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THE INTEGRATION OF TASK-SET COMPONENTS INTO COGNITIVE TASK REPRESENTATIONS

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The present study examined the cognitive representation of tasks ("task sets") using the task-switching paradigm. To do so, we manipulated the task-set components "judgment" (i.e., stimulus categories) and "response modality" orthogonally in two-componential switching experiments. In Experiment 1, we additionally manipulated the type of cues, whereas we manipulated the cue-stimulus interval (CSI) in Experiments 2 and 3. We found that the two task-set components were not represented independently but interacted. Furthermore, preparation was substantially better when both task-set components were cued simultaneously with a long CSI than when only one task-set component could be prepared. Therefore, we suppose that both task-set components were integrated into a single task representation and that task-set integration is necessary prior to response selection. Thus, even components that have been classified as motor-related so far (e.g., the response modality) need to be specified and integrated into a task representation before the selection of a response.

Introduction

Getting up in the morning, taking the bus to work, and writing an article are just some of the many different tasks that we may face during a day. In an environment that offers a whole variety of different tasks, one aim of cognitive psychology is to learn more about the cognitive representation of tasks. In this context, it is important to distinguish between a *task* itself and a *task set* (cf. Rogers & Monsell, 1995). In cognitive psychology, the term task can be basically understood as 'what subjects have to do in an experiment.' For

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example, a colour task might be to press a left key if a stimulus is red and a right key if a stimulus is green. In contrast, the term task set refers to the underlying task concept, or, put differently, to the cognitive representation of a task that enables subjects to perform this task.

In the field of cognitive psychology, one method to explore the cognitive representation of tasks is the task-switching paradigm. In this paradigm, subjects are introduced to different tasks (e.g., task A and B) and are required to execute them in a changing sequence (for reviews see Kiesel, Steinhauser, Wendt, Falkenstein, Jost, Philipp et al. (2010); Koch, Gade, Schuch, & Philipp, 2010; Monsell, 2003). When a task is repeated in two successive trials (e.g., task sequence AA) performance of subjects is usually better than when they have to switch the task from one trial to the next (e.g., task sequence BA). The difference in RT and error rate between a task repetition and a task switch is termed "shift cost" (e.g., Allport, Styles, & Hsieh, 1994; Meiran, 1996; Rogers & Monsell, 1995).

However, there is no general agreement on what actually is a task (set) in task switching. One attempt to explicitly characterise a task set was given by Rogers and Monsell (1995). They suggested that a task set includes all processes between stimulus encoding and response execution. "These processes must include categorization of sensory input with regard to a particular attribute or set of attributes; mapping the attribute's value by means of a decision criterion to one of a predetermined set of response categories; and execution of the motor responses used to signal that response category" (Rogers & Monsell, 1995, p. 208). Similarly, Vandierendonck, Christiaens, and Liefooghe (2008, p. 1248) describe a task set as a "temporary representation [that] contains the parameters needed for the correct execution of a task, such as the relevant stimulus dimension, the stimulus-response mapping, and the response modality". A similar notion of parameters is found in the ECTVA model by Logan and Gordon (2001). Their control parameters contain, besides others, a priority parameter that gives priority to one of certain stimulus features, and a bias parameter that biases the selection of certain response alternatives. Task switching in the context of the ECTVA model is described as switching some (or all) of these control parameters.

Note that all these descriptions mention different components of a task set. In this way, a task set is not assumed to be a unitary concept, as it might be inferred from some models that invoke the notion of central task units (e.g., Gilbert & Shallice, 2002). Rather, a task set is thought to consist of different components.

The assumption that a task set consists of different components brings about the question of which task-set components exist and which are relevant for the cognitive representation of tasks. It could be argued that a task-set component is relevant for the cognitive representation of a task (i.e., at least for the distinct representations of two tasks) if a shift cost was found when subjects switch between two tasks that differ in this task-set component only. Thus, based on previous task-switching studies, the following task-set components can be considered to be relevant for task representations: stimulus modalities (e.g., Lukas, Philipp, & Koch, 2010; Quinlan & Hill, 1999), stimulus dimensions (e.g., Allport et al., 1994), stimulus categories (e.g., Meiran, 1996; Rogers & Monsell, 1995), stimulus category - response category mappings (Sc-Rc mappings; e.g., Kleinsorge, Heuer, & Schmidtke, 2004), and response categories (e.g., Meuter & Allport, 1999; Philipp, Gade, & Koch, 2007). One possible task-set component, namely the response modality (cf. the description of a task set by Vandierendonck et al., 2008), has not received much empirical attention yet. However, although there is no study in which the shift cost for switching between response modalities were measured, a number of studies indicated that response modalities play a critical role in the cognitive representation of tasks (Arrington, Altmann, & Carr, 2003; Philipp & Koch, 2005; Sohn & Anderson, 2003; Yeung & Monsell, 2003).

If we believed that a task set consist of different components and that all of the above mentioned components play a role in the cognitive representation of tasks – there are still two questions that remain to be answered: 1) do all task-set components have the same functional role in the cognitive representation of tasks and 2) when and how are different components structured and integrated into the task set. To further examine these questions, we specifically focus on two task-set components, namely the stimulus categories or judgment (e.g., is a digit odd or even) as a "cognitive" component and the response modality (e.g., respond vocally) as a "motor" component. In the present study, we will propose that 1) different task set components like the judgment and the response modality have the same functional role in a task set and that 2) these task-set components have to be integrated into a single task representation prior to the selection of a response.

