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BRIEF REPORT

Constraints in Task-Set Control: Modality Dominance Patterns Among Effector Systems

Lynn Huestegge and Iring Koch
RWTH Aachen University

Flexibility in configuring task sets allows people to adequately respond to environmental stimuli in different contexts, such as in dual-task situations. In the present study, we examined to what extent response control is influenced by the modality of a concurrently executed response. In Experiment 1, participants responded to auditory stimuli with either vocal responses and/or saccades. In Experiment 2, vocal responses were combined with manual responses. In both experiments, we found asymmetric dual-response costs, that is, the response time difference between single- and dual-response conditions varied between response modalities. It is important to note that the same (vocal) response showed substantial dual-response costs when combined with saccades (Experiment 1) but no such costs when combined with manual responses (Experiment 2). Experiment 3, combining saccades with manual responses, revealed stronger dual-response costs for manual responses than for saccades. Together, these findings suggest an ordinal dominance pattern among response modalities, representing flexible, response-based resource scheduling during task-set configuration.

Keywords: cognitive control, attention, dual-task performance, task sets, resource scheduling

Most stimuli are fundamentally ambiguous with respect to their functional importance for people's current behavioral goals. To adequately respond to environmental cues in different contexts, people need to flexibly adapt behavior on the basis of intentions and tasks. The cognitive representation of a task, the task set (e.g., Jersild, 1927; Rogers & Monsell, 1995), specifies task-relevant stimuli, responses, and their mapping (see also Allport, Styles, & Hsieh, 1994; Monsell, 1996).

Task-set configuration is typically studied in experimental paradigms involving different task requirements, for example, task switching (e.g., Kiesel et al., 2010; Monsell, 2003), the execution of two tasks with variable temporal overlap (psychological refractory period [PRP] paradigm; Pashler, 1994; Welford, 1952), or the execution of simultaneously triggered responses (dual-task paradigm; e.g., Fagot & Pashler, 1992). Generally, these paradigms demonstrated that behavioral demands involving more than one set of responses are associated with performance deficits (multitasking costs).

It is interesting that multitasking costs are often asymmetric, that is, one of the two tasks is subject to more interference than the other. For example, research using the dual-task paradigm typically revealed smaller costs for the faster (vs. slower) response (Holender, 1980; Schumacher et al., 2001; Stelzel, Schumacher, Schubert, & D'Esposito, 2006). This cost asymmetry was even present when two responses were triggered by the same aspect of a single stimulus (redundant-response task; Fagot & Pashler, 1992; Huestegge & Koch, 2009, 2010). Likewise, varying the stimulus onset asynchrony (SOA) in the PRP paradigm revealed that shorter SOAs usually prolong response times (RTs) in the second but not in the first response (i.e., the PRP effect; Pashler, 1994). The PRP effect is hypothesized to occur due to a modality-unspecific response selection bottleneck (RSB) that can only be devoted to one task at a time, such that the second task sometimes has to wait to gain access to the RSB (Pashler, 1994).

An alternative to the RSB framework for explaining cost asymmetries refers to the notion of flexible capacity sharing (Kahneman, 1973; Lehle & Hübner, 2009; Meyer & Kieras, 1997a, 1997b; Tombu & Jolicoeur, 2003). For example, it is possible to strategically prioritize one task over another on the basis of instructions (Navon & Gopher, 1979; Navon & Miller, 1987; Norman & Bobrow, 1975), and flexible capacity scheduling may also be important for configuring task sets involving multiple stimulus and response modalities (e.g., Hazeltine, Ruthruff, & Remington, 2006; Wickens, 1984; see also Stephan & Koch, 2010). Especially on the *input side of processing*, resources are typically known to be unevenly distributed across stimulus modalities. For example, the visual modality usually dominates the auditory modality in tasks involving multiple stimulus modalities (Colavita, 1974; Posner, Nissen, & Klein, 1976). It is surprising, however, that there has

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Lynn Huestegge and Iring Koch, Institute of Psychology, RWTH Aachen University, Aachen, Germany.

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Correspondence concerning this article should be addressed to Lynn Huestegge, Institute for Psychology, RWTH Aachen University, Jägerstrasse 17-19, 52066 Aachen, Germany. E-mail: lynn.huestegge@psych.rwth-aachen.de

been no direct attempt to study modality dominance effects on the *output side of processing*.

