Research Article

Task Switching, Modality Compatibility, and the Supra-Modal Function of Eye Movements

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Abstract. Previous research suggested that specific pairings of stimulus and response modalities (visual-manual and auditory-vocal tasks) lead to better dual-task performance than other pairings (visual-vocal and auditory-manual tasks). In the present task-switching study, we further examined this modality compatibility effect and investigated the role of response modality by additionally studying oculomotor responses as an alternative to manual responses. Interestingly, the switch cost pattern revealed a much stronger modality compatibility effect for groups in which vocal and manual responses were combined as compared to a group involving vocal and oculomotor responses, where the modality compatibility effect was largely abolished. We suggest that in the vocal-manual response groups the modality compatibility effect is based on cross-talk of central processing codes due to preferred stimulus-response modality processing pathways, whereas the oculomotor response modality may be shielded against cross-talk due to the supra-modal functional importance of visual orientation.

Keywords: cognitive control, task switching, modality compatibility, oculomotor response, cross-talk, saccades

Being simultaneously engaged in two or more tasks results in performance costs (Pashler, 1998). The size of such costs has been shown to be determined by several factors, including temporal task structure (e.g., Meyer & Kieras, 1997a, 1997b; Pashler, 1994), processing content (e.g., Navon & Miller, 1987), and training (e.g., Schumacher et al., 2001). Recently, several studies examined stimulus and response modalities and their interrelation in both tasks.

Stimulus and response modalities in dual-tasking were already a prominent research topic in the 1970s and 1980s. Typically, studies utilized two complex continuous tasks (e.g., reading, writing, driving, etc.) which involved same versus different modalities. Whenever two tasks involved the same stimulus or response modality, dual-task costs (regarding response times and/or errors) were greater (e.g., Hirst, Neisser, & Spelke, 1978; Spelke, Hirst, & Neisser, 1976). These results led to multiple resource accounts of multitasking. For example, Wickens (1984, 2008) proposed that dual-task costs are determined by the extent to which time-shared tasks use the same processing structures, which are ordered along three dimensions: stage (e.g., perceptual, central, execution-related), codes (e.g., verbal, spatial), and modalities (e.g., visual, auditory). To the extent that two tasks draw on the same resources along each of these dimensions, performance is predicted to be worse. Note though that many of these studies involved fairly complex continuous tasks, which made it difficult to achieve full experimental control over the timing of cognitive processes (Pashler, 1994).

More recent evidence suggested that not only shared modalities *between* tasks are important, but also combinations of modalities *within* each task. For example, Hazeltine, Ruthruff, and Remington (2006) utilized a dual-task paradigm with simultaneous stimulus onset for both tasks. They compared the performance in a condition including auditory-vocal (AV) tasks and visual-manual (VM) tasks to that in a condition including visual-vocal (VV) and auditory-manual (AM) tasks. In AV tasks, participants responded to three different tones by saying "one," "two," or "three," and in the VM task they responded to visually presented words from the categories bug/food/tree by pressing one of three buttons. In the AM task, participants responded to the tones by pressing the buttons, and in the VV task they responded to the words by saying "bug"/"food"/"tree." The major finding was that combining VM and AV tasks led to smaller dual-task costs compared to combining VV and AM tasks, even though single-task performance was comparable across conditions. Hazeltine et al. (2006) and Ruthruff, Hazeltine, and Remington (2006) attributed this effect of modality compatibility to "natural tendencies" to bind certain stimulus modalities to certain response modalities (*preferred modality-specific S-R processing pathways*). These preferences may be based on overlearned and/or neurophysiologically hardwired modality associations (e.g., Hazeltine et al., 2006; Stephan & Koch, 2010). For example, we usually use visual information to guide manual movements and respond vocally to questions in oral communication. Furthermore, neurophysiological evidence suggested privileged brain pathways between specific sensory and (pre-)motor regions. Specifically, visual stimulation induces activity of the superior ventrolateral premotor (VLP) cortex, which is a part of the premotor cortex necessary for prehension. When stimulated auditorily, the activity in the

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VLP was located more inferiorly, in an area crucial for vocalization (Schubotz, 2007; Schubotz, von Cramon, & Lohmann, 2003). These results indicate that areas responsible for a certain response modality are directly activated by stimulation of the compatible stimulus modality, whereas no such association was found for incompatible modality mappings.

A more specific theoretical framework for explaining the modality compatibility effect refers to the notion of *ideomotor compatibility* (Greenwald, 1972). Greenwald proposed that actions are coded in terms of the anticipated mental image of the sensory feedback they produce, suggesting that the extent to which a stimulus resembles normally occurring sensory feedback of the response (e.g., saying a word in response to hearing it) affects dual-task costs.

In previous studies (Stephan & Koch, 2010), we extended this quite specific concept of ideomotor compatibility by generally suggesting that the identity of the stimulus modality and the modality of the usually occurring sensory consequences of the response may determine the modality compatibility effect (*response-effect modality compatibility*). For example, we typically experience changes in the visual scene as a result from moving our hands, which may result in an advantage for VM (vs. AM) tasks. The advantage for AV (vs. VV) tasks may stem from our experience that speaking typically creates audible effects. On the other hand, manual behavior only occasionally creates audible effects (e.g., while playing an instrument), and speaking seldom immediately results in visible effects. In this sense, action-effect modality congruency might be an underlying principle that accounts for modality compatibility effects, because preferred modality-specific processing pathways may emerge as a consequence of the functional match between specific sensory and motor systems.