To explore the representation of different task-set components (i.e., judgments and response modalities), we used two-componential task switching (cf. Kleinsorge & Heuer, 1999). This means that not *one* task-set component was manipulated but that *two* task-set components were manipulated independently. Thus, subjects in the present study switched between a magnitude judgment (is a digit smaller or larger than 5) and a parity (odd or even) judgment and between two response modalities (e.g., vocal and manual responses). Note that each judgment could be combined with each response modality, so that four different judgment/modality combinations were possible. Thus, in two successive trials both the judgment and the modality could be repeated ("repeat trials"), the judgment could be repeated but the response modality was switched ("modality-switch trial"), the modality could be repeated but the judgment was switched ("judgment-switch trial"), or both the judgment and the response modality could be switched ("two-componential switch trial"). The resulting shift-cost pattern was supposed to indicate how the task-set components judgment and response modality are represented cognitively.

Previous studies with two-componential task switching (e.g., Hahn, Andersen, & Kramer, 2003; Hübner, Futterer, & Steinhauser, 2001; Hunt & Kingstone, 2004; Kleinsorge, 2004; Kleinsorge & Heuer, 1999; Murray, De Santis, Thut, & Wylie, 2009; Vandierendonck et al., 2008) revealed a number of different shift-cost patterns – and different notions about cognitive task representations, respectively. Vandierendonck and colleagues (2008) specifically tested these different notions against each other. The results of their study provide empirical evidence that a task set has a "flat organization" (Vandierendonck et al., p. 1248), in which all task-set components play the same role for the cognitive representation of the task, so that a change in either one or both components results in a new task set. This assumed flat organisation is supported by the fact that all studies mentioned above observed an under-additive shift-cost pattern, indicating that both task-set components are integrated into one single task representation.

In an under-additive shift cost pattern, the cost of switching two task-set components from one trial to the next is smaller than the sum of costs for switching either task-set component individually (i.e., shift cost for switching two components < shift cost for switching the first component + shift cost for switching the second component). Thus, a clearly under-additive pattern occurs when the shift cost for switching two components is the same as the shift cost for switching one component (i.e., shift cost for two components = shift cost for the first component = shift cost for the second component). In contrast, when the cost of switching two task-set components is equal to the *sum* of costs for switching both task-set components individually (i.e., shift cost for two components = shift cost for the first component + shift cost for the second component), the shift-cost pattern is additive.

Whereas an under-additive shift-cost pattern indicates that the task-set components are not switched independently but are integrated into one task set, so that switching either one or two components results in a complete switch of the relevant task set, an additive shift-cost pattern indicates the linear organisation of task-set components. The important point in this notion is that task-set components are ordered in a linear fashion and are represented as individual, independent modules – at least when affecting different processing stages (e.g., response selection, and response execution, see the additive factors logic, Sternberg, 1969). Consequently, switching one component but not the entire task set appears to be possible.

As mentioned above, previous two-componential task-switching studies observed an under-additive shift-cost pattern. However, with respect to these studies it is also important to note that subjects usually had to switch either between two judgments and two stimulus modalities (Hunt & Kingstone, 2004; Murray et al., 2009), two judgments and two stimulus dimensions (Hübner et al., 2001; Vandierendonck et al., 2008), or two judgments and two stimulus-response mapping (Kleinsorge, 2004; Kleinsorge & Heuer, 1999). In either way, one could argue that both task-set components have to be specified (and integrated into a task set) in order to select the correct response. For example, a subject has to know which judgment to apply to select the correct stimulus category and he/she has to know how to map this stimulus category to a response. However, this is different when subjects switch between judgments and response modalities. Here, one could argue that the decision as to which response modality to use in a given trial is necessary only *after* an abstract response category was selected. For example, the response category "right" that might have been selected to indicate an odd number is mapped to the response modality "manual," resulting in a key press with the right index finger. Thus, one could also argue that there is a linear organisation of task-set components in which a manipulation of judgments and response modalities should have additive effects. In other words, switching the judgment and switching the response modality would be independent.

The present study manipulated judgments and response modalities to test whether the proposed flat organisation of task sets (Vandierendonck et al., 2008) can be generalised even to two-componential switching conditions including one motor-related task-set component. Furthermore, we tested the notion of a flat vs. a linear organisation of the task set with respect to task preparation. On the one hand, we used different cues (i.e., one visual and one auditory cue vs. two visual cues vs. an integrated cue) in Experiment 1. On the other hand, we manipulated the preparation time in Experiments 2 and 3.

Experiment 1

In Experiment 1, subjects switched between two numerical judgments (magnitude and parity) *and* two response modalities (vocal and manual). Both task-set components varied independently, so that each judgment could be combined with each response modality.

The corresponding shift-cost pattern was supposed to indicate how response modalities and judgments are represented cognitively. A flat and integrated representation of the task-set components should lead to an under-additive shift-cost pattern. That is, the best performance should be observed in repeat trials; one- and two-componential switch trials should result in about the same performance. In contrast, a linear and independent organisation of task-set components should result in additive effects of judgment switching and response-modality switching.