In the present study, we demonstrate the flexibility of resource scheduling among different response modalities. In Experiment 1, participants responded to single auditory stimuli with either a vocal response, a saccade, or both. In Experiment 2, we combined vocal and manual (instead of saccade) responses. Note that both experiments involve the same vocal responses, which allows us to conduct a between-experiment analysis to determine the influence of the modality of the second response on dual-response costs for vocal responses (as determined by the difference between single-response and dual-response RTs). In an additional Experiment 3, saccades were combined with manual responses.

Two scenarios for explaining cost asymmetries are at stake: First, on the basis of the overwhelming evidence that the second (or slower) response suffers more from interference than the first (or faster) response does, it is possible that a generic, rigid resource scheduling mechanism (such as a RSB) is responsible: Probably, the faster response (as defined by single-response speed) is always processed with greater priority on a first-come, first-served, basis (Pashler, 1994), and processing of the slower response waits for (or generally relies on) spare resources. Alternatively, however, resource scheduling may be more flexible in that the specific identity of the response modalities involved determines processing priorities, eventually resulting in response modality dominance effects.

Experiment 1

Method

Participants. Eighteen participants were tested, 14 women and four men. Mean age was 23 years ($SD = 3.21$). They gave informed consent and received credits for participation.

Apparatus and stimuli. Participants were seated 67 cm in front of a 21-in. CRT (cathode ray tube) screen (temporal resolution = 100 Hz, spatial resolution = 1,024 × 768 pixels). Saccade latencies of the right eye were registered with a 500-Hz Eyelink II eye tracker (SR Research, Mississauga, Ontario, Canada). The integrated voice key function of the programming software (Experiment Builder, Version 1.10.1) was used for measuring vocal RTs.

A green fixation cross (size = 1/3°) in the middle of the screen as well as two green rectangular squares (size = 1/3° each) at 4.25° to the left and right of fixation remained present throughout. Participants were wearing headphones for the presentation of the auditory stimuli, which consisted of a 1000-Hz sine wave presented for 50 ms to either the left or the right ear with an easily audible intensity.

Procedure. Each trial began with the presentation of the auditory stimulus (50 ms) to either the left or the right ear. Subjects were instructed to either respond (as fast and accurately as possible) by moving their gaze to the spatially compatible square on the screen (saccade response in single blocks), saying the spatially compatible word “links” [left] or “rechts” [right] (vocal response in single blocks), or both (dual-response blocks).

In the two conditions that required saccades (saccade response in single and dual-response blocks), subjects were instructed to return to the central fixation cross after response. Each participant completed nine blocks consisting of 30 trials each. Within each block, stimuli to the left and right were presented in randomized sequence with an interstimulus interval of 3,000 ms. Prior to each block, subjects underwent a calibration routine.

Design. The within-subjects variables were modality (saccade vs. vocal response) and response condition (single vs. dual). The order of single-response blocks and dual-response blocks was counterbalanced across participants. Dependent variables were RTs and error rates.

Results and Discussion

Error rates (0.5%) were deemed too low to conduct meaningful statistical analyses. RTs were analyzed for error-free trials only. A 2 × 2 analysis of variance (ANOVA) for RTs (see Table 1) revealed significant main effects of modality (saccade RTs < vocal RTs), $F(1, 17) = 296.63$, $p < .001$, $\eta_p^2 = .95$, and response condition (single-response RTs < dual-response RTs), $F(1, 17) = 12.55$, $p = .003$, $\eta_p^2 = .43$. Crucially, there was a significant interaction, $F(1, 17) = 7.24$, $p = .015$, $\eta_p^2 = .30$, indicating that dual-response costs were greater for the slower response modality (vocal responses, 77 ms) than for the faster response modality (saccades, 10 ms).

Experiment 2

Method

Participants. Eighteen new participants took part, 16 women and two men. Mean age was 22 years ($SD = 3.15$). They gave informed consent and received credits for participation.