Stephan and Koch (2010) further examined the modality compatibility effect in a task-switching paradigm, in which two or more tasks are presented sequentially and performance is compared between task repetitions and task switches. Typically, performance in switch trials is worse than in repetition trials ("switch costs"; see, e.g., Rogers & Monsell, 1995; for reviews see also Kiesel et al., 2010; Vandierendonck, Liefooghe, & Verbruggen, 2010). Specifically, in a modality compatible condition, Stephan and Koch (2010, 2011) had participants respond to visually presented diamonds on the left or right side of the screen by pressing a left or right key on a keyboard, and to tones presented on the left or right side by saying "links" (left) or "rechts" (right). In an incompatible condition, participants responded vocally to the diamonds by saying "links"/"rechts," and manually to the tones by pressing the left/right key. Stimuli were presented individually (i.e., visual *or* auditory) and the stimulus-response mapping was fixed within blocks, so that no additional task cues were necessary. Also note that in each modality compatibility condition, exactly the same visual and auditory stimuli were given, followed by the exact same responses. Therefore, it was possible to collapse the data across the two compatible tasks and across the two incompatible tasks in each condition to control for potential differences due to the specific modalities used in the individual-task combinations. Thus, any specific performance costs associated either with switching the stimulus modality (Lukas, Philipp, & Koch, 2010) or with switching the response modality (Philipp & Koch, 2005, 2010) should affect both modality compatibility conditions equally. As a result, the authors found higher switch costs when participants switched between modality incompatible tasks compared to switching between modality compatible tasks, even though single-task performance was comparable across modality compatibility conditions. These results suggest that whenever two tasks involve modality incompatible mappings, the preferred pattern of modality mappings has to be overcome as a whole. This conflict between mapping patterns should lead to cross-talk, eventually resulting in costs.

However, as of now empirical data and theory with respect to the modality compatibility effect were restricted to only two stimulus and response modalities, namely visual and auditory stimuli and manual and vocal responses (see also Huestegge & Hazeltine, 2011). In the present study, we aimed at further examining the notion of modality compatibility by additionally studying oculomotor responses as an alternative to manual responses. Recent research established that oculomotor responses can be considered as a response modality in the sense that they produce (and are subject to) interference in the context of other response demands (Huestegge, 2011; Huestegge & Adam, 2011; Huestegge & Koch, 2009, 2010a).

In the present study, we maintained the tasks used by Stephan and Koch (2010) for one group of participants (vocal-manual response group) to establish a solid modality compatibility baseline effect. Critically, we also implemented a vocal-oculomotor response group, for which manual responses were replaced by oculomotor responses, resulting in a condition including an AV task combined with a visual-oculomotor (VO) task and a condition with a VV task combined with an auditory-oculomotor (AO) task. Note that, for the sake of readability, we refer to VO tasks as "modality compatible" and to the AO tasks as "modality incompatible," even though the truth of this assumption is essentially at stake in the present study.

On the one hand, some characteristics of the visual system appear to suggest a comparable or even greater modality compatibility effect in the vocal-oculomotor response group compared to the vocal-manual response group. First, each saccade inevitably results in a substantial change of the visual stimulus at the current fixation location, while this is not always the case for manual behavior (e.g., we can move our hands under a table or behind our back). Second, the neurophysiological association between visual stimulus and oculomotor response should be quite strong, because visuo-motor processing is known to be controlled by a tightly knit network (e.g., Hutton, 2008; Munoz, Armstrong, & Coe, 2007; Sweeney, Luna, Keedy, McDowell, & Clementz, 2007), and even early visual processing areas (e.g., V1) directly project toward oculomotor control areas (e.g., Isa & Yoshida, 2009). Third, for the combination of visual stimulus and oculomotor response the same sensorimotor system (i.e., the eye) is involved.

On the other hand, it is also possible that the modality compatibility effect is weaker (or even absent) in the vocal-oculomotor response group. For example, it appears equally important to localize both visual and auditory cues for potential threats as fast as possible (in terms of a visual orientation response), so that both VO and AO tasks could be modality compatible. Furthermore, the visual system typically produces stability of a visual scene across multiple saccades (e.g., Bridgeman, Van der Hejiden, & Velichkovsky, 1994), so that the overall percept of a visual scene does not change as a result of saccade execution in the same way as the visual scene may change when we move our hands within our field of view. Additionally, we may have learned that our eye movements often have less actual impact on our environment than manual action. Due to these factors, the oculomotor response modality may be shielded against cross-talk in dual-task or task-switching situations, so that the modality compatibility effect may not (or to a lesser degree) occur for the vocal-oculomotor response group. The aim of the present study was to explore the status of oculomotor responses for modality compatibility in task switching.

Experiment 1a

Method

Participants

Thirty-two native German speakers with normal hearing and normal (or corrected to normal) vision (22 female and 10 male, mean age = 23.6 years) were tested. They received course credit or payment and gave their informed consent. Participants were randomly divided into two groups of 16 participants (vocal-manual response group vs. vocal-oculomotor response group).