We also examined whether the type of cues influences the (independent or integrated) representation of task-set components. Both the judgment and the response modality were cued simultaneously and the preparation time was held constant at 600 ms. Yet, the way in which both components were indicated varied between subjects. In the first cue group ("2 modalities" group), the form of the cue frame indicated one task-set component and the pitch of a tone indicated the other task-set component. Thus, the cues were presented in different modalities (auditory vs. visual). In the second cue group ("2 visual" group), one task-set component again was indicated by the form of the frame and the second component was indicated by the colour of the frame, leading to two visually presented cues. In the third cue group ("integrated cue" group), the form of the frame indicated both task-set components. Here, four different frames (square, diamond, circle, and triangle) were used. Each frame was assigned to a specific combination of both components (e.g., a square indicated a combination of parity judgment and manual responses).

If the representation of the task-set components were influenced by the type of cues, we would expect a difference between the cue groups. Whereas the use of different cues for each task-set component (as in the 2 modalities group and the 2 visual group) might favour an independent representation of both task-set components, integrated cues might lead to an integrated task representation (see also Vandierendonck et al., 2008 for a discussion). A possible difference between cue groups, thus, might be related to whether a specific cue is associated with both or only one component, leading to an individual vs. integrated retrieval of task-set components (see Gade & Koch, 2007; Miyake, Emerson, Padilla, & Ahn, 2004).

Method

Subjects

Forty-eight subjects (37 female and 11 male, mean age = 25.3 years) were tested and received 10 € for participation. Sixteen subjects were randomly assigned to each of the different experimental cue groups (2 modalities, 2 vocal, and integrated cues).

Stimuli and tasks

The stimuli consisted of the digits 1-9, excluding 5. Subjects had to decide whether a digit was smaller or larger than 5 (magnitude judgment) or whether it was odd or even (parity judgment). Stimuli were presented one at a time in white at the centre of a black screen (15" monitor) connected to an IBM-compatible PC. The digits were 1 cm high and approximately 0.5 cm wide. The viewing distance was approximately 60 cm.

The type of cues was varied between subjects. In the 2 modalities group, for half of the subjects the cue frame served as judgment cue (a diamond, 5.3 cm x 5.3 cm, indicated the magnitude task and a square, 3.8 cm x 3.8 cm, indicated the parity task). The response modality was cued by a tone presented simultaneously to the cue frame for 50 ms. A high tone (600 Hz) always indicated vocal responses and a low tone (200 Hz) indicated manual responses. For the other half of subjects the meaning of the cues was reversed so that the frame indicated the response modality (i.e., diamond for vocal responses and square for manual responses) and the tone indicated the judgment (i.e., the high tone for parity and the low tone for magnitude). In the 2 visual group, for half of the subjects the form of the cue frame served as judgment cue (a diamond indicated the magnitude task and a square indicated the parity task) and the colour of the cue frame served as response-modality cue (red for vocal responses and blue for manual responses). For the other half of subjects the meaning of the cues was reversed so that the colour of the frame indicated the judgment (red for magnitude and blue for parity) and the form of the frame indicated the response modality (diamond for vocal responses and square for manual responses). In the integrated cue group, the form of the cue frame indicated both judgment and response modality. For half of the subjects a diamond indicated the combination of magnitude and vocal responses, a square indicated magnitude/manual, a triangle (5.3 cm x 4.2 cm) indicated parity/vocal, and a circle (4.2 cm x 4.2 cm) indicated parity/manual. For the other half of subjects the diamond indicated magnitude/vocal, the square indicated parity/vocal, the triangle indicated magnitude/manual, and the circle indicated parity/manual.

Vocal responses were expressed by saying "left" or "right" (i.e., subjects had to say the German words "links" and "rechts"). Speech onset was recorded using a voice-key; "left" and "right" responses were online coded by the experimenter with the left and right cursor key. Manual responses were made on an external keyboard with two response keys (1.2 cm x 1.7 cm) for the left and right index finger. Response keys were separated by 3.8 cm.

Procedure

The experiment was run with one subject at a time in a single session of approximately 75 minutes. Instructions were both given on the monitor and orally. Instructions emphasised speed as well as accuracy. An instruction sheet concerning the meaning of the cues and the Sc-Rc mapping (e.g., odd-left) was placed in front of subjects throughout the experiment. The Sc-Rc mappings were counterbalanced across subjects.

A trial started with a black screen followed by a cue. After 600 ms preparation time (cue-stimulus interval, CSI), the stimulus was presented in the middle of the cue frame. The interval between the response and the following cue (response-cue interval, RSI) was 1000 ms after manual responses. Vocal trials had approximately the same RCI. However, the fixed RCI interval of non-vocal trials was reduced by 300 ms in vocal trials in order to compensate for the time the experimenter needed to code the vocal response. Subjects always received visual error feedback for 500 ms when they pressed the wrong key or responded with the wrong response modality (German: “Falsche Antwort”).

The experiment started with one practice block with twenty trials. The experiment itself consisted of eight blocks of 96 trials each. The sequence of trials was controlled for an equal number of each numerical judgment, stimulus category (odd vs. even, or smaller vs. larger), judgment sequence (judgment repetition vs. judgment switch), response modality, response side per modality (right vs. left), and modality sequence (modality repetition vs. modality switch). Immediate repetition of a stimulus was excluded.