Apparatus, stimuli, procedure, and design. Everything was comparable to Experiment 1, except that vocal responses were combined with manual (instead of saccade) responses. Participants were instructed to remain fixated on the central fixation cross throughout the experiment (controlled via eye tracking). On the keyboard, two keys (from the bottom row) with a distance of 30

Table 1

Mean Response Times (in Milliseconds) in Single- and Dual-Response Conditions and Dual-Response Costs (in Milliseconds) as a Function of Response Modality and Experiment

	Single response		Dual response		
Modality	*M*	*SE*	*M*	*SE*	Dual-response costs
Experiment 1					
Saccade	234	10.7	244	6.8	10
Vocal	704	29.6	781	39.6	77^{**}
Experiment 2					
Manual	301	11.4	375	23.3	74^{**}
Vocal	702	22.3	674	25.4	−28
Experiment 3					
Saccade	210	5.6	219	6.0	9^{*}
Manual	330	13.0	404	18.2	74^{**}

Note. Values for p are based on two-tailed post hoc t tests.
$^{*} p < .05$. $^{**} p < .01$.

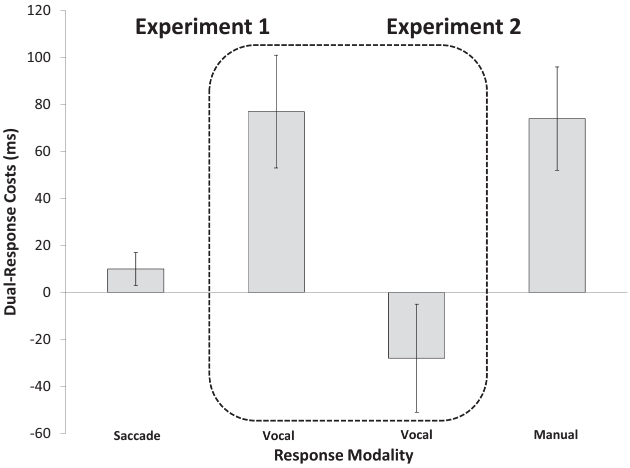

Figure 1. Multitasking costs (in milliseconds) for vocal responses and the respective contextual responses in Experiments 1 and 2. Error bars represent standard errors.

cm (corresponding to 12°) were chosen as response keys. Participants responded with their left and right index fingers.

Results and Discussion

Again, errors only occurred rarely (0.6%). The ANOVA for RTs (see Table 1) revealed a significant main effect of modality (manual RTs < vocal RTs), $F(1, 17) = 225.32$, $p < .001$, $\eta_p^2 = .93$; no significant effect of response condition, $F(1, 17) = 1.99$, $p = .18$; but a significant interaction, $F(1, 17) = 10.56$, $p < .001$, $\eta_p^2 = .38$. Unlike in Experiment 1, dual-response costs were greater for the faster response modality (i.e., manual responses, 74 ms) than for the slower response modality (vocal, −28 ms). Overall, this pattern is reversed when compared with the results of Experiment 1, demonstrating that it is not universally true that the slower response modality is associated with greater costs.[1]

An additional mixed ANOVA of vocal RTs with the independent variables response condition (single vs. dual) and response context (saccades from Experiment 1 vs. manual responses from Experiment 2) revealed no significant effects of task condition, $F(1, 34) = 2.08$, $p = .16$, or response context, $F(1, 34) = 1.94$, $p = .17$. However, the interaction was significant (see Figure 1), $F(1, 34) = 10.09$, $p = .003$, $\eta_p^2 = .23$, indicating greater dual-response costs for vocal responses in Experiment 1 (77 ms) vs. Experiment 2 (−28 ms).

Experiment 3

The previous experiments suggested that saccades are prioritized over vocal responses and vocal responses are prioritized over manual responses. If this pattern represents an ordinal structure of response modality dominance, saccades should also be prioritized over manual responses. To directly test this prediction, we combined saccades and manual responses.

Method

Participants, apparatus, stimuli, procedure, and design. We tested 18 new participants (mean age = 23 years, seven men). All methodological details were like those in the other experiments.

Results and Discussion

Errors occurred rarely (<0.5%). We observed significant main effects of modality, $F(1, 17) = 214.51$, $p < .001$, $\eta_p^2 = .93$, and response condition, $F(1, 17) = 27.13$, $p < .001$, $\eta_p^2 = .62$. It is important to note that dual-response costs for manual responses (74 ms) were greater than for saccades (9 ms), $F(1, 17) = 13.62$, $p = .002$, $\eta_p^2 = .45$ (see Table 1), suggesting that saccades were indeed prioritized over manual responses (replicating Experiment 1 of Huestegge & Koch, 2009).

