Cue the Effects: Stimulus-Action Effect Modality Compatibility and Dual-Task Costs

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The pairings of tasks’ stimulus and response modalities affect the magnitude of dual-task costs. For example, dual-task costs are larger when a visual-vocal task is paired with an auditory-manual task compared with when a visual-manual task is paired with an auditory-vocal task. These results are often interpreted as reflecting increased crosstalk between central codes for each task. Here we examine a potential source: modality-based crosstalk between the stimuli and the response-induced sensory consequences (i.e., action effects). In five experiments, we manipulated experimentally induced action effects so that they were either modality-compatible or -incompatible with the stimuli. Action effects that were modality-compatible (e.g., visual stimulus, visual action effect) produced smaller dual-task costs than those that were modality-incompatible (e.g., visual stimulus, auditory action effect). Thus, the relationship between stimuli and action effects contributes to dual-task costs. Moreover, modality-compatible pairs showed an advantage compared with when no action effects were experimentally induced. These results add to a growing body of work demonstrating that postresponse sensory events affect response selection processes.

Public Significance Statement
Actions are typically associated with a goal of producing an environmental effect. For example, a pianist must monitor the sound produced by a key press to ensure the proper note was played. In the present study, we demonstrate how a response’s anticipated environmental effects affect the coordination of two tasks (i.e., dual-task performance). These results have implications for theoretical accounts of dual-task performance and demonstrate that the expected consequence of actions can partly determine the composition of selection processes.

Keywords: action effects, crosstalk, dual-task costs, modality pairings

Much of daily life involves coordinating multiple tasks. For example, individuals might talk while driving or browse the Internet while listening to music with seemingly little interference or effort. However, although many individuals are unaware of performance decrements when coordinating two tasks, laboratory tasks reveal that coordinating even simple key presses can result in significant increases in both response time (RT) and error rates (ER) compared with when each task is executed alone—a phenomenon known as dual-task costs (Allport, Antonis, & Reynolds, 1972; Koch, Poljac, Müller, & Kiesel, 2018; Navon & Gopher, 1979; Navon & Miller, 1987; Pashler, 1984, 1994; Wickens, 1980). Most accounts of dual-task costs (e.g., bottleneck accounts, Meyer & Kieras, 1997a, 1997b; Navon & Miller, 2002; Pashler, 1984, 1994; Welford, 1952; capacity-sharing accounts, Kahneman, 1973; Tombu & Jolicoeur, 2003) have focused on the central operations that select a response given a categorized stimulus, rather than the peripheral processes associated with identifying a stimulus or producing a response. However, a rigorous characterization of these central operations has remained elusive.

The Role of Modality Pairings on Dual-Task Costs
One clue regarding the source of the dual-task costs is that the composition of the tasks affects the magnitude of the performance decrement (e.g., increases in RT, see, Göthe, Oberauer, & Kliegl, 2016; Halvorson & Hazeltine, 2015; Hazeltine, Ruthruff, & Remington, 2006; Schumacher et al., 2001; Stelzel, Schumacher, Schubert, & D’Esposito, 2006). For example, Hazeltine and colleagues (2006) observed smaller dual-task costs when a visual-manual (VM) task was paired with an auditory-vocal (AV) task than when a visual-auditory (VV) task was paired with an auditory-manual (AM) task. Critically, these modality pairing effects were observed only in dual-task performance; single-task RTs were similar across all stimulus–response (S-R) pairings. Later studies have shown analogous effects in switch (Fintor, Stephan, & Koch, 2018;...
coordinating modality-compatible tasks (VM and AV), dual-task costs may be reduced because the modality of an action effect corresponds with the modality of the stimulus (e.g., Wickens, Sandry, & Vidulich, 1983). In this case, the visual stimulus cues a manual response that produces an action effect with a visuospatial component and the auditory stimulus cues a vocal response that produces an action effect with an auditory component. In contrast, costs may be greater when coordinating modality-incompatible tasks (VV and AM) because the shared stimulus and action effect modalities cross tasks. Here, the visual stimulus cues a vocal response that produces an action effect with an auditory component and the auditory stimulus cues a manual response that produces an action effect with a visuospatial component. With these pairings, there may be crosstalk among the coactivated representations of each action, if those representations contain both stimulus and action effect information.

### Action Effects and Response Selection

A critical point here is that action effects occur after a response has been executed. If they affect response selection processes, they must include the anticipated response-related consequences. That is, the action effects must be integrated into task representation (Hommel, 1993, 1996).

To examine the influence of action effects on response selection processes, researchers often introduce experimentally induced action effects following response execution. By experimentally induced action effects, we refer to the presentation of stimuli that consistently follow the production of particular responses. Such stimuli do not eliminate the sensory consequences typically associated with the action in the absence of experimenter intervention and thus are not the only sensory consequences associated with a response. For example, pressing a key produces tactile and proprioceptive action effects. However, because it is difficult to manipulate the effects of responses that are inherent to their production, researchers often introduce additional perceptual events as action effects to assess how the relationships among stimulus, response, and action effect codes affect performance.

A key assumption here is that if action effects are anticipated prior to response execution, then the compatibility between stimulus or response codes and (experimentally induced) action effects should affect response execution and alter response selection processes. Indeed, there is converging evidence that stimulus–effect and response–effect compatibility can speed performance. For example, a spatial response (e.g., left key press) followed by a spatially compatible action effect (e.g., flashing left-sided light) is produced faster and more accurately than when followed by a spatially incompatible action effect (e.g., flashing right-sided light; Kunde, 2001). Likewise, vocal responses are produced faster when followed by a semantically compatible written word (e.g., vocal response: “blue”; action effect: written word blue) than when followed by an incompatible written word (e.g., written word red; Koch & Kunde, 2002).

In the context of dual-task costs, understanding how action effects influence response selection processes is critical, as dual-task costs are theorized to stem from overlapping and interacting response selection processes for the concurrently performed tasks (e.g., Pashler, 1994). Along these lines, there is evidence that experimentally induced postresponse action effects can affect dual-task performance. For example, when the monitoring process (i.e., the duration of the action effect associated with the response) for one task overlaps with the
selection processes for a second task, dual-task costs are larger (Ulrich et al., 2006). That is, monitoring the action effects for one response can delay the selection of the other (for similar findings using experimentally induced action effects, see Kunde, Wirth, & Janczyk, 2018; Wirth, Janczyk, & Kunde, 2018).

Critically, dual-task costs are also affected by the specific codes associated with the action effects. Janczyk, Pfister, Hommel, and Kunde (2014) showed that the backward crosstalk effect (e.g., Hommel, 1998) in dual-task performance depends on the relationship between the response features of one task and the (experimentally induced) action effects of the other task. When a second task produced an action effect that was spatially incompatible with the response for the first task (e.g., Task 1 response: left key press; Task 2 effect: right-sided light), performance was impaired—even if the responses themselves were spatially compatible (e.g., both tasks required a left key press). Likewise, when combining a mental rotation task with a manual rotation task that entailed a visual rotation action effect, performance was facilitated when the directions of the mental rotation and the visual action effect—but not the manual rotation itself—were the same (Janczyk, Pfister, Crogna, & Kunde, 2012).

Together, these findings suggest that response selection processes include some of the components involved in the anticipation and monitoring of action effects and that these components can interact across tasks during dual-task performance (e.g., Elsner & Hommel, 2001; Janczyk & Lerche, 2019; Janczyk, Pfister, Wallmeier, & Kunde, 2014; Koch & Kunde, 2002; Kunde, Koch, & Hoffmann, 2004; Kunde, Pfister, & Janczyk, 2012; Paelcke & Kunde, 2007; Welford, 1952). The critical point is that response selection processes are facilitated when the action effects representing the outcome of a response are compatible with, or resemble, a stimulus or response. This may provide clues regarding the source of the modality compatibility effect, and thus benefit our understanding of how action effects can impact dual-task performance and, more generally, how dual-task costs can be reduced in the real world.

The Present Study

Here, we build on the idea that action effects are included in representations used by selection processes by testing whether the compatibility between the modalities of stimuli and action effects affects dual-task performance. In a series of five experiments, we investigated the role of stimulus-action effect modality compatibility on dual-task costs. To do this, we designed a dual-task paradigm whereby manipulated action effects (i.e., additional perceptual events associated with the responses) were introduced following response execution. Regarding the naming of the conditions, we use the terms manipulated and unmanipulated action effects because, like most actions, the responses produce both body-related (e.g., proprioceptive effects of a key press) and environment-related (e.g., visual changes in the environment associated with a key press) effects regardless of the events added by the experimenter. Our focus is on the impact of providing additional environment-related effects, and the term manipulated differentiates environmental-related effects that are added by the experimenter from those that occur without intervention. The modality of these manipulated action effects was either compatible or incompatible with the modality of the stimulus within an individual task. For example, in the compatible-effect condition, visual stimuli required responses that produced visual action effects, and auditory stimuli required responses that produced auditory action effects. In the incompatible-effect condition, visual stimuli required responses that produced auditory action effects, and auditory stimuli required responses that produced visual action effects. We also included an unmanipulated-effect condition, in which the response did not produce experimentally induced action effects.

In Experiments 1 and 2, we examined how stimulus-action effect compatibility affected dual-task costs in two stimulus–response modality pairings shown to produce different magnitudes of dual-task costs (Göthe et al., 2016; Hazeltine et al., 2006; Stelzel et al., 2006): VM/AV (Experiment 1) and VV/AM (Experiment 2). We determined whether the influence of stimulus–response compatibility generalizes to different stimulus–response pairings and whether manipulated effects override the influence of stimulus–response pairings. To account for potential strategies imposed on the participants that may arise from vocal responses, we used two tasks involving manual responses in Experiment 3. Finally, Experiments 4 and 5 extended the finding to stimulus–effect pairings that were not compatible at a representational level.