Design

Judgment transition (judgment repetition vs. judgment switch) and modality transition (modality repetition vs. modality switch) were within-subject independent variables. Cue type (2 modalities vs. 2 visual vs. integrated cues) was a between-subjects variable. RTs and error percentage were measured as dependent variables. For all analyses, significance was tested at alpha = .05.

Results

The first two trials of each block were discarded from analysis. Additionally, all trials with RT below 200 ms (0.2% of the remaining trials) were discarded from both RT and error analysis. For RT analysis, only correct trials preceded by at least one other correct trial were included. RT analysis was based on median RT because the median RT is known to be less affected by outliers (cf. Ratcliff, 1993). The use of median RT seemed to be indicated by a rather high variability in vocal responses. Error analysis was based on the mean error rate of all trials that were preceded by at least one correct trial. The overall error rate of all trials was 8.1%. RT and error data are shown in Table 1.

RT analysis

A three-way repeated measures analysis of variance (ANOVA) with judgment transition and modality transition as within-subject variables and with cue type as between-subjects variable was conducted. The analysis revealed significant main effects of judgment transition ($F(1, 45) = 68.6$; MSE = 20537.8; $p < .001$; $\eta_p^2 = .604$) and modality transition ($F(1, 45) = 94.7$; MSE = 26580.7; $p < .001$; $\eta_p^2 = .678$). Importantly, the interaction of judgment transition and modality transition was significant ($F(1, 45) = 38.6$; MSE = 14168.2; $p < .001$; $\eta_p^2 = .461$).

Table 1

Experiment 1: RT in ms (error percentage) as a function of judgment transition (judgment repetition vs. judgment switch), modality transition (modality repetition vs. modality switch), and type of cues (2 modalities vs. 2 visual vs. integrated cues)

	Judgment transition			
	repetition		switch	
	Modality transition			
	repetition	switch	repetition	switch
	repeat trials	modality-switch trials	judgment-switch trials	two-componential switch trials
2 modalities group				
CSI 600	791 (4.4)	1064 (11.9)	1024 (6.8)	1131 (9.4)
2 visual group				
CSI 600	690 (2.6)	1032 (8.4)	982 (6.1)	1133 (8.7)
Integrated cues group				
CSI 600	690 (3.8)	1082 (9.7)	999 (7.8)	1109 (9.3)

To specify the interaction of judgment transition and modality transition, the RTs of repeat, judgment-switch, modality-switch and two-componential switch trials were compared with paired samples t-tests (2-tailed; see Figure 1). For these post-hoc analyses the alpha-level was adjusted according to the Bonferroni correction (alpha was reduced to 0.008). Trials in which both judgment and response modality were repeated (i.e., repeat trials, 723 ms) differed significantly from modality-switch trials (1059 ms, $t(47) = 9.3$; $p < .001$), judgment-switch trials (1001 ms, $t(47) = 8.3$; $p < .001$), and two-componential switch trials (1124 ms, $t(47) = 10.3$; $p < .001$). The difference between modality-switch trials and judgment-switch trials was close to significance ($t(47) = 2.8$; $p = .008$). Judgment-switch trials ($t(1, 47) = 6.2$; $p < .001$) and modality-switch trials ($t(47) = 3.7$; $p = .001$) were significantly faster than two-componential switch trials.

The main effect of cue type was not significant ($F < 1.1$) and did not interact with any within-subject variable (Fs < 1). Thus, the data indicate that the type of cues did not influence judgment switching or modality switching. Most important, cue type also had no effect on the interaction of judgment and response modality.

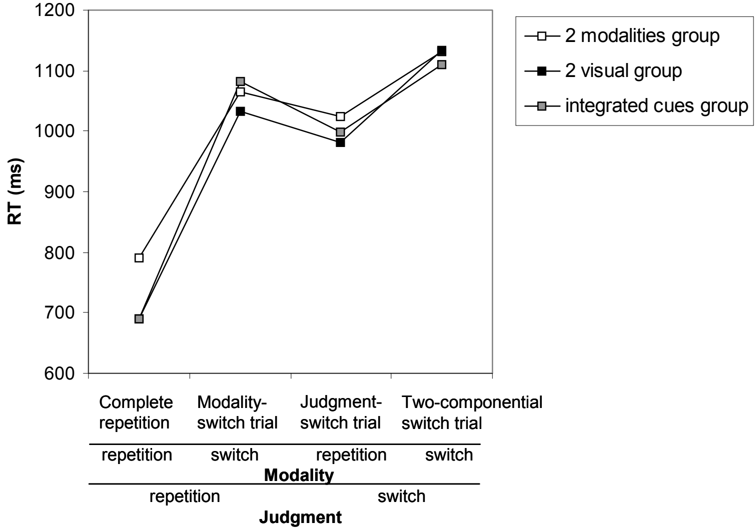

Figure 1
Experiment 1. Reaction times (RTs) as a function of judgment transition (judgment repetition vs. judgment switch) and modality transition (modality repetition vs. modality switch)