Stimuli and Apparatus

In the *vocal-manual response group*, we used a setup as in a previous study (Stephan & Koch, 2010). Visual stimuli were white diamonds (width and height of 1.5 cm), presented against a black background either 1.25 cm left or right to the center of a 15″ display. Viewing distance amounted to 60 cm. As auditory stimuli we used 400 Hz tones presented via headphones either on the left or right ear. Vocal responses were made by saying the words "links" (left) or "rechts" (right). Accuracy was coded online by the experimenter, and a voice key was used to measure vocal RTs. Manual responses were registered by pressing a left (Ctrl) or right (Alt) key on a QWERTZ keyboard with the left versus right index fingers. Responses were always spatially compatible to the stimuli.

In the *vocal-oculomotor response group*, auditory stimuli and vocal responses were as in the vocal-manual response group. As visual stimuli, we presented a green fixation cross (width and height of 0.4 cm) on black background at the center of a 21″ display. Additionally, two green squares (width and height of 0.4 cm) were displayed to the left and right of the fixation cross, which were present throughout the experiment and served as targets for the oculomotor responses. In each trial, the central fixation cross was replaced by a white arrow (width of 1.6 cm and height of 0.9 cm) pointing to the left or right, which served as the imperative stimulus. Viewing distance amounted to 67 cm. Oculomotor responses were made by executing a saccade to the left or right target (green square) as indicated by arrow direction.

Saccade onset (of the right eye) was registered by using a head-mounted EyeLink II infrared reflection system (SR Research, Canada) with a temporal resolution of 500 Hz. Saccades were coded as correct if they reached the area of 1.5° surrounding the correct target (green square). A horizontal three-point calibration occurred at the beginning of each experimental block. A chin rest served to control viewing distance and minimized head movements. Whenever no oculomotor response was required, participants were instructed to remain fixated on the central fixation cross. Saccades (as well as manual responses) toward the incorrect direction and responses given in the incorrect modality were coded as errors.

Procedure

The experiment was run in a single session of about 45 min. At the beginning of the experiment, instructions were presented visually on the screen and orally by the experimenter. Participants were requested to respond accurately and fast.

Each participant took part in the modality compatible condition (i.e., VM and AV tasks for the vocal-manual response group and VO and AV tasks for the vocal-oculomotor response group) and in the incompatible condition (i.e., VV and AM tasks for the vocal-manual response group and VV and AO tasks for the vocal-oculomotor response group), with condition order counterbalanced across participants. In each modality compatibility condition, two single-task blocks (counterbalanced order) were followed by two task-switching blocks. In the single-task blocks, only one task was presented for eight practice trials and 40 experimental trials. The modality mapping was fixed within blocks. The two task-switching blocks contained both tasks (both either modality compatible or modality incompatible) in random order. In each condition, the first task-switching block was preceded by 16 practice trials. Both task-switching blocks consisted of 80 trials each.

In all blocks, the stimulus and response sequence was random, with the constraint that each stimulus appeared equally often. Each trial started with the onset of the imperative stimulus and lasted until a response was made or until 1,500 ms had elapsed. The response-stimulus interval (RSI) amounted to 600 ms.

Design

Group served as an independent between-subjects variable (vocal-manual response group vs. vocal-oculomotor response group). The independent within-subjects variables were modality compatibility (incompatible vs. compatible) and task transition (switch vs. repetition). RT and percentage of error (PE) were measured as dependent variables.

Table 1. Mean response times (RTs) and percentage of error (PE) for all response groups in Experiments 1a and 1b as a function of modality compatibility and task transition

	Task transition			
	Single task	Repetition	Switch	Switch costs
Experiment 1a				
Vocal-oculomotor response group				
Incompatible				
RT	310 (46)	387 (61)	459 (55)	72
PE	8.1 (3.9)	7.0 (7.3)	16.6 (8.8)	9.6
Compatible				
RT	330 (46)	383 (51)	467 (59)	84
PE	3.8 (2.2)	6.6 (3.9)	14.1 (8.3)	7.5
Vocal-manual response group				
Incompatible				
RT	332 (36)	460 (55)	554 (72)	94
PE	2.1 (1.8)	2.5 (2.7)	4.4 (2.5)	1.9
Compatible				
RT	345 (45)	452 (62)	510 (71)	58
PE	1.4 (1.7)	1.5 (1.8)	3.3 (2.9)	1.8
Experiment 1b				
Vocal-manual response group				
Incompatible				
RT	386 (41)	480 (56)	566 (52)	86
PE	1.5 (1.4)	1.8 (1.8)	3.6 (3.4)	1.8
Compatible				
RT	393 (49)	477 (55)	525 (73)	48
PE	3.0 (2.5)	1.8 (1.6)	2.5 (1.9)	0.7

Results and Discussion

Practice trials as well as the first two experimental trials in each block were excluded. Responses given within the first 50 ms after stimulus onset were discarded (1% in the vocal-manual response group; 3.1% in the vocal-oculomotor response group). Additionally, all trials in which no response was detected were excluded (5.5% in the vocal-manual response group; 2% in the vocal-oculomotor response group). RTs exceeding ±3 *SD* (intraindividually) from the mean were discarded as outliers (1.4% for the vocal-manual response group; 1.3% for the vocal-oculomotor response group). Also, error trials and immediately subsequent trials were excluded from the RT analysis. For each group, mean RTs and PEs were then collapsed across the two modality compatible tasks and across the two modality incompatible tasks to control for specific effects of the individual stimulus or response modalities (see Stephan & Koch, 2010). Statistical tests utilized an alpha level of 5%.