Experiment 1

To examine how stimulus-action effect compatibility affects dual-task costs, we used tasks that shared stimulus and response pairings but differed in terms of the modalities of the experimentally induced action effects. In three conditions, we manipulated the correspondence between the modality of the stimulus and the modality of the experimentally induced action effect while holding constant the mapping between the stimuli and responses. In the response-compatible/effect-compatible (RCEC) condition, stimuli were mapped to modality-compatible responses (e.g., visual stimuli to manual responses and auditory stimuli to vocal responses, see Stephan & Koch, 2010, 2011), which in turn produced modality-compatible action effects (e.g., responses to visual stimuli produced visual effects and responses to auditory stimuli produced auditory effects). In the response-compatible/effect-incompatible (RCEI) condition, the same stimulus–response mapping was used, but the responses produced modality-incompatible action effects (e.g., responses to visual stimuli produced auditory effects and responses to auditory stimuli produced visual effects).1 We also included an unmanipulated action-effect (RCEU) condition. In this condition, there were no added action effects, but, of course, the unmanipulated sensory consequences associated with the responses were present (e.g., tactile and proprioceptive action effects from manual responses), as in the other conditions.

Across all experiments, we used three block types: homogenous single-task blocks, in which one stimulus from one of the tasks was presented on each trial; mixed-task blocks (OR blocks), in which

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1 Of course, this also affects the relationship between the modality of the unmanipulated action effect (from the response) and the modality of the manipulated action effect. For example, when an AV task produces a visual action effect, the modalities of the unmanipulated (sound of the voice) and manipulated action effects (visual action effect stimulus) are incompatible. Although the relationship between the manipulated and unmanipulated action effects offers an additional way to describe the conditions, we instead label the conditions based on the compatibility between the stimuli and unmanipulated or manipulated action effects, because this is consistent with previous descriptions of the modality compatibility effect (e.g., Hazeltine et al., 2006; Stephan & Koch, 2011, 2016). We return to this issue in Experiment 2.
one stimulus from either task was presented on each trial (Halvorson et al., 2013; Tombu & Jolicoeur, 2004); and dual-task blocks (AND blocks), in which two stimuli were presented simultaneously, one from each task, and two responses were required on each trial.

Our primary interest was the dual-task cost, which was computed as the difference between AND blocks which require task coordination and OR blocks in which participants must perform one of two tasks. However, we also examined mixing costs. Mixing costs, which represent performance differences between OR blocks and single-task blocks, reflect the additional time needed to prepare for both tasks within a block instead of just one task (Los, 1996; Rubin & Meiran, 2005). Mixing costs are theorized to stem from either an increase in working memory load (Braver, Reynolds, & Donaldson, 2003; Los, 1996) or conflict associated with the ambiguity of which task to perform (Rubin & Meiran, 2005).

Like dual-task costs, mixing costs are affected by the combinations of stimulus and response (along with the response’s action effect’s) modalities. Schacherer and Hazeltine (2019b; see also, Hazel et al., 2006) observed larger mixing costs in VV/AM pairings compared with VM/AV pairings. Larger mixing costs in the VV/AM pairing may reflect the difficulty of maintaining stimulus–effect pairs that use different modality-specific codes in working memory (e.g., Baddeley, 1986). For example, an auditory stimulus and the vocal response (and its auditory action effect) may both engage verbal codes, putting a greater load on working memory processes. When related codes belong to different tasks, mixing costs may be greater. Alternatively, the larger costs may reflect greater task confusion. For example, in the real world, we often respond vocally (producing auditory action effects) to auditory stimuli and manually (producing visuospatial action effects) to visual stimuli. Task settings that follow this tendency may decrease ambiguity in the VM/AV pairings, resulting in smaller costs.

Method

Participants. To determine the sample size needed to obtain statistical power at a level of .8 (Cohen, 1988), we conducted a power analysis using the effect size of \( r^2 = .699 \) from Session 1 dual-task cost data of Experiment 2a from Hazel et al. (2006), in which participants performed either VM/AV or VV/AM tasks. The power analysis, based on the main effect of a single-factor ANOVA with three levels, indicated that 27 participants (nine for each of our three conditions) would be needed to obtain 80% power. However, to be sensitive to smaller effect sizes that may be related to action effect manipulations \( r^2 = .370 \), we tested 24 participants per condition (72 per experiment).

Ninety-one students from the University of Iowa participated in partial fulfillment of an introductory psychology course requirement. Data from 19 participants whose overall accuracy was less than 85% (Halvorson & Hazel, 2015) were discarded and not analyzed, leaving 72 total participants whose data were analyzed. In most cases, it appeared that the voice recognition software did not accurately identify vocalizations for the participants whose data were discarded. The remaining participants were equally divided (24 per condition) into three conditions: response-compatible/effect-compatible (RCEC; 19 female, \( M_{age} = 19.00, SD_{age} = 0.88 \); response-compatible/effect-incompatible (RCEI; 15 female, \( M_{age} = 19.17, SD_{age} = 0.76 \); or response-compatible/effect-unmanipulated (RCEU; 16 female, \( M_{age} = 19.08, SD_{age} = 0.78 \)). Vision and hearing were reported as normal or corrected-to-normal. Consent was obtained prior to the experiment. All methods and procedures were approved by the Institutional Review Board at the University of Iowa.

Stimuli and apparatus. The experiment was conducted using Microsoft VisualBasic software with the Microsoft Speech Recognition API (Version 8.0). Visual stimuli were a colored rose, leaf, or pond presented within a 6.7° horizontal × 6.6° vertical black colored rectangle on a black background presented for 350 ms on a 19-in. computer monitor located approximately 57 cm from the participant. Auditory stimuli were a dog’s bark, cat’s meow, or a bird’s chirp presented via headphones sampled at 11.025 Hz with a duration of 350 ms. Manual responses were the q/w/e keys on a standard QWERTY keyboard. Vocal responses were the words tax, tough, or time gathered via microphone attached to the headphones. The RCE condition provided action effects in a modality compatible with that of the stimulus. For the VM task, the visual action effect was a black-and-white picture of a rose, leaf, or pond. For the AV task, the auditory action effect was the spoken word dog, cat, or bird. The RCEI condition reversed this stimulus–effect modality compatibility, such that the effect was in a modality incompatible with the stimulus. For the VM task, the auditory action effect was the spoken word rose, leaf, or pond. For the AV task, the visual action effect was a black-and-white picture of a dog, cat, or bird. Finally, the RCEU condition had participants perform the VM and AV tasks with no additional action effects provided (see Figure 1). Stimulus, response, and action effect pairings for the manipulated action effect conditions are shown in Table 1.

These stimuli and responses were chosen to have minimal conceptual overlap both within and between tasks. Conceptual overlap, which exists when components of the stimulus–response set refer to similar concepts (e.g., Kornblum, 1992; Lu & Proctor, 2001; Proctor, Wang, & Vu, 2002), has been shown to facilitate response selection when present within a task and interfere with response selection when present between tasks (Schacherer & Hazel, 2019b). In Experiments 1–4, our goal was to emphasize the relationship between stimuli and action effects, so we used action effects that had strong physical and/or conceptual overlap with the stimuli and minimal conceptual overlap with the responses (see Table 1). For example, when the auditory stimulus was a dog’s bark, the action effect would be either the spoken word dog (RCEC condition) or a picture of a dog (RCEI condition). However, in this case, there would be minimal conceptual overlap between a dog’s bark and the word tax (stimulus–response within task); between a dog’s bark and the q key (stimulus–response between tasks); between a dog’s bark and a rose (stimulus–stimulus between tasks); and between the word tax and the q key (response–response between tasks).

Procedure. Participants first completed a speech recognition training program, in which they were required to read aloud a series of sentences presented on the computer. This was done to tune the recognition software to the individual participant’s speech. The procedure took about 5 min to complete. Verbal and written instructions were provided prior to the start of the experiment and provided on the computer prior to the start of each
block. The instructions emphasized both speed and accuracy on all block types.

Participants in the RCEC and RCEI conditions completed 14 blocks of 36 trials each. The first two blocks were homogeneous single-task, in which participants were presented the visual or auditory word, PRESS or SPEAK (for the VM and AV tasks, respectively), with the instructions to press or say any of the three responses with the goal of producing an action effect. Participants were allowed to freely choose their responses, as no response was deemed correct or incorrect. These blocks were included to establish the link between the motor responses with action effects. Participants in the RCEU condition did not complete the PRESS/SPEAK blocks, as no action effects were presented following responses. Thus, they completed 12 blocks. Otherwise, the task procedure was identical across conditions.

For the 12 blocks performed by all participants, the first four were single-task blocks in which stimuli were presented indicating the appropriate response. The final eight blocks were divided into pairs of alternating OR and AND blocks. The OR blocks consisted of 36 single-task trials of either task (18 of each task) intermixed at random. The AND blocks consisted of 36 trials in which both stimuli were presented simultaneously (i.e., 0 ms SOA), and two responses were required on each trial. Participants performed two blocks of one type and then two blocks of the other, switching every two blocks for the remainder of the experiment. Participants were instructed to respond as quickly and accurately as possible on AND blocks, but no explicit instructions were given regarding how to prioritize the tasks.

Figure 1. Task procedure for Experiment 1. In the compatible-effect condition (top), action effects were in a modality compatible with the stimulus (e.g., visual stimulus, visual effect). In the incompatible-effect condition (middle), action effects were in a modality incompatible with the stimulus (e.g., visual stimulus, auditory effect). In the unmanipulated-effect condition (bottom), no additional effect was presented (e.g., visual stimulus, no added effect). All experiments followed a similar procedure, albeit with different S-R modality pairings (Experiment 2: visual-vocal/auditory-manual; Experiments 3–5: visual-manual/auditory-manual) or different S-E pairings (Experiments 4–5). Colored leaf photograph was retrieved from https://commons.wikimedia.org/wiki/File:Pear_Leaf.jpg. See the online article for the color version of this figure.
For the RCEC and RCEI conditions, the instructions were organized as follows: First, participants were instructed to produce a manipulated action effect that corresponded to the presented stimulus (e.g., “When you hear the DOG’S BARK, make the DOG picture appear”). That is, the instructions emphasized the link between stimuli and action effects. Then, participants were provided instructions for linking stimuli to the respective responses (e.g., “When you hear the DOG’S BARK, say ‘tax’”). For the RCEU condition, only the latter instructions were provided. Instructions were similar across all experiments.