Error analysis

The same three-way ANOVA with judgment transition, modality transition, and cue type was conducted on the error data. The analysis revealed significant effects of both judgment transition ($F(1, 45) = 10.8$; MSE = 6.4; $p < .01$; $\eta_p^2 = .194$) and modality transition ($F(1, 45) = 53.2$; MSE = 17.1; $p < .001$; $\eta_p^2 = .542$). The interaction of judgment transition and modality transition was significant ($F(1, 45) = 43.4$; MSE = 4.8; $p < .001$; $\eta_p^2 = .491$). The same post-hoc analyses were conducted as described in the RT analysis. Again repeat trials (3.6%) were different from modality-switch trials (10.0%, $t(47) = 8.9$; $p < .001$), judgment-switch trials (6.9%, $t(47) = 6.8$; $p < .001$), and two-componential switch trials (9.1%, $t(47) = 7.2$; $p < .001$). The comparison of both one-componential switch trials showed more errors when switching the modality only as compared to switching the judgment only ($t(47) = 5.1$; $p < .001$). Whereas a modality-switch trial was not different from a two-componential switch trial ($t(47) = 1.8$; $p = .083$), the error rate in a judgment-switch trial was significantly lower than in a two-componential switch trial ($t(47) = 3.8$; $p < .001$).

The main effect of cue type was not significant ($F < 1$). Additionally, neither modality-shift cost nor the interaction of judgment transition and modality transition were affected by cue type ($F < 1$). The data pattern suggested that the 2 visual group (1.9%) and the integrated cues group (1.9%) had larger judgment-shift cost than the 2 modalities group (-0.1%) but the corresponding interaction of judgment transition and cue type was not significant ($F(2, 45) = 3.1$; MSE = 6.4; $p = .055$; $\eta_p^2 = .121$).

Discussion

The pattern of results showed both an effect of judgment switching and an effect of modality switching. Most important, the interaction of judgment transition and modality transition demonstrated that both effects were not independent of each other. Subjects had a clear repetition benefit when both the judgment and the response modality were repeated from one trial to the next. Additionally, although two-componential switch trials led to slower responses than any one-componential switch trial, the data pattern was clearly underadditive. The result pattern in the error data confirmed the non-additivity but differed slightly from the RT pattern, such that switching the judgment only resulted in fewer errors than a two-componential switch, whereas there was no difference between switching the modality only and a two-componential switch.

The data pattern did not show significant differences between the cue groups (i.e., 2 modality, 2 visual, and integrated cues). This finding indicates that the representation and integration of two task-set components is independent of the way those components are indicated. The type of cues, thus, appears to have no influence on how the task-set component is represented.

Taken together, the shift-cost pattern of Experiment 1 clearly contradicts the idea that judgment and response modality are represented independently. Rather, the interaction of judgment switching and response modality switching indicates that both task-set components are integrated into one cognitive task representation (e.g., the representation of a magnitude/vocal task). To further explore this assumed integration process, the duration of the preparation time has to be taken into account as a possible influencing factor. A study of Kleinsorge, Heuer, and Schmidtke (2002) provided first evidence that the duration of the preparatory interval can influence the shift-cost pattern in a two-componential switching study. With no preparation time, these authors report that the performance level depended on the type of switch trial. However, when the preparation time was increased to 1200 ms, subjects showed a similar performance level in all types of switch trials (cf. Hübner et al., 2001). Thus, it could be argued that the preparation time affects the shift-cost pattern.

Experiment 2

In Experiment 2, we held the type of cues constant (i.e., 2 modality cues; form of a frame and pitch of a tone) but manipulated the preparation time. That is, both cues were provided simultaneously either 100 ms or 1000 ms before the imperative stimulus.

Method

Subjects

Twenty-four new subjects (19 female and 5 male, mean age = 24.0 years) were tested and received 10 € for participation.

Stimuli, tasks, procedure, and design

One subject was tested at a time in a single session of approximately 75 minutes. Stimuli and numerical judgments were identical to Experiment 1. Thus, subjects switched between two numerical judgments and between two response modalities. However, to increase the generality, we used three different response-modality combinations in Experiment 2: vocal vs. manual responses, vocal vs. foot response, or manual vs. foot responses. Subjects were evenly assigned to these response-modality combinations. Foot responses were given on a separate external keyboard with two response keys (6.0 cm by 6.0 cm, separated by 23.5 cm) for the left and right foot.

The form of the cue frame indicated the relevant judgment (diamond for magnitude and square for parity), and a high or low tone indicated response modality. The high tone always indicated the (anatomically) “higher” modality (i.e., vocal responses in the vocal/manual and vocal/foot combination and manual responses in the manual/foot combination) and the low tone the “lower” modality. Both cues were presented either 100 ms or 1000 ms before stimulus onset.

Two practice blocks were run with ten trials each. One practice block had a short CSI (100 ms), the other a long CSI (1000 ms). The experiment itself consisted of eight blocks of 96 trials each. Before each block, subjects were informed about the CSI in the next block. Blocks with short and long CSI alternated; CSI duration in the first block was counterbalanced across subjects.

Judgment transition (judgment repetition vs. judgment switch), modality transition (modality repetition vs. modality switch), and CSI (100 ms vs. 1000 ms) were within-subject independent variables. Response-modality combination (vocal/manual vs. vocal/foot vs. manual/foot) was a between-subject variable. RTs and error percentage were measured as dependent variables.

Results

The first two trials of each block and all trials with an RT below 200 ms (0.2% of the remaining trials) were discarded. RT analysis was based on median RT and included only correct trials preceded by at least one other correct trial. Error analysis was based on the mean error rate of all trials that were preceded by at least one correct trial. The overall error rate of all trials was 12.4%. RT and error data are shown in Table 2.