Single-Task Performance

To examine whether single-task performance differs between modality compatibility conditions and groups, a mixed ANOVA with group (manual vs. oculomotor) and the independent within-subject variable modality compatibility (compatible vs. incompatible) was run. For RT, it revealed a significant effect of modality compatibility, $F(1, 30) = 6.12$, $p < .05$, $\eta_p^2 = .169$, indicating faster RTs in incompatible tasks (321 ms) than in compatible tasks (337 ms). There was no significant main effect of group, $F(1, 30) = 1.78$, $p = .193$, $\eta_p^2 = .056$, and no significant interaction, $F < 1$.

For PE, the effect of modality compatibility was significant, too, $F(1, 30) = 13.22$, $p < .005$, $\eta_p^2 = .306$, indicating higher PE in incompatible tasks (5.1%) than in compatible tasks (2.6%). Note that this main effect of modality compatibility was reversed in the RT data, suggesting a speed-accuracy tradeoff. There was also a main effect of group, $F(1, 30) = 47.49$, $p < .001$, $\eta_p^2 = .613$, indicating smaller PE in the vocal-manual response group (1.8%) than in the vocal-oculomotor response group (5.9%). The interaction was significant, too, $F(1, 30) = 6.60$, $p < .05$, $\eta_p^2 = .180$, showing that the effect of modality compatibility was smaller in the vocal-manual response group (0.7%) than in the vocal-oculomotor response group (4.2%).

Taken together, the single-task data show that performance in the vocal-oculomotor group was generally somewhat more errorprone, but there was no clear performance difference for modality compatible and incompatible tasks, suggesting that overall task difficulty is not a relevant factor for any influence of modality compatibility in task switching.

Task-Switching Performance

RTs in task-switching blocks were submitted to a mixed ANOVA with the independent variables modality

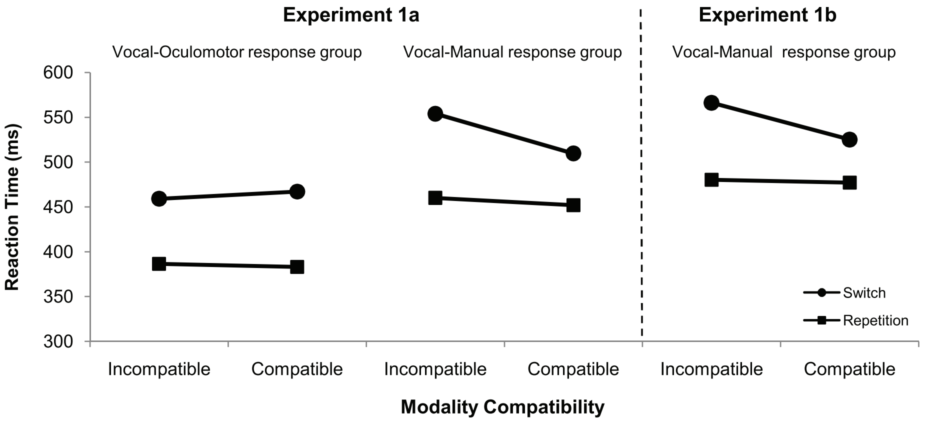

Figure 1. Mean response times (RTs) for all response groups as a function of modality compatibility and task transition.

compatibility, task transition, and group (manual vs. oculomotor). The effect of task transition was significant, $F(1, 30) = 196.01$, $p < .001$, $\eta_p^2 = .867$, indicating higher RTs on switches (497 ms) than on repetitions (421 ms). There was also a main effect of group, $F(1, 30) = 13.64$, $p < .005$, $\eta_p^2 = 312$, indicating longer RTs in the vocal-manual response group than in the vocal-oculomotor response group (494 vs. 424 ms) due to the overall short latencies of saccades. Crucially, the three-way interaction between group, modality compatibility, and task transition was significant, too, $F(1, 30) = 8.16$, $p < .01$, $\eta_p^2 = .214$. No other effect or interaction was significant (main effect of modality compatibility: $F(1, 30) = 2.35$, $p = .136$; $\eta_p^2 = .073$; interaction between modality compatibility and group: $F(1, 30) = 3.33$, $p = .078$, $\eta_p^2 = .100$; interaction between task transition and modality compatibility: $F(1, 30) = 2.21$, $p = .147$, $\eta_p^2 = .069$; interaction between task transition and group: $F < 1$; see Table 1; see Figure 1).

To further qualify the three-way interaction, we conducted separate two-way ANOVAs for each group. The ANOVA for the vocal-manual response group revealed a significant effect of task transition, $F(1, 15) = 73.82$, $p < .001$, $\eta_p^2 = .831$, indicating longer RTs on switches (532 ms) than on repetitions (456 ms). The effect of modality compatibility was significant, too, $F(1, 15) = 6.15$, $p < .05$, $\eta_p^2 = .291$, indicating shorter RT in compatible tasks than in incompatible tasks (481 vs. 507 ms). Importantly, the two-way interaction between task transition and modality compatibility was significant, $F(1, 15) = 13.04$, $p < .005$, $\eta_p^2 = .465$, indicating larger RT switch costs in incompatible tasks (94 ms) than in compatible tasks (58 ms), nicely confirming the data of Stephan and Koch (2010, 2011).