For all conditions, each trial began with the onset of the fixation cross for 500 ms, followed by the presentation of the stimulus for up to 350 ms and a response interval that lasted up to 3,000 ms. In the RCEC and RCEI conditions, action effects were presented for 350 ms immediately following response production; whereas in the RCEU condition, a blank field was presented for 350 ms. If the response was executed during stimulus presentation (i.e., RT less than 350 ms), the stimulus was overridden and replaced by the manipulated action effect (RCEC and RCEI conditions) or a blank field (RCEU condition). The next trial began 500 ms later. No error feedback was given when the response was incorrect. Participants were told to produce the sensory event that corresponded with the presented stimulus. For example, if the stimulus was a dog’s bark and the action effect was the spoken word dog, the participant would learn that they produced a correct response. Thus, monitoring the action effects served as a form of feedback regarding the accuracy of the response. At the end of each block, participants were shown their overall accuracy and mean RT for the block. Completion of the entire experiment took between 45 and 60 min.

**Statistical analysis.** In the RCEC and RCEI conditions, the first four blocks (two practice, two single-task) were excluded from analysis and treated as practice. In the RCEU condition, the first two blocks (two single-task) were excluded from analysis. Thus, across all conditions, we analyzed data from 10 blocks—two single-task, four mixed, and four dual-task blocks. Additionally, the first four trials in each block were excluded from analysis. All responses given within the first 200 ms (0.2%) after stimulus onset or any RTs greater than 2,500 ms (1.6%) were excluded from analysis. Lastly, trials in which no response was detected, in which one or both of the responses were incorrect, and trials following an error were removed from analysis of RT (9.2%). In total, we removed 11.0% of trials from our final analysis.

### Table 1

<table>
<thead>
<tr>
<th>Experiment (modality pairing)</th>
<th>Task</th>
<th>Stimulus</th>
<th>Response</th>
<th>Action effect</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>COMP</td>
</tr>
<tr>
<td>1 VM/AV</td>
<td>VM</td>
<td>color leaf</td>
<td>q</td>
<td>b&amp;w leaf</td>
</tr>
<tr>
<td></td>
<td></td>
<td>color pond</td>
<td>w</td>
<td>b&amp;w pond</td>
</tr>
<tr>
<td></td>
<td></td>
<td>color rose</td>
<td>e</td>
<td>b&amp;w rose</td>
</tr>
<tr>
<td></td>
<td>AV</td>
<td>dog bark</td>
<td>“tax”</td>
<td>“dog”</td>
</tr>
<tr>
<td></td>
<td></td>
<td>cat meow</td>
<td>“tough”</td>
<td>“cat”</td>
</tr>
<tr>
<td></td>
<td></td>
<td>bird chirp</td>
<td>“time”</td>
<td>“bird”</td>
</tr>
<tr>
<td>2 VV/AM</td>
<td>VV</td>
<td>color leaf</td>
<td>“tax”</td>
<td>b&amp;w leaf</td>
</tr>
<tr>
<td></td>
<td></td>
<td>color pond</td>
<td>“tough”</td>
<td>b&amp;w pond</td>
</tr>
<tr>
<td></td>
<td></td>
<td>color rose</td>
<td>“time”</td>
<td>b&amp;w rose</td>
</tr>
<tr>
<td></td>
<td>AM</td>
<td>dog bark</td>
<td>q</td>
<td>“dog”</td>
</tr>
<tr>
<td></td>
<td></td>
<td>cat meow</td>
<td>w</td>
<td>“cat”</td>
</tr>
<tr>
<td></td>
<td></td>
<td>bird chirp</td>
<td>e</td>
<td>“bird”</td>
</tr>
<tr>
<td>3 VM/AM</td>
<td>VM</td>
<td>color leaf</td>
<td>q</td>
<td>b&amp;w leaf</td>
</tr>
<tr>
<td></td>
<td></td>
<td>color pond</td>
<td>w</td>
<td>b&amp;w pond</td>
</tr>
<tr>
<td></td>
<td></td>
<td>color rose</td>
<td>e</td>
<td>b&amp;w rose</td>
</tr>
<tr>
<td></td>
<td>AM</td>
<td>dog bark</td>
<td>u</td>
<td>“dog”</td>
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<tr>
<td></td>
<td></td>
<td>cat meow</td>
<td>i</td>
<td>“cat”</td>
</tr>
<tr>
<td></td>
<td></td>
<td>bird chirp</td>
<td>o</td>
<td>“bird”</td>
</tr>
<tr>
<td>4 VM/AM</td>
<td>VM</td>
<td>color road</td>
<td>q</td>
<td>b&amp;w leaf</td>
</tr>
<tr>
<td></td>
<td></td>
<td>color pond</td>
<td>w</td>
<td>b&amp;w pond</td>
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<td></td>
<td>AM</td>
<td>dog bark</td>
<td>u</td>
<td>“dog”</td>
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<tr>
<td></td>
<td></td>
<td>cat meow</td>
<td>i</td>
<td>“cat”</td>
</tr>
<tr>
<td>5 VM/AM</td>
<td>VM</td>
<td>color leaf</td>
<td>q</td>
<td>white circle</td>
</tr>
<tr>
<td></td>
<td></td>
<td>color pond</td>
<td>w</td>
<td>white square</td>
</tr>
<tr>
<td></td>
<td></td>
<td>color rose</td>
<td>e</td>
<td>white triangle</td>
</tr>
<tr>
<td></td>
<td>AM</td>
<td>dog bark</td>
<td>u</td>
<td>{buzz}</td>
</tr>
<tr>
<td></td>
<td></td>
<td>cat meow</td>
<td>i</td>
<td>{honk}</td>
</tr>
<tr>
<td></td>
<td></td>
<td>bird chirp</td>
<td>o</td>
<td>{whistle}</td>
</tr>
</tbody>
</table>

**Note.** In the effect-compatible (COMP) condition, stimuli and action effects are in the same modality (i.e., visual stimulus, visual effect; auditory stimulus, auditory effect). In the effect-incompatible (INCOMP) condition, stimuli and action effects are in different modalities (i.e., visual stimulus, auditory effect; auditory stimulus, visual effect). In the unmanipulated-effect condition (not shown), stimulus–response pairings were identical to those used in the COMP and INCOMP conditions, but no added action effect was presented following a response. VM = visual-manual; AV = auditory-manual; VV = visual-vocal; AM = auditory-manual; COMP = effect-compatible; INCOMP = effect-incompatible; b&w = black & white.
Because we did not provide explicit instructions on how to prioritize the tasks in dual-task blocks, it is possible that participants engaged the tasks using different strategies. Some participants may have prioritized the visual task and some the auditory task. Therefore, we combined the dual-task costs, as well as mixing costs, for both the VM and AV tasks, as in previous work (Halvorson et al., 2013; Halvorson & Hazeltine, 2015, 2019; Hazeltine et al., 2006).

Results and Discussion

Planned analyses. In each experiment, we examined two dependent variables—RT and ER—and conducted three primary analyses for single-task performance, mixing costs, and dual-task costs. The mean RTs and ERs for all conditions are shown in Table 2.

To examine how stimulus-action effect modality compatibility affects single-task performance, single-task RTs or ERs—separated by task (visual or auditory stimulus)—were submitted to separate single-factor ANOVAs with condition (COMP, INCOMP, UNMANIP) as a between-subjects factor.

For our analysis of mixing costs, we summed the mixing costs (e.g., OR RT/ER single-task RT) across both tasks because participants may have prioritized the tasks differently (see, Halvorson & Hazeltine, 2015, 2019). The summed mixing costs were submitted to a single-factor ANOVA with condition as a between-subjects factor. The summed mixing costs for the three conditions are shown in Figure 2.

Lastly, for our analysis of dual-task costs, we again summed dual-task costs (e.g., AND RT/ER OR RT) across the two tasks and submitted them to an identical single-factor ANOVA as that used in previous work.

Table 2
Mean RTs and ERs for Experiments 1–5

<table>
<thead>
<tr>
<th>Experiment (S-R pairing)</th>
<th>Trial type</th>
<th>Reaction time (ms)</th>
<th>Error rate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>COMP</td>
<td>INCOMP</td>
</tr>
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<td>Dual-task costs</td>
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Note. Mixing costs were calculated as the difference between the sum of RT/ERs in OR blocks minus the sum of RT/ERs in single-task blocks. Dual-task costs were calculated as the difference between the sum of RT/ERs in AND blocks minus the sum of RT/ERs in OR blocks. VM = visual-manual; AV = auditory-manual; VV = visual-vocal; AM = auditory-manual; COMP = effect-compatible; INCOMP = effect-incompatible; UNMANIP = effect-unmanipulated.
for analyzing mixing costs. The combined dual-task costs across tasks are shown for the three conditions in Figure 3. Dual-task costs for individual tasks are presented in Table 3.

If an ANOVA revealed a significant effect of condition, we conducted follow-up independent-samples t tests to test for differences across conditions.

Single-task. For the VM task, there was unequal variance across conditions for both RT (Levene’s p = .043) and ER (Levene’s p = .021), so we used the Brown-Forsythe test statistic for comparisons. We observed no significant differences across conditions for both RT (RCEC: 536 ms; RCEI: 536 ms; RCEU: 525 ms), F(2, 63.66) = 0.25, corr p = .777, η² = .007; and ER (RCEC: 2.1; RCEI: 2.0; RCEU: 4.8), F(2, 41.17) = 3.22, corr p = .050, η² = .080. For the AV task, there were no significant differences across conditions for both RT (RCEC: 968 ms; RCEI: 986 ms; RCEU: 996 ms), F(2, 69) = 0.13, p = .879, η² = .004, and ER (RCEC: 7.0; RCEI: 6.6; RCEU: 7.7), F(2, 69) = 0.15, p = .864, η² = .004.