RT analysis

A four-way ANOVA with judgment transition, modality transition, and CSI as within-subject variables and with response-modality combination as between-subjects variable was conducted. The analysis revealed significant main effects of judgment transition ($F(1, 21) = 29.3$; MSE = 27166.6; $p < .001$; $\eta_p^2 = .583$) and modality transition ($F(1, 21) = 77.7$; MSE = 17872.5; $p < .001$; $\eta_p^2 = .787$); the interaction of judgment transition and modality transition was significant ($F(1, 21) = 24.8$; MSE = 17723.2; $p < .001$; $\eta_p^2 = .541$).

Table 2

Experiment 2: RT in ms (error percentage) as a function of judgment transition (judgment repetition vs. judgment switch), modality transition (modality repetition vs. modality switch), response-modality combination (vocal/manual vs. vocal/foot vs. manual/foot), and cue-stimulus interval (CSI; 100 ms vs. 1000 ms)

	Judgment transition			
	repetition		switch	
	Modality transition			
	repetition	switch	repetition	switch
	repeat trials	modality-switch trials	judgment-switch trials	two-componential switch trials
Vocal/manual group				
CSI 100	1043 (4.9)	1424 (18.0)	1327 (9.3)	1539 (17.2)
CSI 1000	709 (7.0)	904 (16.3)	878 (10.2)	944 (20.8)
Vocal/foot group				
CSI 100	922 (4.6)	1275 (14.6)	1192 (7.1)	1277 (10.2)
CSI 1000	687 (5.6)	823 (13.7)	857 (8.6)	939 (10.1)
Manual/foot group				
CSI 100	916 (6.0)	1273 (16.9)	1167 (14.3)	1207 (15.3)
CSI 1000	705 (5.8)	877 (13.8)	908 (9.9)	869 (11.7)

As regards preparation time, the main effect of CSI was significant ($F(1, 21) = 122.1$; MSE = 54312.7; $p < .001$; $\eta_p^2 = .853$). RTs decreased with a long preparation time as compared to a short preparation time (842 ms vs. 1214 ms). CSI did not affect judgment transition ($F < 2.0$; $p > .17$) but modality transition ($F(1, 21) = 22.0$; MSE = 10041.8; $p < .001$; $\eta_p^2 = .512$). Additionally, the three-way interaction of judgment transition, modality transition, and CSI was significant ($F(1, 21) = 10.3$; MSE = 4283.6; $p = .01$; $\eta_p^2 = .328$). To qualify this interaction, the RTs of repeat, judgment-switch, modality-switch, and two-componential switch trials were compared with paired samples t-tests (2-tailed). To examine the effect of short and long preparation time on the shift-cost pattern, this comparison was calculated for blocks with short and blocks with long CSI separately. The alpha-level was adjusted according to the Bonferroni correction (alpha was reduced to 0.008).

With a short preparation time, trials in which both judgment and response modality were repeated (960 ms, Figure 2) differed significantly from modality-switch trials (1324 ms, $t(23) = 9.6$; $p < .001$), judgment-switch trials (1229 ms, $t(23) = 7.6$; $p < .001$), and two-componential switch trials (1341 ms, $t(23) = 9.1$; $p < .001$). Switching the judgment only was significantly different

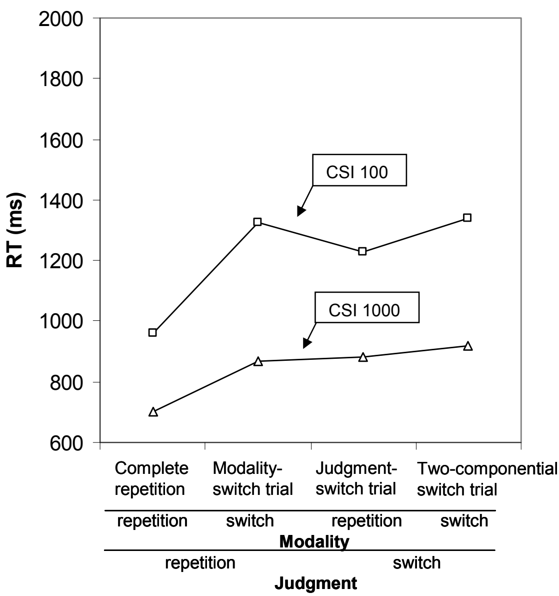

Figure 2

Experiment 2. Reaction times (RTs) as a function of judgment transition (judgment repetition vs. judgment switch), modality transition (modality repetition vs. modality switch), and cue-stimulus interval (CSI; 100 ms vs. 1000 ms).

from switching the modality only ($t(23) = 4.0$; $p = .001$) and from switching both components ($t(23) = 4.3$; $p < .001$), whereas the difference between switching the modality only and switching both components was not significant ($t < 1$). With a long preparation time, again repeat trials (700 ms) differed significantly from modality-switch trials (878 ms, $t(1, 23) = 4.3$; $p < .001$), judgment-switch trials (881 ms, $t(23) = 4.0$; $p = .001$), and two-componential switch trials (918 ms, $t(23) = 4.5$; $p < .001$). However, the three types of switch trials did not differ from each other ($ts < 2.1$; $ps > .05$).

The effect of the response-modality combination variable was not significant ($F < 1.0$) and this variable did not interact with any within-subject variable ($Fs < 3.0$; $ps \geq .08$).