General Discussion

Previous research on task sets involving multiple responses produced overwhelming empirical evidence that the second (in the PRP paradigm) or slower (in the dual-task paradigm) of two responses is subject to greater interference than is the first or faster response (e.g., Fagot & Pashler, 1992; Holender, 1980; Schumacher et al., 2001; Stelzel et al., 2006). Although some portion of this asymmetry can be explained within the RSB framework (e.g., the PRP effect; see Pashler, 1994), it appears that there are also further, more general mechanisms requiring specification (Fagot & Pashler, 1992; Huestegge, 2011). In the present study, a single auditory stimulus triggered either one response or two simultaneous responses involving different response modalities (i.e., saccades, vocal responses, or manual responses).

Experiments 1 and 2 demonstrate that interference for vocal responses is strongly determined by the context response. Although vocal responses showed strong dual-response interference when combined with saccades, this was not the case when combined with manual responses. Instead, the latter condition revealed stronger interference for manual (vs. vocal) responses. If we interpret the differences in multitasking costs across response modalities as an indicator of processing priorities, it appears that saccade responses are prioritized over vocal responses, whereas

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[1] Additionally, we tested whether the manual dual-response costs were due to response grouping in dual-response conditions. Response grouping is defined as a strategy to select the first response but then hold it in waiting until the second response is also ready to be performed (Ulrich & Miller, 2008). If this strategy was generally applied, we should observe a constant, small interresponse interval (IRI) throughout the distribution of vocal RTs in dual-response conditions (see Huestegge & Koch, 2009, for similar analyses). Vocal RTs were ranked individually and divided into four bins (fastest to slowest trials). A one-way ANOVA with vocal RT bin (1–4) as an independent variable and IRI as a dependent variable yielded a significant linear trend, $F(1, 17) = 150.68$, $p < .001$, $\eta_p^2 = .91$, indicating a substantial increase of IRIs with increasing vocal latencies ($M = 63$ ms, 248 ms, 459 ms, and 609 ms, respectively). Thus, responses were not generally grouped with a fixed IRI. Furthermore, we checked whether the manual dual-response costs were solely due to a small portion of specifically slow (withheld) manual responses. One indication for a subgroup of withheld manual responses would be a bimodal manual RT distribution in dual-response conditions, which we did not observe. Additionally, we reanalyzed the dual-response data after excluding slow manual responses (i.e., with RTs +/−200 ms around the mean vocal dual-response RT of 674 ms). However, we still observed manual dual-response costs (55 ms), $t(17) = 2.20$, $p = .042$, indicating that the assumption of withheld manual responses (response grouping) cannot explain our data.

vocal responses are prioritized over manual responses. Experiment 3 further confirmed this priority pattern by showing that saccades are prioritized over manual responses. This ordinal structure may represent a response modality dominance pattern, similar to the visual dominance effect on the input side of processing (Colavita, 1974; Posner, Nissen, & Klein, 1976; Spence, 2009). Such effects may have gone unnoticed in previous research, which typically used responses in two particular modalities: manual and vocal (see also Philipp & Koch, 2005).

Note that the data from Experiment 2 clearly violated the assumption that the slower response is always associated with greater costs. This observation rules out at least three potential major alternative explanations: First, and in line with previous data from redundant-responses tasks (Fagot & Pashler, 1992), our results are at variance with an RSB account of the cost asymmetry: If the faster response is selected first and the slower response waits for bottleneck clearance, this should have resulted in greater costs for the slower response in Experiment 2, which we did not observe. Second, Experiment 2 also showed that the faster response (as defined by single-response speed) is not always processed with greater priority on a first-come, first-served, basis, so we can rule out a corresponding general, rigid resource-scheduling mechanism. Third, these data are also at variance with the assumption that the slower response may generally have more time to receive interference from the faster response during parallel processing.

At first sight, it may appear puzzling that we did not observe greater costs for vocal responses than for manual responses in Experiment 2, given that previous dual-task research reported greater costs for vocal responses (e.g., Fagot & Pashler, 1992; Holender, 1980; Schumacher et al., 2001; Stelzel et al., 2006). Note, however, that these studies used visual instead of auditory stimuli and did not control for saccade occurrence. These differences in the range of modalities involved may well influence resource scheduling patterns.