Mixing costs. There were no significant differences across conditions for both RT (RCEC: 150 ms; RCEI: 157 ms; RCEU: 120 ms) F(2, 69) = 0.40, p = .675, η² = .011; and ER (RCEC: −0.8; RCEI: −1.0; RCEU: −0.2), F(2, 69) = .68, p = .934, η² = .002 (see Table 1). Thus, action effects do not appear to significantly affect mixing costs.

Dual-task costs. We observed a significant effect of condition, F(2, 69) = 3.94, p = .024, η² = .102. Follow-up independent-samples t tests revealed a significant difference between the RCEI (670 ms) and RCEC (449 ms) conditions, t(46) = 2.62, p = .012, Cohen’s d = 0.76 but no difference between the RCEC and RCEU (548 ms), t(46) = 1.34, p = .186, d = 0.39, or between the RCEI and RCEU conditions, t(46) = 1.59, p = .126, d = 0.45. The dual-task costs in the RCEU condition were comparable to those reported (430 ms) in Hazeltine et al. (2006), which used a similar procedure. For ER, there were no significant differences between conditions (RCEC: 3.7; RCEI: 4.8; RCEU: 1.5), F(2, 69) = 1.08, p = .344, η² = .030.

Given that the stimuli and responses were identical across conditions, the results of Experiment 1 are consistent with the idea that the modality compatibility effect on dual-task costs may stem in part from the interaction between stimuli and action effect codes. Dual-task costs were reduced when the modality of the stimulus matched the modality of the manipulated action effects (RCEC condition: visual stimulus, visual effect; auditory stimulus, auditory effect) compared with when there was a mismatch between the modality of stimulus and the modality of the manipulated action effect (RCEI condition: visual stimulus, auditory effect; auditory stimulus, visual effect).

![Figure 2](image1.png)

*Figure 2.* Mixing costs for Experiments 1–5. Mixing costs represent performance differences between OR–single-task blocks. Light gray bars represent compatible-effect tasks; medium-gray bars represent incompatible-effect tasks; and dark gray bars represent unmanipulated-effect tasks. Error bars represent standard error of the mean. VM = visual-manual; AV = auditory-vocal; VV = visual-vocal; AM = auditory-manual.

![Figure 3](image2.png)

*Figure 3.* Dual-task costs for Experiments 1–5. Dual-task costs represent performance differences between AND–OR blocks. Light gray bars represent compatible-effect tasks; medium-gray bars represent incompatible-effect tasks; and dark gray bars represent unmanipulated-effect tasks. Error bars represent standard error of the mean. VM = visual-manual; AV = auditory-vocal; VV = visual-vocal; AM = auditory-manual.
This finding suggests increased crosstalk between the codes associated with the RCEI conditions. For example, according to one version of this account, when a visual stimulus is mapped to a visual action effect and an auditory stimulus is mapped to a vocal response, the production of the responses—can reduce dual-task costs (see Experiments 3 and 4). This is consistent with the proposal that dual-task performance may be organized by perceptual codes, rather than motor codes (e.g., Mechsner, Kerzel, Knoblich, & Prinz, 2001).

Manual responses typically do not produce auditory effects and vocal responses rarely produce visuospatial effects in real-world settings, raising the possibility that the incompatible effect pairings produce greater costs due to violations of expectations (e.g., Spence, Nicholls, & Driver, 2001). However, there were no observed differences in single-task blocks. If the effect in the dual-task costs stemmed from violations of expectations, then it would have been observable in single-task conditions (e.g., Parmentier, Elsley, André, & Barceló, 2011).

Although these results highlight the interaction between stimulus and effect codes, we cannot ignore the role of the response modalities, which typically entail their own set of action effects. For example, vocal responses usually produce auditory effects. In Experiment 1, all three conditions used tasks with compatible stimuli and unmanipulated effects (from the response). That is, all conditions used a VM task, in which the visual stimulus was mapped to an unmanipulated visuospatial effect (from the manual response), and an AV task, in which an auditory stimulus was mapped to an unmanipulated auditory effect (from the vocal response). Thus, it is of interest as to whether this effect persists with different stimulus–response modality pairings. Experiment 2 explores this question.

### Experiment 2

In Experiment 1, dual-task costs were largest when the modality of the stimulus was incompatible with the modality of the manipulated action effect (RCEI condition). Given that all conditions used the same stimulus–response (VM/AV) pairings, differences in dual-task costs must result from the manipulated action effects. Thus, the motivation for Experiment 2 is to examine whether these differences generalize to other stimulus–response mappings and whether the manipulated action effects override the influence of the unmanipulated action effects.

To address this question, Experiment 2 used tasks with modality incompatible stimulus–response (and unmanipulated action effect) pairings (VV/AM), whereas the modality compatibility between the stimulus and manipulated action effect varied, as in Experiment 1. Thus, a VM task was paired with an AM task. In the response-incompatible/effect-compatible (RIEC) condition, the stimulus and manipulated action effect occurred in the same modality (e.g., visual stimulus, visual effect), but the unmanipulated action effect produced by the response (e.g., auditory effect) occurred in a modality that is incompatible with both the stimulus and the manipulated action effect. In the response-incompatible/effect- incompatible (RIEI) condition, the stimulus and manipulated action effect occurred in different modalities (e.g., visual stimulus, manipulated auditory effect), and the modality of the unmanipulated action effect occurred in a modality (e.g., auditory) that was incompatible with the stimulus but compatible with the manipulated action effect (e.g., unmanipulated auditory effect, manipulated auditory effect). In the response-incompatible/effect-

<table>
<thead>
<tr>
<th>Experiment (S-R pairing)</th>
<th>Stimulus (task)</th>
<th>Dual-task costs (ms)</th>
<th>Statistics</th>
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<td>INCOMP</td>
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<td>390</td>
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</table>

Note. Dual-task costs were calculated as the difference between AND blocks and OR blocks (see Table 1 for individual RTs for those block types). Across all experiments, there was a significant effect of task (visual or auditory), with dual-task costs consistently larger in the visual task (cf. Experiment 2), regardless of stimulus–effect pairings. There was a significant effect of condition in Experiments 1 and 3–5 (see individual experiments for statistical comparisons across conditions). VM = visual-manual; AV = auditory-manual; VV = visual-vocal; AM = auditory-manual; COMP = effect-compatible; INCOMP = effect-incompatible; UNMANIP = effect-unmanipulated.
unmanipulated (RIEU) condition, participants performed the VV and AM tasks with no manipulated action effect provided.

If dual-task performance is affected by the relationship between the stimuli and the manipulated effect codes, then the results should mirror those observed in Experiment 1: Smaller dual-task costs should be observed in the effect-compatible condition because these codes reside in similar representational domains. However, if response and unmanipulated action effects play a major role in dual-task costs even when additional (manipulated) action effects are included, then costs should be large across all three conditions because of increased crosstalk between codes. That is, across all conditions, stimuli are mapped to incompatible unmanipulated action effects (e.g., visual stimulus mapped to an auditory action effect from the vocal response), and this incompatibility may drive dual-task costs.

**Method**

**Participants.** Ninety-two students from the University of Iowa who did not participate in Experiment 1 participated in partial fulfillment of an introductory psychology course requirement. Data from 20 participants whose overall accuracy was less than 85%, likely from failures of the voice recognition software, were discarded and not analyzed, leaving 72 total participants whose data were analyzed. As in Experiment 1, there were three conditions: effect-compatible, -incompatible, and -unmanipulated. Participants were equally divided (24 per condition) among the conditions: effect-compatible, -incompatible, and -unmanipulated. Participants were equally divided (24 per condition) among the three conditions: response-incompatible/effect-compatible (RIEC; 20 female, $M_{age} = 19.33, SD_{age} = 1.17$); response-incompatible/effect-incompatible (RIEI; 17 female, $M_{age} = 19.17, SD_{age} = 1.05$); or response-incompatible/effect-unmanipulated (RIEU; 16 female, $M_{age} = 19.08, SD_{age} = 0.78$). Vision and hearing were reported as normal or corrected-to-normal.

**Procedure.** The procedure was identical to Experiment 1, with the exception that participants responded vocally to visually presented stimuli (VV task) and manually to aurally presented stimuli (AM task). The stimuli, responses, and manipulated action effects were identical to those used in Experiment 1 (see Table 1).

**Statistical analysis.** The analyses were conducted in a corresponding fashion to Experiment 1. In the RIEC and RIEI conditions, the first four blocks were excluded from analysis and treated as practice. In the RIEU condition, the first two blocks were excluded from analysis. The first four trials of each block were excluded from analysis. Therefore, we analyzed data from 10 blocks: two single-task, four OR, and four AND blocks. All responses given within the first 200 ms (0.2%) after stimulus onset or any RTs greater than 2,500 ms (2.5%) were excluded from analysis. Additionally, trials in which no response was detected were removed from analysis, in which one of both of the responses were incorrect, and trials following an error were removed from analysis of RT (10.0%). In sum, we removed 12.7% of trials from our final analysis.

**Results and Discussion**

**Single-task.** For the VV task, we observed no significant differences across conditions for RT (RIEC: 726 ms; RIEI: 743 ms; RIEU: 755 ms), $F(2, 69) = 0.39, p = .681, \eta^2 = .011$; and ER (RIEC: 6.5; RIEI: 7.2; RIEU: 4.8), $F(2, 69) = 0.68, p = .510, \eta^2 = .019$. For the AM task, we again observed no significant differences across conditions for RT (RIEC: 670 ms; RIEI: 611 ms; RIEU: 683 ms), $F(2, 69) = 1.63, p = .203, \eta^2 = .045$. For ER the AM task, there was unequal variance (Levene’s $p = .037$), therefore we switched to Brown-Forsythe $t$ tests. There were no observed differences between any of the three conditions (RIEC: 4.6; RIEI: 4.3; RIEU 2.4), $F(2, 36.108) = 2.94, p = .066, \eta^2 = .078$.