Error analysis

The same four-way ANOVA on the error data revealed significant effects of both judgment transition ($F(1, 21) = 5.6$; MSE = 18.8; $p < .05$; $\eta_p^2 = .210$) and modality transition ($F(1, 21) = 28.9$; MSE = 83.2; $p < .001$; $\eta_p^2 = .579$). The interaction of judgment transition and modality transition was significant ($F(1, 21) = 36.5$; MSE = 10.4; $p < .001$; $\eta_p^2 = .635$).

The effect of CSI was not significant in the error data ($F < 1.0$). Also, the three-way interaction of judgment transition, modality transition, and CSI was not significant ($F(1, 21) = 4.3$; MSE = 9.2; $p = .051$; $\eta_p^2 = .169$). As neither the main effect of CSI nor the three-way interaction of judgment transition, modality transition, and CSI were significant we did not conduct the same post-hoc analyses as described in the RT analysis.

Like in RT data, the main effect of response-modality combination was not significant ($F < 1.1$) in the error data. However, there was a significant interaction of judgment transition, modality transition, and response-modality combination ($F(2, 21) = 4.2$; MSE = 10.4; $p < .05$; $\eta_p^2 = .285$). This interaction can be best characterised by the fact that the error rate in the vocal/manual group was rather high in two-componential switch trials, so that the error rate in two-componential switch trials was higher than the error rate in modality-switch trials. In both other groups, the error rate was higher in a modality-switch trial than in a two-componential switch trial. Also, both vocal/manual combination and manual/foot combination showed a judgment-shift cost, whereas the vocal/foot combination showed a small trend in the opposite direction (judgment-shift cost of -0.7%) but the interaction of judgment transition and response-modality combination was not significant ($F(2, 21) = 2.9$; MSE = 18.8; $p = .078$; $\eta_p^2 = .215$). Finally, the analysis revealed a significant interaction of CSI and response-modality combination ($F(2, 21) = 3.5$; MSE = 21.5; $p < .05$; $\eta_p^2 = .251$). In the manual/foot group, a long CSI numerically reduced the error rate (from 13.2% to 10.3%, $F(1, 7) = 3.9$; MSE = 34.2; $p =$

.089; $\eta_p^2 = .357$), whereas in the other groups the error rate was even slightly increased with a long CSI (12.3% vs. 13.6%, $F(1, 7) < 1.3$, $p > .3$, in the vocal/manual group, and 9.1% vs. 9.5%, $F < 1$, in the vocal/foot group). No other main effect or interaction was significant (Fs < 1.5; ps > .2).

Discussion

As regards the general shift-cost pattern, Experiment 2 replicated the under-additive interaction between judgment switching and response-modality switching. Although we found some effects of the response-modality combination, we could not demonstrate any substantial differences in the general shift-cost pattern. Therefore, we cautiously conclude that there are no important differences as a function of which two response modalities are used in a two-componential switching experiment. Most important in this context is the finding that, for each response-modality combination, the shift-cost pattern clearly demonstrates an under-additive interaction of both task-set components.

The manipulation of preparation time showed that subjects were faster after a long preparation time than after a short preparation time and this preparation benefit was larger in switch trials (on average 409 ms) than in repetition trials (260 ms), replicating results from one-componential switching studies (e.g., Meiran, 1996). The most important question concerning the preparation time, however, was whether a long preparation time changes the shift-cost pattern (cf. Kleinsorge et al., 2002). We could replicate this finding for the RT data, for which we found no difference in the three types of switch trials in blocks with a long preparation time, whereas the three types of switch trials differed in blocks with short preparation time. In contrast, in the error data the shift-cost pattern was not substantially influenced by the duration of the preparatory interval (like in Kleinsorge et al., 2002).

Importantly, the expected signature for a flat organisation of the task set (i.e., no difference between the different types of switch trials; cf. Vandierendonck et al., 2008) was clearly present after a long preparation time. As in one-componential tasks there seems to be a "residual shift-cost pattern," in which there is no difference between one- and two-componential switch trials (cf. Hübner et al., 2001; Kleinsorge et al., 2002). To account for this finding, one could assume that the integration of task-set components into one task representation is possible during the preparatory interval and can be completed if the preparation time is long enough. In such a case, switching the task is the same irrespective of whether one or two components are switched from one trial to the next. An important consequence of this assumption would be that preparation time in a two-componential switching experiment is most effective when both task-set components are indicated before the onset of the imperative stimulus, so that task-set integration is possible. To test this assumption, we manipulated the preparatory interval for both task-set components individually in Experiment 3.

Experiment 3

In Experiment 3, we focused on the preparation of one vs. two task-set components. To do so, judgment and response modality were cued independently. Consequently, subjects were able to prepare for none, one, or two of the relevant task-set components during a long preparatory interval (1000 ms vs. 100 ms).

To disentangle the effects of judgment preparation and modality preparation, we analyse the four different preparation conditions as factorial combination of judgment preparation and modality preparation. If preparation was specifically effective when both task-set components were presented 1000 ms before the onset of the imperative stimulus, we should find an interaction of judgment preparation and modality preparation. If, however, both task-set components can be prepared individually, the effects should be additive.

Method

Subjects

Sixteen (11 female and 5 male, mean age = 24.3 years) new subjects participated. All subjects received 10 € or partial course credit for participation.