The same ANOVA for the vocal-oculomotor response group also revealed a significant effect of task transition, $F(1, 15) = 141.58$, $p < .001$, $\eta_p^2 = .904$, indicating higher RT on switches (463 ms) than on repetitions (385 ms). Most importantly, however, neither the main effect of modality compatibility nor the interaction was significant, Fs < 1, indicating that in the vocal-oculomotor response group switch costs were not significantly affected by modality compatibility. Note that the nonsignificance of the main effect of modality compatibility and the interaction between modality compatibility and task transition cannot be due to a floor effect, since RTs in single tasks were even much lower (320 ms) than in any of the task-switching conditions (see Figure 1).

The same three-way ANOVA on PE revealed a significant effect of task transition, $F(1, 30) = 71.65$, $p < .001$, $\eta_p^2 = .705$, indicating that mean PE was greater on switches (9.6%) than on repetitions (4.4%). There was also a main between-subject effect of group, $F(1, 30) = 47.25$, $p < .001$, $\eta_p^2 = .612$, indicating larger PE in the vocal-oculomotor response group than in the vocal-manual response group (11.1% vs. 2.9%).

While neither the main effect of modality compatibility nor its interactions were significant, Fs < 1, there was a significant two-way interaction between task transition and group, $F(1, 30) = 29.81$, $p > .001$, $\eta_p^2 = .498$, indicating larger PE switch costs in the vocal-oculomotor response group (8.6%) than in the vocal-manual response group (1.9%). Importantly, however, this interaction does not affect the interpretation of the crucial three-way interaction in the RT data because it could not account for the substantial difference regarding the modality compatibility effect between groups.

Further Analyses

To further investigate the difference in the modality compatibility effect between the two groups, we analyzed potential differences in the specific compatibility relations between the auditory versus visual stimulus and the manual versus oculomotor response. To this end, we conducted an additional ANOVA with the independent variable stimulus modality (auditory vs. visual) and the independent between-subjects variable response modality (manual vs. oculomotor) using the uncollapsed RT and PE data.

For RTs, the ANOVA revealed no significant main effect of stimulus modality, $F(1, 30) = 3.52$, $p = .07$, $\eta_p^2 = .105$, but a significant main effect of response modality, $F(1, 30) = 31.83$, $p < .001$, $\eta_p^2 = .515$, indicating overall faster RTs for oculomotor responses (333 ms) than for manual responses (428 ms). Interestingly, the two-way

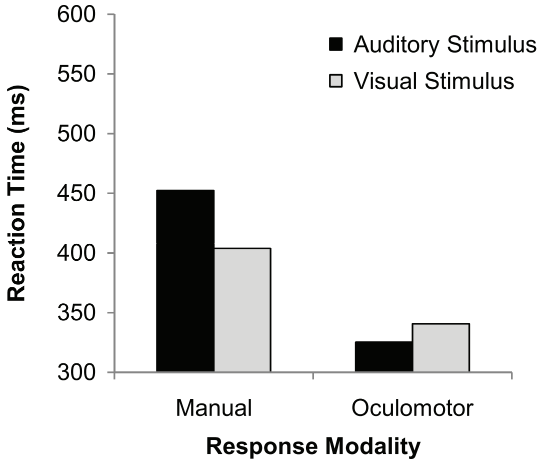

Figure 2. Mean response times (RTs) in Experiment 1a for the visual-manual task, the auditory-manual task, the visual-oculomotor task, and the auditory-oculomotor task as a function of stimulus modality and response modality.

interaction between stimulus and response modality was significant, too, $F(1, 30) = 13.24$, $p < .005$, $\eta_p^2 = .306$ (see Figure 2), indicating a stronger influence of the stimulus modality on manual responses (difference between auditory and visual stimulus: 48 ms) than for oculomotor responses (−16 ms, respectively; see Table 2).

For PE, the same two-way ANOVA yielded a significant effect of stimulus modality, $F(1, 30) = 8.36$, $p < .01$, $\eta_p^2 = .218$, indicating smaller PE in tasks with visual stimuli (2.8%) than in tasks with auditory stimuli (4.6%). There was also a significant effect of response modality, $F(1, 30) = 6.93$, $p < .05$, $\eta_p^2 = .188$, indicating smaller PE on oculomotor responses (2.4%) than on manual responses (5.1%) (see Table 2). The interaction was not significant, $F < 1$.

Taken together, the data show that the influence of modality compatibility in task switching is robust when using manual responses (replicating earlier findings; Stephan & Koch, 2010, 2011). However, this influence seems to disappear with oculomotor responses.

Note though that the different types of visual stimuli between groups may potentially compromise our group comparison. Specifically, we designed the oculomotor task in a way to make it more comparable to the processing demands of the manual task from Stephan and Koch (2010), but this included using a symbolic visual stimulus (i.e., a centrally presented left vs. right pointing arrow) instead of visually defined by physical spatial location. Therefore, it cannot be ruled out that differences in the visual stimuli might have any influence on the pattern of results. We conducted Experiment 1b to rule out such influences by using symbolic visual stimuli (instead of spatially defined visual stimuli) in a symbolic vocal-manual response group. Experiment 1b was aimed to replicate the modality compatibility effect in task switching with symbolic visual stimuli, and any difference of these data to that of the vocal-oculomotor response group in Experiment 1a cannot be due to stimulus differences between groups.