**Mixing costs.** We observed no significant differences in mixing costs across conditions for both RT (RIEC: 199 ms; RIEI: 256 ms; RIEU: 275 ms), $F(2, 69) = 1.49, p = .233, \eta^2 = .041$; and ER (RIEC: 4.8; RIEI: 3.6; RIEU 4.8), $F(2, 69) = 2.71, p = .073, \eta^2 = .073$, replicating what was observed in Experiment 1.

**Dual-task costs.** There were no significant differences in dual-task costs across the three conditions for both RT (RIEC: 903 ms; RIEI: 864 ms; RIEU: 885 ms), $F(2, 69) = 0.12, p = .887, \eta^2 = .003$; and ER (RIEC: 5.4; RIEI: 9.4; RIEU: 5.9), $F(2, 69) = 1.33, p = .271, \eta^2 = .037$.

Unlike Experiment 1, dual-task costs were similar across the compatible-, incompatible-, and unmanipulated-effect conditions. The lack of differences across conditions indicates that the stimulus–response pairings, independent of the manipulated action effects, played a role in the dual-task costs. This may result from the unmanipulated action effects associated with the responses. That is, across all conditions, a visual stimulus was mapped to an unmanipulated auditory action effect (from the vocal response) and an auditory stimulus was mapped to an unmanipulated visual spatial action effect (from the manual response). For example, even though the stimuli and manipulated action effects are compatible in the RIEC condition (e.g., visual stimulus, visual effect), the response (e.g., vocal) produces distal effects that may activate the competing (auditory) task. As such, crosstalk may have been high in all conditions, which may explain why dual-task costs were similar across conditions. The unmanipulated-effect condition showed robust and comparable dual-task costs to the manipulated-effect conditions, suggesting that the relationship between stimuli and unmanipulated effect (from the response) codes—a relationship theorized to underlie the modality compatibility effect (e.g., Hazeltine et al., 2006; Stephan & Koch, 2010, 2011)—may drive dual-task costs.

Although these findings support theories that attribute dual-task costs to increased crosstalk between the modalities of stimuli and (un)manipulated action effects, the results suggest that the effects of crosstalk do not appear to be additive. For instance, in the RIEC condition, both the stimulus-unmanipulated effect (e.g., visual stimulus, auditory effect from the vocal response) and unmanipulated effect-manipulated effect (e.g., auditory effect from the vocal response, manipulated visual effect) relationships are incompatible. Likewise, in the RIEI condition, both the stimulus-unmanipulated effect (e.g., visual stimulus, auditory effect from the vocal response) and unmanipulated effect-manipulated effect (e.g., auditory effect from the vocal response, manipulated visual effect) relationships are incompatible. When comparing the unmanipulated-effect conditions—which are most similar to previous studies examining the modality compatibility effect on dual-task costs—between Experiments 1 (VM/AV) and 2 (VV/AM), we observed a significant effect of Experiment, $t(46) = 4.31, p < .001, d = 1.25$, demonstrating that dual-task costs were smaller when the modalities of the stimuli and the unmanipulated action effects of the response were compatible. These results align with those previously reported in the literature (e.g., Göthe et al., 2016; Hazeltine et al., 2006; Stelzel et al., 2006).
unmanipulated effect and the stimulus-manipulated effect (e.g., visual stimulus, auditory effect from the vocal response) relationships are incompatible. Although there was an added source of crosstalk in these situations, dual-task costs were near-equivalent to those observed in the RIEU condition, in which there was only a single source of incompatibility—between the stimuli and unmanipulated action effects (from the responses). However, although there is an additional source of conflict in both the RIEC and RIEI conditions compared with the RIEU condition, each of the former conditions also includes a compatible mapping, either between the stimuli and manipulated effects (RIE condition; e.g., auditory stimulus-auditory manipulated effect) or between the unmanipulated and manipulated effects (RIEI condition; e.g., auditory effect from a vocal response-auditory manipulated effect). With this additional source of compatibility, the effects of one of the incompatible mappings may be diminished. In any case, it may simply be the presence, rather than the number, of competing codes in the incompatible modality that increases dual-task costs.

**Experiment 3**

Dual-task costs were smallest in the RCEC condition in Experiment 1, where the stimulus, unmanipulated effect (from the response), and manipulated effect codes resided in a similar representational domain within each task. Costs were larger in the RCEI condition of Experiment 1 and the RIEC and RIEI conditions of Experiment 2. Although these differences in dual-task costs between the compatible- and incompatible-manipulated effect conditions can be explained by increased crosstalk between tasks, an alternative possibility is that the costs may reflect changes in strategy: Participants may have delayed their vocal responses to not speak during the presentation of the auditory stimulus and/or manipulated auditory action effect. For example, participants in the RCEI condition of Experiment 1 may have delayed their vocal response so they did not speak over the auditory action effect of the other task to avoid interference. Likewise, participants in both the RIEC and RIEI conditions in Experiment 2 may have delayed their vocal response to not speak over the auditory stimulus of the other task. Alternatively, participants in the incompatible-effect conditions (Exp. 1: RCEI; Exp. 2: RIEI) may have postponed their manual response because it produced an auditory action effect that could have interfered with the auditory stimulus (Exp. 1) or vocal response (Exp. 2) of the other task. One aspect of the data supports this idea. Across experiments, manual responses were always produced faster than vocal responses, regardless of stimulus–effect modality compatibility. If participants responded manually to a stimulus that produced an auditory action effect, this may have caused them to delay their vocal response for the opposite task, thereby increasing dual-task costs. Alternatively, participants may have delayed a manual response that produced an auditory effect to ensure that they heard the auditory stimulus (of the other task) in full.

Note that it is never possible to respond to a stimulus for one task and speak over the stimulus for the other task if the tasks are performed correctly, because the stimuli are always presented at the same time. Nonetheless, participants may have adopted different strategies out of fear over speaking over the stimulus for the other task. In Experiment 3, we attempt to reduce these potential strategies by using two tasks with manual responses. Despite there being overlap between the response modalities for the two tasks—its a potential source of interference—we assume that this manipulation will reduce the likelihood of such strategies.

By testing two tasks that require manual responses, we aim to determine whether action effects impact dual-task costs when a single response modality is used. In the task-switching literature, it has been shown that modality compatibility effects on switch costs require that the two tasks have variability in both stimulus and response codes (and, thus, the response-related action effects; Fintor et al., 2018). It appears that when a single response modality is used, the modalities of the action effects do not alter switch costs, perhaps because there is no longer confusion about which response modality is appropriate. With regard to switch costs, modality incompatible action effects may not increase dual-task costs when there is a single response modality because the action effects would not increase confusion about the appropriate response modality.

In addition to shedding light on the source of the effect, extending these findings to tasks that both involve manual responses will demonstrate that action effects play a role in dual-task costs in situations involving two manual responses, which are common in both experimental and real-world settings.

**Method**

**Participants.** Eighty-one students from the University of Iowa who had not participated in Experiments 1 or 2 participated in partial fulfillment of an introductory psychology course requirement. Data from nine participants whose overall accuracy was less than 85% were discarded and not analyzed, leaving 72 total participants whose data were analyzed. Participants were equally divided into three conditions: response-manual/effect-compatible (RMEC; 19 female, $M_{\text{age}} = 18.79, SD_{\text{age}} = 1.18$); response-manual/effect-incompatible (RMEI; 19 female, $M_{\text{age}} = 18.83, SD_{\text{age}} = 1.09$); or response-manual/effect-unmanipulated (RMEU; 19 female, $M_{\text{age}} = 18.79, SD_{\text{age}} = 1.41$). Vision and hearing were reported as normal or corrected-to-normal.

**Procedure.** The procedure was identical to Experiments 1 and 2, except that participants responded manually to both visual and auditory stimuli. The VM task was identical to the VM task used in Experiment 1: participants responded manually (q/w/e keys) to a colored rose, leaf, or pond. The AM task was identical to the AM task used in Experiment 2, but different keys (u/i/o) were used: participants responded manually to a dog’s bark, cat’s meow, or bird’s chirp. The action effects were identical to those used in Experiments 1 and 2. Stimulus, response, and action effect pairings are shown in Table 1.

