converging evidence for the arrangement of human central information-processing architecture and suggest, along with the results from the other authors cited here, that the classical conception of response selection needs to be reconsidered.

AUTHOR NOTE

This research was supported by Natural Sciences and Engineering Research Council of Canada (NSERC) Grant 327454 to S.W. and by an NSERC postgraduate scholarship (PGS-D) and an Ontario Graduate Scholarship to S.J.T. We are grateful to members of McMaster University's Cognitive Science Laboratory for assistance with data collection, and to Bruce Milliken and Karin R. Humphreys for useful discussions about this work. Correspondence concerning this article should be sent to S. J. Thomson or S. Watter, Department of Psychology, Neuroscience and Behaviour, McMaster University, 1280 Main Street West, Hamilton, ON, L8S 4K1 Canada (e-mail: thomsosj@mcmaster.ca or watter@mcmaster.ca).

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(Manuscript received May 5, 2009;
revision accepted for publication May 3, 2010.)