Experiment 1b

Method

Participants

Sixteen new native German speakers with normal hearing and normal (or corrected to normal) vision (14 female and 2 male, mean age = 22.1 years) were tested. They received course credit or payment and gave their informed consent.

Stimuli, Apparatus, Procedure, and Design

Auditory stimuli and vocal and manual responses were the same as in both response groups in Experiment 1a. In the symbolic vocal-manual response group, we used a maximally similar stimulus setup as in the vocal-oculomotor response group in Experiment 1a; for the analyses, we also included the data of that group for a direct comparison. Specifically, in each trial the central fixation cross was replaced by a white arrow (width of 1.6 cm and height of .09 cm) pointing to the left or right, which was the imperative stimulus.

Results and Discussion

Data analyses proceeded as in Experiment 1a. We excluded practice trials, the first two experimental trials in each block and responses given within the first 50 ms after stimulus onset (RT < 50 ms; 1.5%). Additionally, all trials in which no response was detected were excluded (5.4%). For RT analyses, outliers (1.4%) as well as error trials and immediately subsequent trials were excluded.

Single-Task Performance

We performed a mixed ANOVA with the independent within-subject variable modality compatibility (compatible vs. incompatible) and group (manual vs. oculomotor). For RT, this ANOVA revealed a significant effect of group, $F(1, 30) = 24.43$, $p < .001$, $\eta_p^2 = .449$, indicating faster RTs in the vocal-oculomotor group (320 ms) than in the symbolic vocal-manual group (390 ms). There was no significant main effect of modality compatibility, $F(1, 30) = 3.02$, $p = .092$, $\eta_p^2 = .092$, and no significant interaction between modality compatibility and group, $F < 1$.

For PE, the same ANOVA revealed a significant main effect of group, $F(1, 30) = 31.57$, $p < .001$, $\eta_p^2 = .513$, indicating smaller PE in the vocal-manual group (2.2%) than in the vocal-oculomotor group (5.9%). The effect of modality compatibility was not significant, $F(1, 30) = 3.93$, $p = .057$, $\eta_p^2 = .116$, but the interaction was significant, $F(1, 30) = 18.41$, $p < .001$, $\eta_p^2 = .380$, showing that the effect of modality compatibility was even smaller in the symbolic vocal-manual response group (−1.6%) compared to the vocal-oculomotor response group (4.2%). Thus,

Table 2. Mean response times (RTs) and percentage of error (PE) for all response groups in Experiments 1a and 1b as a function of task transition and modality compatibility for the individual tasks (*SD* in parentheses)

	Experiment 1a					Experiment 1b	
	Vocal-oculomotor response group			Vocal-manual response group		Vocal-manual response group	
	Repetition	Switch		Repetition	Switch	Repetition	Switch
	M (*SD*)	*M* (*SD*)		*M* (*SD*)	*M* (*SD*)	*M* (*SD*)	*M* (*SD*)
RT			RT				
Incompatible			Incompatible				
VV	482 (71)	559 (70)	VV	521 (76)	602 (91)	558 (70)	624 (70)
AO	291 (62)	359 (59)	AM	399 (61)	506 (64)	403 (60)	508 (59)
Compatible			Compatible				
AV	462 (80)	557 (89)	AV	538 (74)	578 (83)	560 (64)	603 (88)
VO	305 (40)	377 (57)	VM	366 (62)	442 (70)	394 (61)	447 (69)
PE			PE				
Incompatible			Incompatible				
VV	11.7 (13.2)	29.4 (18.2)	VV	0.2 (0.8)	1.1 (1.5)	0.5 (1.5)	2.5 (2.6)
AO	2.2 (3.1)	3.8 (2.3)	AM	4.8 (5.3)	7.7 (4.7)	3.0 (3.1)	4.6 (5.6)
Compatible			Compatible				
AV	12.0 (7.6)	25.9 (16.7)	AV	1.2 (2.2)	0.9 (1.6)	1.5 (1.9)	1.4 (1.8)
VO	1.3 (2.9)	2.4 (3.3)	VM	1.9 (3.1)	5.8 (5.4)	2.2 (1.8)	3.7 (3.2)

the effects of modality compatibility in single tasks cannot explain the effects in task switching.

Task-Switching Performance

The same three-way ANOVA as in Experiment 1a was conducted to compare performance between the vocal-oculomotor group (from Expt. 1a) and the symbolic vocal-manual group. The overall pattern of results was identical to that in Experiment 1a. Specifically, the effect of task transition on RTs was significant, $F(1, 30) = 203.35$, $p < .001$, $\eta_p^2 = .871$, indicating higher RT on switches (504 ms) than on repetitions (432 ms). There was also an effect of group, $F(1, 30) = 23.99$, $p < .001$, $\eta_p^2 = .444$, indicating longer RTs in the vocal-manual group than in the vocal-oculomotor group (512 vs. 424 ms). Crucially, the three-way interaction was significant, too, $F(1, 30) = 5.71$, $p < .05$, $\eta_p^2 = .160$. No other effect or interaction was significant (modality compatibility: $F(1, 30) = 2.08$, $p = .16$, $\eta_p^2 = .065$; interaction between modality compatibility and group: $F(1, 30) = 3.15$, $p = .086$, $\eta_p^2 = .095$; interaction between task transition and modality compatibility: $F(1, 30) = 1.65$, $p = .208$, $\eta_p^2 = .052$; interaction between task transition and group: $F(1, 30) = 1.2$, $p = .282$, $\eta_p^2 = .038$; see Figure 1).