**Statistical analysis.** In the RMEC and RMEI conditions, the first four blocks (two practice, two single-task) were excluded from analysis and treated as practice. In the RMEU condition, the first two blocks (single-task) were excluded from analysis. As in Experiments 1 and 2, we analyzed data from 10 blocks—two single-task, four mixed, and four dual-task blocks. All responses given within the first 200 ms (2.0%) after stimulus onset or any RTs greater than 2500 ms (2.4%) were excluded from analysis. Additionally, we excluded trials in which no response was detected, in which one or both responses were incorrect, and trials following an error (6.9%). In sum, we removed 11.3% of trials from our final analysis.
Results and Discussion

**Single-task.** For the VM task, we observed no significant differences in single-task performance for both RT (RMEC: 528 ms; RMEI: 527 ms; RMEU: 547 ms), F(2, 69) = 0.55, p = .578, \( \eta^2_p = .016 \); and ER (RMEC: 3.4; RMEI: 4.0; RMEU: 3.4), F(2, 69) = 0.19, p = .830, \( \eta^2_p = .005 \). When compared with the identical VM task used in Experiment 1, there were no significant differences for both RT and ER across Experiments (RT: F1, 138 = 0.02, p = .896, \( \eta^2_p = .000 \); ER: F1, 138 = 0.81, p = .371, \( \eta^2_p = .006 \)); conditions (RT: F[2, 138] = 0.06, p = .939, \( \eta^2_p = .001 \); ER: F[2, 138] = 1.34, p = .266, \( \eta^2_p = .019 \)); nor a significant interaction (RT: F[2, 138] = 0.80, p = .452, \( \eta^2_p = .011 \); ER: F[2, 138] = 2.16, p = .119, \( \eta^2_p = .030 \)). For the AM task, we observed no significant differences between conditions for both RT (RMEC: 641 ms; RMEI: 643 ms; RMEU: 661 ms), F(2, 69) = 0.18, p = .837, \( \eta^2_p = .005 \), and ER (RMEC: 2.7; RMEI: 3.8; RMEU: 2.9), F(2, 69) = .578, p = .563, \( \eta^2_p = .016 \). When compared with the identical AM task used in Experiment 2, there were no significant differences for RT across Experiments, F(1, 138) = 0.07, p = .791, \( \eta^2_p = .001 \); conditions, F(2, 138) = 1.29, p = .279, \( \eta^2_p = .018 \); nor a significant interaction, F(2, 138) = 0.70, p = .501, \( \eta^2_p = .010 \). Likewise, for ER, there was no significant effect of Experiment, F(1, 138) = 0.27, p = .603, \( \eta^2_p = .002 \), nor an interaction, F(2, 138) = 0.72, p = .716, \( \eta^2_p = .010 \), but there was a significant effect of condition, F(2, 138) = 3.23, p = .042, \( \eta^2_p = .045 \).

**Mixing costs.** There were no significant differences in mixing costs across the three conditions for both RT (RMEC: 234 ms; RMEI: 268 ms; RMEU: 295 ms), F(2, 69) = 1.06, p = .351, \( \eta^2_p = .030 \), and ER (RMEC: 4.4; RMEI: 0.8; RMEU: 0.4), F(2, 69) = 2.86, p = .064, \( \eta^2_p = .077 \). These nonsignificant results replicate those observed in Experiments 1 and 2.

**Dual-task costs.** There was a significant effect of condition on dual-task costs, F(2, 69) = 3.39, p = .040, \( \eta^2_p = .089 \), indicating a similar pattern as observed in Experiment 1. Follow-up independent-samples t-tests revealed that dual-task costs were significantly smaller in the RMEC condition (831 ms) compared with either the RMEI (974 ms; t[46] = 2.27, p = .028, d = 0.65) and RMEU (973 ms; t[46] = 2.17, p = .035, d = 0.63) conditions, demonstrating that the compatibility between the stimulus and effect codes facilitates dual-task performance. There was no difference between the RMEI and RMEU conditions, t(46) = 0.02, p = .982, d = 0.01. For ER, there were no significant differences across conditions (RCEC: 1.8; RCEI: 5.2; RCEU: 2.9), F(2, 69) = 0.93, p = .399, \( \eta^2_p = .026 \).

As in Experiment 1, we observed smaller dual-task costs when the stimuli and action effects were compatible than when they were incompatible, even though the stimuli and responses were identical across conditions. By using tasks that both required manual responses, we removed the concern that participants were delaying vocal responses so that they would not interfere with auditory stimuli. However, it remains possible that participants strategically delay producing the auditory effects associated with the manual responses so that they did not interfere with the auditory stimulus, even though performing the task correctly should prevent this possibility. Moreover, the dual-task costs for the AM task, across all stimulus–effect modality pairings, were significantly smaller than for the VM task, F(1, 69) = 119.07, p < .001, \( \eta^2_p = .633 \) (see Table 3). This is inconsistent with the proposal that participants were delaying the auditory action effect to prevent interference with the auditory stimulus.

Although all conditions of Experiment 3 used two tasks that both required manual responses, dual-task costs were dependent on the compatibility between stimulus and manipulated effect codes. These results support the idea that modality compatibility effects reflect the interaction between stimulus and (response-related) action effect codes. When there is increased crosstalk between these codes, as in the RMEI condition, dual-task costs are larger. However, we note that the effects of action effects may be more pronounced in dual-task situations (compared with task-switching, e.g., Fintor et al., 2018), given that the action effects for both tasks are concurrently relevant, thereby increasing the likelihood of cross-task interactions.

Lastly, although the stimuli and manipulated effects were the same in the compatible conditions in Experiments 1 and 3, dual-task costs were much smaller in Experiment 1. We hypothesize that this is because Experiment 1 used two tasks with compatible stimulus-unmanipulated effect (from the response) modality pairings (VM, AV) whereas Experiment 3 used tasks with both compatible (VM) and incompatible (AM) stimulus-unmanipulated effect modality pairings. When both tasks require manual responses, the proprioceptive effects of the manual response in the AM task may activate the visual stimulus in the VM task, perhaps producing greater crosstalk between tasks.

**Experiment 4**

In Experiments 1–3, the stimuli and corresponding manipulated action effects were highly compatible at a representational level (see Table 1). That is, the stimuli depicted some physical aspect of the manipulated action effects related to the appropriate response, consistent with the principle of ideomotor compatibility (e.g., Greenwald & Shulman, 1973). In particular, in the compatible-effect visual task (i.e., visual stimulus, visual effect) in each experiment, the stimuli and manipulated action effects physically resembled one another (e.g., visual stimulus: colored leaf; visual effect: black-and-white leaf). This task with similar stimuli and manipulated action effects was never present in the incompatible-effect condition, which may explain why dual-task costs were larger in that condition in Experiments 1 and 3. Thus, it remains an open question whether the effects of the manipulated action effects are derived from their perceptual similarity or the shared modality with the stimuli.

To test this, we changed the stimuli and manipulated action effects in the compatible VM task so they were no longer physically similar. For example, if the visual stimulus was a picture of a lake, then the compatible visual action effect was a picture of a boat, whereas the incompatible auditory effect was the spoken word boat. Now, stimuli and effects no longer overlap in terms of physical compatibility, but only in terms of modality and conceptual compatibility.

Thus, if the modality compatibility effect is based on the physical resemblance between a perceptual event and its action effects, then dual-task costs should be similar between compatible- and incompatible-effect conditions, as there is no direct correspondence between stimuli and effects in the current experiment. However, if the modality compatibility effect is based on the compat-
ibility between the modalities of stimuli and action effects, then dual-task costs should be smaller when these modalities are compatible than when they are incompatible.

Method

Participants. Seventy-nine students from the University of Iowa who had not participated in the other three experiments completed the experiment in partial fulfillment of an introductory psychology course requirement. Data from seven participants whose overall accuracy was less than 85% were discarded and not analyzed, leaving 72 total participants whose data were analyzed. Participants were equally divided into three conditions: response-manual/effect-compatible (RMEC; 16 female, $M_{\text{age}} = 19.54, SD_{\text{age}} = 3.23$); response-manual/effect-incompatible (RMEI; 20 female, $M_{\text{age}} = 18.63, SD_{\text{age}} = 0.82$); or response-manual/effect-unmanipulated (RMEU; 14 female, $M_{\text{age}} = 18.58, SD_{\text{age}} = 0.78$). Vision and hearing were reported as normal or corrected-to-normal.

Procedure. The procedure was similar to Experiment 3. Two manual responses were again used to reduce potential strategic limitations on dual-task performance. We also used two-choice tasks rather than a pair of three-choice tasks (like Experiments 1–3) to reduce the overall dual-task costs. The visual stimuli were a colored picture of a road or pond presented within a 6.7° horizontal × 6.6° vertical black colored rectangle on a black background, and the auditory stimuli were a dog’s bark or a cat’s meow (350 ms duration, 11,025 Hz). Participants responded to the visual stimuli with the $q$ or $w$ keys and to the auditory stimuli with the $r$ or $i$ keys. Stimulus, response, and action effect pairings are shown in Table 1.

In the compatible effect condition, visual action effects were either a black-and-white picture of a car or boat, and the auditory action effects were either the spoken word dog or cat. In the incompatible effect condition, the visual action effects were either a black-and-white picture of a dog or cat, and the auditory action effects were either the spoken word car or boat. As in Experiments 1–3, participants were instructed to produce an action effect that corresponded to the input stimulus (e.g., seeing a picture of a road and producing a response that results in a picture of a car). The unmanipulated condition was identical, with the exception that a blank screen was presented following response execution for 350 ms.

As before, to emphasize the importance of linking a response with an action effect, participants in the RMEC and RMEI conditions first completed two practice blocks in which they were required to respond to the visually- or aurally presented word PRESS with any of the two key presses. The RMEU condition was identical with the exception that there were no PRESS practice blocks. Following those blocks, there were six single-task blocks divided equally between the VM and AM tasks. Next, they completed four mixed (OR) blocks and four dual-task (AND) blocks, with the order of these blocks counterbalanced across participants.

Statistical analysis. In the RMEC and RMEI conditions, the first four blocks were excluded from analysis and treated as practice. In the RMEU condition, the first two blocks were excluded from analysis. In sum, our final data analysis consisted of two single-task (one VM, one AM), four OR, and four AND blocks. All responses given within the first 200 ms (1.1%) after stimulus onset or any RTs greater than 2,500 ms (1.3%) were excluded from analysis. Additionally, we excluded trials in which no response was detected, one or both responses were incorrect, and trials following an error (5.3%). In sum, we removed 7.7% of trials from our final analysis.

Results and Discussion

Single-task. For the VM task, we observed no significant differences across conditions for both RT (RMEC: 497 ms; RMEI: 464 ms; RMEU: 486 ms), $F(2, 69) = 1.11, p = .336, \eta^2_p = .031$; and ER (RMEC: 3.5; RMEI: 3.8; RMEU: 5.3), $F(2, 69) = 1.44, p = .245, \eta^2_p = .400$. Similarly, for the AM task, we observed no significant differences across conditions for both RT (RMEC: 562 ms; RMEI: 559 ms; RMEU: 536 ms), $F(2, 69) = 0.29, p = .750, \eta^2_p = .008$; and ER (RMEC: 2.7; RMEI: 1.2; RMEU: 2.0), $F(2, 69) = 2.44, p = .095, \eta^2_p = .066$.