Overall, our results are consistent with recent flexible capacity sharing and resource scheduling accounts during task-set configuration (e.g., Meyer & Kieras, 1997a, 1997b; Navon & Miller, 2002; Tombu & Jolicoeur, 2003). Specifically, the data suggest that processing priorities are flexibly determined on the basis of the specific combination of response modalities, showing that the identity and the specific combination of response modalities are an integral part of task-set specification. Thus, task sets appear to be modality specific instead of representing a schema of rather abstract stimulus and response elements and rules.

A specific model of resource scheduling in task-set control is *executive control of the theory of visual attention* (ECTVA; Logan & Gordon, 2001). In ECTVA, task instructions are interpreted to specify a set of control parameters. For example, the parameter beta (see Bundesen, 1990) is relevant for categorizing stimuli along the dimension(s) relevant for current action goals (e.g., referring to the attributes "left" vs. "right" of a stimulus). Another parameter, kappa (Nosofsky & Palmeri, 1997), quantifies the margin by which the activation of a response must be ahead of competing responses to be selected and executed. The activation of all potential responses is represented by individual response counters, and the accumulation of activation is conceptualized as a stochastic process (e.g., a random walk). The parameter alpha specifies the time required for each step in the random walk, and capacity limitations in response selection are reflected in the size of alpha. A specific mechanism explaining dual-response costs in the present study directly follows from ECTVA's features. Generally, all potential responses should compete against each other in every trial. Thus, dual-response conditions involve more competition (based on more potential responses) than do single-response conditions. Because the winning response needs to accumulate kappa more counts than the next highest alternative, the likelihood that an inappropriate response accumulates a large number of counts increases with the number of responses. Therefore, it takes more time to reach the margin (specified by kappa) in dual-response conditions than in single-response conditions. Unfortunately, ECTVA does not explicitly specify a mechanism for response modality weighting. Probably, this could be reflected either in separate response weighting parameters (equivalent to TVA's attention weight parameters; see Bundesen, 1990) or in distinct alpha parameters for response counters associated with individual effector systems. Future research also needs to address the question of whether response modality weighting is based on voluntary strategies or rather on learned, quasiautomatic mechanisms.

An interesting additional theoretical topic relates to the question of whether our dual-response conditions involve one complex or two separate task sets. Because parametric models like ECTVA are built around the assumption that each executed response represents the winner of a race of competing response counters, one might conclude that situations involving the execution of two responses (i.e., running ECTVA twice) would be associated with two task sets (which may well be executed in parallel and may be dependent in that they share specific parameter settings). However, theories referring to more generic mechanisms (e.g., the RSB framework) highlight the dependency of responses in redundant-responses tasks and formally determine the number of tasks by referring to the number of abstract decisions (here, one left–right decision) *necessary* to define all responses involved (equivalent to a shared beta parameter in ECTVA). In the light of these alternatives, we favor the view that our dual-response condition is also a dual-task condition, because previous research suggested that response modalities are essential for defining a task set (e.g., Stephan & Koch, 2010) and IRI analyses here and in previous work (Huestegge & Koch, 2009) did not support the assumption of compound (grouped) responses.

Another potential explanation for the observed processing priorities could refer to ecological considerations. For example, a typical situation involving coordinated saccades and vocal responses is oral reading. Here, efficient visual text parsing (involving saccade control) is usually more important than (and a necessary prerequisite of) pronunciation. Furthermore, a general prioritization of saccade control (over vocal control) may help to detect important (e.g., life-threatening) environmental changes. In contrast, coordinating manual and vocal action is prevalent in communication, where gestures typically support verbal utterances. Given that most information is contained in people's utterances (rather than in gestures), prioritizing vocal over manual processing might have generalized to situations like that in Experiment 2. However, it is clear that ecological considerations need to be accompanied by specifications of functional mechanisms, such as those specified in models like ECTVA.

Taken together, our observations further support the general idea that task-set control greatly depends on contextual factors, including stimulus and response modalities (Huestegge & Hazeltine, 2011). This supports the notion of a highly flexible cognitive system that easily adapts to environmental demands and response requirements. Finally, our results highlight the importance of studying a greater variety of response modalities to provide a more complete theoretical picture of architectural and functional constraints in cognition.

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