A separate two-way ANOVA for the symbolic vocal-manual group revealed a significant effect of task transition, $F(1, 15) = 74.23$, $p < .001$, $\eta_p^2 = .823$, indicating higher RTs on switches (546 ms) than on repetitions (479 ms). The effect of modality compatibility was significant, too, $F(1, 15) = 8.60$, $p < .05$, $\eta_p^2 = .363$, indicating shorter RTs in compatible tasks than in incompatible tasks (501 vs. 523 ms). Importantly, the two-way interaction between task transition and modality compatibility was significant, $F(1, 15) = 5.78$, $p < .05$, $\eta_p^2 = .278$, indicating larger switch costs in incompatible tasks (86 ms) than in compatible tasks (48 ms), nicely confirming the modality compatibility effect in Experiment 1a (see Table 1).

For PE, the three-way ANOVA revealed a significant effect of task transition, $F(1, 30) = 61.01$, $p < .001$, $\eta_p^2 = .670$, indicating that mean PE was greater on switches (9.2%) than on repetitions (4.3%). There was also a main effect of group, $F(1, 30) = 55.70$, $p < .001$, $\eta_p^2 = .650$, indicating larger PE in the vocal-oculomotor response group than in the vocal-manual response group (11.1% vs. 2.4%). The two-way interaction between task transition and group was significant, too, $F(1, 30) = 33.96$, $p > .001$, $\eta_p^2 = .531$, indicating larger PE switch costs in the vocal-oculomotor group (8.6%) than in the symbolic vocal-manual group (1.2%). But neither the main effect of modality compatibility nor its interactions were significant (interaction of task transition and modality compatibility: $F(1, 30) = 1.61$, $p = .215$, $\eta_p^2 = .051$; all other Fs < 1). As in Experiment 1a, there was a speed-accuracy trade-off concerning the main effect of group when comparing the vocal-oculomotor response group and the symbolic vocal-manual response group. However, note that this trade-off does not affect the interpretation of the theoretically significant three-way interaction indicating the substantial group difference regarding the modality compatibility effect.

A separate two-way ANOVA only for the symbolic vocal-manual group revealed a significant effect of task transition, $F(1, 15) = 6.93$, $p < .05$, $\eta_p^2 = .316$, indicating that mean PE was greater on switches (3.0%) than on repetitions (1.8%). Neither the main effect of modality compatibility, $F(1, 15) = 1.314$, $p = .27$, $\eta_p^2 = .081$, nor the interaction, $F(1, 15) = 1.434$, $p = .25$, $\eta_p^2 = .087$, was significant.

We additionally conducted an analysis including both vocal-manual groups across experiments. Here we focus on effects of group. For RT in single-task blocks, the ANOVA revealed an effect of group, $F(1, 30) = 13.50$, $p < .005$, $\eta_p^2 = .310$, indicating faster RTs in the vocal-manual group (339 ms) than in the symbolic vocal-manual group (390 ms). The interaction of modality compatibility and group was not significant, $F < 1$. The same analysis for PE revealed no significant main effects [group: $F < 1$; modality compatibility: $F(1, 30) = 1.03$, $p = .32$, $\eta_p^2 = .033$], but the interaction was significant, $F(1, 30) = 7.82$, $p < .01$, $\eta_p^2 = .207$, showing that the effect of modality compatibility was slightly larger in the vocal-manual group (0.7%) than in the symbolic vocal-manual group (−1.6%). For RTs in the task-switching blocks, the critical interaction of task transition and modality compatibility was significant, $F(1, 30) = 15.71, p < .001, \eta_p^2 = .344$, indicating larger RT switch costs in incompatible tasks (90 ms) than in compatible tasks (53 ms), but this effect was not modulated by group, *F*s < 1, and there were no other significant effects of group, *F*s < 1. The same analysis for PE revealed, like for RT, no significant effect of the group variable, *F*s < 1. Taken together, these results show that the change in imperative stimuli across experiment had no sizable effect on task-switching performance.

Taken together, this additional analysis replicates the pattern of results found in Experiment 1a very well, including the critical three-way interaction. This strongly supports the conclusion that the absence of a modality compatibility effect on switch costs in the vocal-oculomotor group was not due to differences in the type of visual stimuli.

General Discussion

The present study was aimed at further examining the mechanisms behind the previously observed modality compatibility effects on switch costs in task switching by looking at the role of specific response modalities involved. To this end, we modified the task-switching procedure from Stephan and Koch (2010) by additionally examining modality compatibility with oculomotor responses (in a vocal-oculomotor response group) as an alternative to the previously studied manual responses (in two variants of a vocal-manual response group). In Experiment 1a, the procedure in the vocal-manual group was identical to that in Stephan and Koch (2010). In Experiment 1b, the stimulus conditions in the vocal-manual group were made more comparable to those in the vocal-oculomotor group.