Mixing costs. There was a marginally significant effect of condition on mixing costs, $F(2, 69) = 3.10, p = .051, \eta^2_p = .082$, with numerically smaller costs in the RMEC condition (216 ms) compared with the RMEI (262 ms) and RMEU (301 ms) conditions. There was unequal variance for ER (Levene’s $p = .038$); therefore, we applied the Brown-Forsythe correction. There were no significant differences in ER across the three conditions (RMEC: 1.38; RMEI: 1.72; RMEU: 5.45), $F(2, 53.89) = 3.05, corr\ p = .055, \eta^2_p = .081$. This pattern is similar to that observed in Experiment 3.

Dual-task costs. There was a significant effect of condition on dual-task costs, $F(2, 69) = 3.53, p = .035, \eta^2_p = .093$. Follow-up $t$ tests revealed a significant difference between the RMEC (449 ms) and RMEI (570 ms) conditions, $t(46) = 2.74, p = .009, d = 0.79$. There were no significant differences between the RMEC and RMEU (531 ms) conditions, $t(46) = 1.68, p = .099, d = 0.48$ and between the RMEI and RMEU conditions, $t(46) = 0.83, p = .409, d = 0.24$. These results nearly replicate Experiment 3, with the exception that the difference between the RMEC and RMEU conditions was not significant, although the trend was in the same direction.

Error rates revealed a similar pattern. We observed a significant effect of condition on ER, $F(2, 69) = 6.13, p = .004, \eta^2_p = .151$. There were significant differences between the RMEI (2.2) and RMEU (3.4) conditions, $t(46) = 2.63, p = .012, d = 0.76$; and between the RMEI (2.8) and RMEU conditions, $t(46) = 3.15, p = .003, d = 0.91$. There was no observed difference between the RMEC and RMEI conditions, $t(46) = -.35, p = .750, d = 0.10$.

Although the stimuli and action effects were no longer similar at a representational level (e.g., visual stimulus: colored road; visual effect: black-and-white car), dual-task costs were still larger in the RMEI condition compared with the RMEC condition, replicating Experiment 3. Thus, these results are inconsistent with the idea that perception and action only interact if they have highly overlapping codes (i.e., physically compatible). Rather, perception and action appear to be bound by content-specific codes that can share modality- or conceptually related features.

Experiment 5

Although the results from Experiments 1, 3, and 4 demonstrate that dual-task costs are reduced when the modality of the stimulus and the modality of the manipulated action effect are compatible,
there are questions whether this extends to cases where the action effects are conceptually unrelated to the stimulus, because there is evidence that modality compatibility effects may stem from conceptual relatedness between codes (e.g., many AV tasks share verbal codes when both stimuli and responses are categorically related words; Schacherer & Hazeltine, 2019b). In each experiment conducted thus far, regardless of stimulus–effect compatibility, these codes have been conceptually related. In many real-world situations the action effects are not clearly related even conceptually to the stimuli and actions that led to their production. Thus, we examine whether the effect extends to cases where the relationship among the stimuli and action effects is arbitrary.

In Experiment 5, we used tasks without any conceptual relatedness between stimuli and action effects, on the assumption that under these conditions, conceptual relatedness will be equal across compatible and incompatible stimuli–effect pairings. The manipulated action effects associated with the nature images and animal noises were now arbitrary shapes and sounds. For instance, if the visual stimulus was a leaf, then the compatible visual action effect was a white circle, whereas the incompatible auditory action effect was a buzz sound. Although we have no independent measure of conceptual overlap, we assume that these stimuli and action effects have minimal conceptual overlap. Lastly, unlike previous experiments, we only tested conditions using manipulated action effects. That is, we elected not to include an unmanipulated-effect condition in the current experiment. Because the stimuli and responses were identical to those used in Experiment 3, the unmanipulated condition, in which no manipulated action effects are present, would have been identical to that used in Experiment 3.

Method

Participants. Fifty-four students from the University of Iowa who had not participated in any of the previous experiments completed the experiment in partial fulfillment of an introductory psychology course requirement. Data from six participants whose overall accuracy was less than 85% were discarded and not analyzed, leaving 48 participants whose data were analyzed. Participants were equally divided between the two conditions: response-manual/effect-compatible (RMEC; 15 female, $M_{age} = 18.71$, $SD_{age} = 0.99$); or response-manual/effect-incompatible (RMEI; 18 female, $M_{age} = 18.50$, $SD_{age} = 0.78$).

Procedure. The procedure was identical to Experiment 3. Participants responded manually to both visual colored images (leaf, rose, pond) and auditory animal sounds (dog, cat, bird). However, rather than providing action effects that were conceptually similar to the stimuli (as in Experiments 1–4), we provided action effects that had minimal conceptual relationship to the stimuli. The visual action effects were one of three white shapes: circle, square, or triangle; and the auditory action effects were one of three sounds: buzz, honk, or whistle. Because the action effects were no longer conceptually related to the stimuli, we used the same action effects for both the RMEC and RMEI conditions. For example, in the RMEC condition, participants linked colored stimuli to shape action effects and animal sounds to sound action effects. In the RMEI condition, participants linked colored images to sound action effects and animal sounds to shape action effects. Stimulus, response, and action effect pairings are shown in Table 1.

Results and Discussion

Single-task. For the VM task, there were no observed differences between conditions for both RT (RMEC: 521 ms; RMEI: 517 ms), $F(1, 46) = 0.05$, $p = .831$, $\eta^2 = .001$; and ER (RMEC: 4.4; RMEI: 4.4), $F(1, 46) < 0.001$, $p > .999$, $\eta^2 < .001$. Likewise, for the AM task, there were no observed differences between conditions for both RT (RMEC: 603 ms; RMEI: 642 ms), $F(1, 46) = 1.40$, $p = .244$, $\eta^2 = .029$; and ER (RMEC: 3.5; RMEI: 4.2), $F(1, 46) = 0.27$, $p = .604$, $\eta^2 = .006$. These results replicate those from the previous four experiments, demonstrating that the compatibility between the modalities of stimuli and action effects has no significant influence on single-task RTs and ER.

Mixing costs. For mixing costs, there were no differences between the conditions for both RT (RMEC: 271 ms; RMEI: 289 ms), $F(1, 46) = 0.18$, $p = .674$, $\eta^2 = .004$; and ER (RMEC: 3.07; RMEI: 4.23), $F(1, 46) = 0.16$, $p = .604$, $\eta^2 = .004$. Mixing costs were comparable to those observed in Experiment 3 (RMEC: 235 ms; RMEI: 264 ms) and Experiment 4 (RMEC: 213 ms; RMEI: 259 ms), which also used two manual-response tasks.

Dual-task costs. We observed a significant effect of condition on dual-task costs, $F(1, 46) = 4.90$, $p = .032$, $\eta^2 = .096$, demonstrating that dual-task costs were smaller in the RMEC condition (824 ms) than the RMEI condition (944 ms). There was a marginally significant difference in ER between conditions (RMEC: 0.68; RMEI: 0.79), $F(1, 46) = 4.01$, $p = .051$, $\eta^2 = .080$.

The results from Experiment 5 are consistent with those from Experiments 1, 3, and 4, indicating that when the stimulus and manipulated action effect share their modality, dual-task costs are reduced. Experiment 5 reveals that this effect generalizes to stimulus-manipulated effects that are not conceptually related—it appears to relate to the modalities of the stimuli and action effects. The results were highly similar to those of Experiment 3. Thus, when action effects share their modality with the stimuli of the other task, crosstalk is increased.

General Discussion

Theoretical accounts detailing the modality compatibility effect in dual-task performance (e.g., Göthe et al., 2016; Hazeltine et al., 2006; Stelzel et al., 2006) have proposed that dual-task costs are reduced for some task pairings because they involve combinations of modalities that are compatible. However, the idea of what makes the modalities of stimuli and responses compatible is muddy. Some accounts propose modality compatible task pairings engage central codes that interfere less with each other (e.g., Göthe...
et al., 2016; Hazeltine et al., 2006; Wickens, 1980, 1984), whereas other accounts propose that they reflect tendencies observed in everyday behavior (e.g., Hazeltine et al., 2006; Stephan & Koch, 2010, 2011, 2016) or connectivity with the brain (e.g., Stelzel et al., 2006).

In the present study, we note that vocal responses typically produce auditory action effects and manual responses produce action effects in a visuospatial domain and that this may be a source of the modality pairing effect. This idea is inspired by theories holding that actions (i.e., responses) are represented by their sensory consequences (i.e., action effects; Hommel et al., 2001; Prinz, 1990). Indeed, some researchers have theorized that modality compatibility may reflect the correspondence between stimulus and action effect modalities (e.g., Greenwald, 1972; Greenwald & Shulman, 1973; Halvorson & Hazeltine, 2015); yet no study had directly tested this idea. Here, we do so by examining how the correspondence between the stimulus and both unmanipulated (from the response) and manipulated action effect modalities influenced dual-task performance.

In Experiment 1, which used modality-compatible stimulus–response pairings (VM/AV), dual-task costs were smaller when the modality of the stimulus and the modality of the manipulated action effect were compatible compared with when they were incompatible or when there was no added action effect. To examine whether these effects generalize to other stimulus–response pairings, Experiment 2 used tasks with modality-incompatible stimulus–response pairings (VV/AM). Unlike Experiment 1, dual-task costs were similar across all conditions, suggesting that stimulus–response pairings, independent of (manipulated) action effects, affect dual-task performance. To account for potential speech-delaysing strategies (e.g., postponing vocal responses due to fear of speaking over the auditory stimulus or auditory action effect belonging to the other task) and explore the generality of the effect, Experiment 3 used two manual tasks (VM/AM). Like Experiment 1, dual-task costs were smallest in the compatible-effect condition. To determine whether these findings were dependent upon the perceptual similarity between stimuli and action effects (e.g., visual stimulus: colored leaf; visual effect: black-and-white leaf), we reduced the correspondence between these codes in Experiment 4. Again, costs were smallest in the compatible-effect condition. Lastly, to determine whether this modality compatibility effect extends to cases where stimuli and action effects are conceptually unrelated, we used tasks with minimal conceptual relatedness (e.g., dog’s bark stimulus, arbitrary sound effect) in Experiment 5. Like previous experiments (except Experiment 2), dual-task costs were smallest when stimulus–effect pairings were modality-compatible.