While substantial switch costs were observed for all groups, the modality compatibility effect on switch costs was substantially greater in the vocal-manual response groups than in the vocal-oculomotor response group. Performance differences in single-task conditions cannot explain this differential pattern of results in task-switching conditions.

The substantial modality compatibility effect in the vocal-manual response groups replicates previous results (Stephan & Koch, 2010, 2011). To explain why specific modality bindings are compatible (e.g., VM and AV tasks) whereas others are not (e.g., VV and AM tasks), we reason that this may be due to usually experienced co-occurrences between modalities of responses and their typical sensory consequences (*response-effect modality compatibility*, see Stephan & Koch, 2010). Specifically, we argue that the prevalent tendency to bind stimuli in a certain stimulus modality to responses in the compatible response modality may need to be overcome when two incompatible tasks are combined. Thus, the conflict between preferred versus required binding patterns may result in cross-talk on the level of central processing codes whenever two modality incompatible tasks are combined (Stephan & Koch, 2010, 2011). In single-task situations, however, the absence of ambiguity for the individual modality bindings may explain why no beneficial modality compatibility effects are observed in single tasks.

However, VO tasks did not elicit a modality compatibility effect despite the fact that oculomotor responses are always followed by visual changes at fixation location (e.g., Huestegge & Koch, 2010b) and despite the neurophysiologically tightly knit network of visuo-motor processing (e.g., Hutton, 2008; Isa & Yoshida, 2009; Munoz et al., 2007; Sweeney et al., 2007). Thus, in the vocal-oculomotor group the cross-talk mechanism referred to above does not seem to affect performance. A potential explanation for this finding may be derived from the comparison between performance in the tasks with manual and oculomotor responses. In the condition with manual responses, there was a stronger performance advantage if stimuli were presented visually than when they were presented auditorily. In contrast, oculomotor performance was equally effective for both visual and auditory stimuli. Probably, the oculomotor system is unique in that it responds equally well to auditory and visual stimulation under certain conditions (e.g., Zambarbieri, 2002), so that in fact both VO and AO tasks could be considered modality compatible. This may be due to the importance to locate both visual and auditory cues for potential threats as fast as possible (in terms of a visual orientation response). In this way, both stimulus modalities were strongly bound to the oculomotor response modality. The exceptional strength of these bindings may have led to a relative shielding of the oculomotor response system from cross-talk in task-switching settings. Specifically, since the modality compatibility effect only occurs when *two* modality incompatible tasks are combined (and not in single-task conditions), one would not expect a strong modality compatibility effect if only one of the two tasks involves a non-preferred modality pairing.

Another potential explanation for the absence of the modality compatibility effect in the vocal-oculomotor group refers to the concept of response-effect modality compatibility. Although saccades do result in the acquisition of new visual information at the fovea, the visual system is known to maintain perceptual stability over time, and thus the percept is integrated over multiple saccades (e.g., Bridgeman et al., 1994; Melcher & Colby, 2008). Therefore, it could be argued that individual saccades typically do not result in a substantial change in the percept of a scene in general, even though new fixations may be targeted at different objects in a given scene. Thus, the cognitive system may have learned that oculomotor behavior does not impact on the real world in the same way as manual responses, which can substantially influence the visual scene. These factors may additionally have contributed to the lack of a privileged route between visual stimulus and oculomotor response.

Based on the results from Experiment 1a alone, one could have argued that the different types of visual stimuli between groups may potentially compromise the interpretation of group differences. In Experiment 1a, we designed the tasks in the vocal-manual response group in a way to ensure that we observe the same robust modality compatibility effect as found in previous studies (e.g., Stephan & Koch, 2010), which is an important precondition for a conclusive comparison with the new data from the vocal-oculomotor response group. Therefore, we decided against using the same visual stimuli in the vocal-oculomotor response group as in the vocal-manual response group to make task requirements for manual and oculomotor tasks more comparable in terms of the mental processes involved: the onset of peripheral visual stimuli in the vocal-oculomotor response group would have resulted in quasi-automatic attention shifts, whereas the visual stimuli in the vocal-manual response group do not automatically trigger manual responses. In the present design, both manual and oculomotor responses involve a similar amount of mental transformation processes (e.g., mapping a tone on the left ear to a movement of the left index finger, and mapping the direction of an arrow to the direction of a saccade). However, Experiment 1b clearly showed that the same results emerged when stimuli were comparable across groups. The central arrows used for the vocal-manual group in Experiment 1b slowed down single-task RTs compared with the peripheral stimuli from Experiment 1a, an effect similar to that known from literature on central (or endogenous) versus peripheral (or exogenous) cueing (e.g., Müller & Rabbitt, 1989; Posner, Snyder, & Davidson, 1980). Importantly, however, the comparison across experiments demonstrated that this stimulus change did not alter the result pattern in task-switching conditions, while the change of response modalities (manual vs. oculomotor) yielded quite substantial effects. This finding further highlights the overall importance of modality pairings (compared with factors like stimulus type) for cognitive mechanisms during multitasking.

In conclusion, preferred processing pathways (based on response-effect modality compatibility) may generally represent a basis for cross-talk effects whenever two modality incompatible tasks are combined. However, oculomotor responses appear to be shielded from this particular type of cross-talk. Accordingly, the modality compatibility effect appears to be strongly determined by the specific stimulus and response modalities and their characteristics, a finding that further supports the idea of modality-specific mechanisms in dual-task control.

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