We propose that these findings are consistent with crosstalk accounts of dual-task costs (e.g., Hazeltine et al., 2006). According to these accounts, dual-task costs are reduced with compatible stimulus–effect pairs because there is less crosstalk between codes as they exist in a common representational domain within a task (e.g., Logan & Gordon, 2001; Navon & Miller, 1987). That is, central codes can easily map the two sources of auditory information to one another and the two sources of visual information to one another, reducing dual-task costs. In contrast, when stimulus–effect pairs are incompatible, a visual stimulus must be mapped to an auditory effect and an auditory stimulus must be mapped to a visual effect. Thus, the auditory information activated by a stimulus in one task may interfere with the auditory information activated by the action effect in the opposite task. As these codes are nearly simultaneously activated on dual-task trials, this increases crosstalk, resulting in larger dual-task costs. If the action effects are included in the central codes (see Stephan & Koch, 2016; Welford, 1952), then a VM task producing auditory action effects would interfere more with an AV task than would a VM task producing visual action effects.

Alternative Explanations

Although these results are consistent with crosstalk accounts (e.g., Hazeltine et al., 2006; Logan & Gordon, 2001; Navon & Miller, 1987), there are alternative explanations for these findings. For instance, dual-task costs may be smallest in compatible-effect pairings because stimulus and effect codes within a task all tap a similar working memory subsystem (e.g., Baddeley, 1986). That is, the codes in the visual stimulus/visual effect task may access a shared visuospatial working memory subsystem, and the codes in the auditory stimulus/auditory effect task may access a shared sound-based working memory subsystem. In incompatible-effect pairings, the stimuli and action effects within tasks access different working memory subsystems (visual stimulus/auditory effect; auditory stimulus/visual effect). Having to access multiple working memory subsystems may put a greater load on these shared systems, resulting in larger costs (see Hazeltine & Wifall, 2011).

Both the crosstalk and working memory accounts suggest that differences in dual-task performance stem from structural limitations inherent in the cognitive architecture (e.g., the inability to simultaneously process two tasks involving similar codes; see also, Oberauer & Kliegl, 2006). However, it is also possible that the differences in dual-task costs instead reflect strategic adaptations to the task demands (e.g., Meyer & Kieras, 1997a, 1997b). For example, in tasks involving auditory action effects, participants may have delayed their responses, so that the effects did not overlap with the auditory stimulus or vocal response for the other task. Note that because the stimuli for the two tasks were always presented simultaneously on dual-task trials, any response made after the triggering response should not have interfered with the perception of the stimulus for the other task. Nonetheless, this aspect of the design may not have prevented participants from taking a cautious approach. To reduce this possibility, we eliminated vocal responses in Experiment 3–5 and instead used tasks which both required manual responses. Regardless, the auditory action effect associated with the manual responses may have induced the same strategy, and it remains possible that dual-task costs were largest in the incompatible-effect condition because participants delayed producing an auditory effect for one task so it did not interfere with the auditory stimulus or vocal response of the other task.

However, the data argue against this interpretation. In four of the five experiments, dual-task costs were consistently greater for the visual (stimulus) task than the auditory (stimulus) task (see Table 3), even when the auditory action effect was in the opposite task than the auditory stimulus (i.e., incompatible-effect tasks). If the larger dual-task costs in the incompatible-effect conditions represented an effort to ensure that the auditory effect does not interfere with the auditory stimulus in the other task, the opposite
pattern—larger dual-task costs in the auditory task—would be expected in the incompatible-effect condition.

Perceptual Basis of Dual-Task Performance

In the present experiments, one surprising finding was that in conditions involving the coordination of two manual responses (Experiments 3 and 4), there were significantly (Experiment 3) or numerically (Experiment 4) smaller dual-task costs when responses produced modality-compatible action effects (i.e., compatible-effect condition) compared with when responses produced no manipulated action effects (i.e., unmanipulated-effect condition). That is, anticipating additional manipulated action effects reduced dual-task costs, highlighting the crucial role of action effects in determining dual-task costs. Intuitively, having to monitor additional action effects (e.g., an experimentally induced visual effect following response) should pose higher demands and produce greater dual-task costs than monitoring the unmanipulated tactile and proprioceptive action effects from pressing a key. However, if participants conceptualize the tasks as visual and auditory tasks (e.g., Hommel et al., 2001), rather than as two manual tasks (e.g., Heuer, 1995), then responses may be coded more efficiently, resulting in less crosstalk or confusability between tasks in the compatible-effect condition (see, Mechsner et al., 2001). This finding may have real world implications as it suggests that adding the appropriate action effects can allow tasks to be performed with less interference from other ongoing operations.

As such, these findings contrast traditional accounts of bimanual coordination (e.g., Heuer, 1995), which propose that dual-task costs arise from crosstalk between motor programs (i.e., manual responses). Rather than depending on the similarity between underlying motor responses, dual-task costs appear to be reduced according to how the two tasks are internally coded in terms of postresponse action effects. Taken together, these results suggest that dual-task coordination may be organized by representations of perceptual goals (i.e., action effects), rather than as the coordination of two motor processes (see also, Hazeltine, 2005; Mechsner et al., 2001).

Mixing Costs

Although accounts of dual-task costs (e.g., bottleneck, capacity-sharing, crosstalk) and mixing costs (e.g., working memory, task ambiguity) propose different underlying sources, both phenomena are influenced by manipulating stimulus–response pairings (e.g., Hazeltine et al., 2006; Schacherer & Hazeltine, 2019b), which suggests they may share an underlying cognitive control process (Hirsch, Nolden, Decker, & Koch, 2018).

However, the current findings suggest that dual-task and mixing costs may have distinct sources. Manipulated action effects were shown to significantly affect dual-task costs, but not mixing costs. In fact, all within-experiment analyses of mixing costs revealed no differences across any of the three conditions (compatible, incompatible, unmanipulated), whereas there were significant differences between compatible and incompatible conditions on dual-task costs in four of the five experiments. The finding that mixing costs (like single-task RTs) were not affected by action effects, but that dual-task costs were, suggests that action effects primarily affect online processes rather than preparatory ones. That is, representations of action effects may only be activated during the selection of specific responses.

Limitations

Although the present findings indicate that the relationship between stimuli and action effects affects dual-task performance, some limitations must be noted. Notably, despite our instructions emphasizing the link between stimuli and action effects, we have no independent measure of how the instructions and presentation of the action effects altered the participants’ representation of the task and the extent to which they intended to produce the manipulated action effect versus the motor movements. However, the fact that dual-task costs were consistently smaller (except Experiment 2) when the modalities of stimuli and action effects were compatible suggests that participants integrated the action effects into their representation of the task.

This issue raises the question of whether the modality compatibility effect is entirely due to action effects, or if action effects are just a contributor. To our knowledge, this is the first study to manipulate the modalities of stimuli and action effects in a dual-task procedure. In cases where no action effects are added, the responses still produce environmental consequences, and two features of the present data suggest that these may contribute to dual-task costs given that the manipulated effects do.

First, it appears that stimulus modalities and manipulated action effect modalities interact in a similar manner to how stimulus and unmanipulated action effect (i.e., distal effects of a motor response) modalities interact. That is, the pattern of dual-task costs in cases with no manipulated action effects is consistent with the pattern of action effects observed when they are manipulated. More specifically, dual-task costs were smaller (cf., Experiment 2) when the modality of the stimulus was compatible with the modality of the manipulated action effect, independent of unmanipulated action effects. Similarly, dual-task costs were smaller when the modality of the stimulus was compatible with the modality of the unmanipulated action effects.

Second, the results of Experiments 1 and 2 suggest that manipulated action effects interact with stimulus-unmanipulated effect (from the response) modality pairings. The fact that the three conditions in Experiment 2 showed near-equivalent dual-task costs is consistent with the proposal that both unmanipulated and manipulated action effects contribute to dual-task costs, given that the costs were high in all conditions. This pattern of uniformly large costs is expected if all conditions have crosstalk between the stimulus modality and the unmanipulated action effect (from the response) modality.

Finally, the current experiments involved only a single 1-hr session, and some studies of how modality pairings affect dual-task costs suggest that their role may be larger after several sessions of practice (e.g., Hazeltine et al., 2006). We can only speculate as to how the role of action effects would change over training. It is possible that practice would increase their impact as the associations between the response and action effect is strengthened with repeated performance. If so, then action effects would show a similar pattern to the stimulus–response modalities pairings, which would be consistent with the proposal that both reflect the complex representations engaged by response selection mech-
anisms. Alternatively, if the action effects alter strategy or create confusion between the stimuli and action effects, the opposite prediction that they would diminish with practice may hold. Future empirical work involving multiple sessions would therefore be useful in this regard.

Summary

In sum, the present experiments add to a growing body of work demonstrating how postresponse action effects are integrated into representation used by response selection processes. More specifically, these experiments demonstrate how the correspondence between the modality of the stimuli and the modality of the action effects affects the magnitude of dual-task costs. By specifying a mechanism underlying the modality compatibility effect in dual-task performance, the present findings highlight the role of stimulus and action effect representations in the cognitive architecture of response selection processes.

References


Received June 9, 2019
Revision received November 8, 2019
Accepted November 8, 2019

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