Stimuli, tasks, procedure, and design

The experiment was run with one subject at a time in a single session of approximately 75 minutes. Stimuli and numerical judgments were identical to previous experiments. For all participants, we used two independent visual cues (cf. the 2 visual group of Experiment 1). The cue frame served as judgment cue (a diamond indicated the magnitude task and a square indicated the parity task) and the colour of the cue frame served as response-modality cue (red for vocal responses and blue for manual responses, please note that we used vocal vs. manual responses only in Experiment 3 as the response-modality combination had no influence on the data pattern in Experiment 2).

As each task-set component (i.e., judgment and response modality) was independently cued either 100 ms or 1000 ms before the onset of the imperative stimulus, four different cuing conditions can be differentiated. 1) "No preparation," that is both task-set components were cued simultaneously 100 ms prior to stimulus onset by a coloured diamond or square. 2) The judgment was indicated before the response modality. In this case, a white frame indicating the judgment was presented 1000 ms prior to stimulus, which turned red or blue 100 ms prior to stimulus onset. 3) The response modality was indicated before the judgment. In this case, a red or blue cue with the shape of a star (i.e., diamond and square were superimposed) was presented 1000 ms prior to stimulus onset, which changed its shape to a diamond or square 100 ms prior to stimulus onset. 4) Both task-set components were cued simultaneously 1000 ms prior to stimulus onset by a coloured diamond or square. The four cuing conditions were intermixed in blocks (i.e., one practice block with 16 trials and ten blocks with 96 trials each) and unpredictable for subjects.

Judgment transition (judgment repetition vs. judgment switch), modality transition (modality repetition vs. modality switch), judgment preparation (judgment indicated at 100 ms vs. 1000 ms), and modality preparation (judgment indicated at 100 ms vs. 1000 ms) were within-subject independent variables. RTs and error percentage were measured as dependent variables. We focus on theoretically important effects only in the Result section. Yet, the full pattern of main effects and interactions is shown in Table 3, RT data are shown in Figure 3.

Results

The first two trials of each block and all trials with an RT below 200 ms (0.1% of the remaining trials) were discarded from analysis. RT analysis was based on median RT and included only correct trials preceded by at least one other correct trial. Error analysis was based on the mean error rate of all trials that were preceded by at least one correct trial. The overall error rate of all trials was 12.5%.

RT analysis

A four-way ANOVA with judgment transition, modality transition, judgment preparation, and modality preparation was conducted. In a first step, we focus on the shift-cost pattern in general to see whether the results are comparable to previous experiments. The analysis revealed significant main effects of judgment transition and modality transition as well as the theoretically important interaction between these variables (see Table 3). To qualify this interaction, the RTs of repeat, judgment-switch, modality-switch and two-componential switch trials were compared with paired samples t-tests (2-tailed). Again, the alpha-level was reduced to 0.008 according to the Bonferroni correction. As in the previous experiments, repeat trials differed significantly from modality-switch trials, judgment-switch trials, and two-componential switch trials (*t*s > 6.5; *p*s < .001). For the comparison of switch trials, only the difference between judgment-switch trials and two-compo-

Table 3
Experiment 3: Summary of statistical analyses on RT and error data according to judgment transition, modality transition, judgment preparation, and modality preparation

(A) RT analysis	F(1,15)	MSE	p	η_p^2
Judgment transition (JT)	28.8	93424.3	< .001	.658
Modality transition (MT)	42.0	146830.0	< .001	.737
Judgment preparation (JP)	167.5	14916.6	< .001	.918
Modality preparation (MP)	61.9	16801.5	< .001	.805
JT x MT	50.1	15208.2	< .001	.769
JT x JP	< 1	12637.6	n.s.	.029
JT x MP	10.8	9105.8	< .01	.417
MT x JP	8.1	7306.7	< .05	.350
MT x MP	< 1	13148.6	n.s.	.033
JP x MP	40.1	16724.9	< .001	.728
JT x MT x JP	1.4	10457.7	.259	.084
JT x MT x MP	1.7	8069.9	.218	.099
JT x JP x MP	< 1	15150.1	n.s.	.000
MT x JP x MP	4.8	11254.4	< .05	.241
JT x MT x JP x MP	1.8	9319.3	n.s.	.107
(B) Error analysis	**F(1,15)**	**MSE**	**p**	**η_p^2**
Judgment transition (JT)	9.2	38.7	< .01	.380
Modality transition (MT)	26.3	88.3	< .001	.637
Judgment preparation (JP)	< 1	24.3	n.s.	.016
Modality preparation (MP)	2.5	10.6	.138	.141
JT x MT	29.9	28.2	< .001	.666
JT x JP	< 1	35.6	n.s.	.000
JT x MP	< 1	19.0	n.s.	.016
MT x JP	< 1	16.1	n.s.	.019
MT x MP	< 1	47.2	n.s.	.051
JP x MP	1.7	19.1	.210	.103
JT x MT x JP	< 1	35.1	n.s.	.139
JT x MT x MP	< 1	27.8	n.s.	.027
JT x JP x MP	< 1	27.7	n.s.	.009
MT x JP x MP	< 1	31.0	n.s.	.048
JT x MT x JP x MP	< 1	17.1	n.s.	.54

n.s. = not significant
MSE = mean squared error

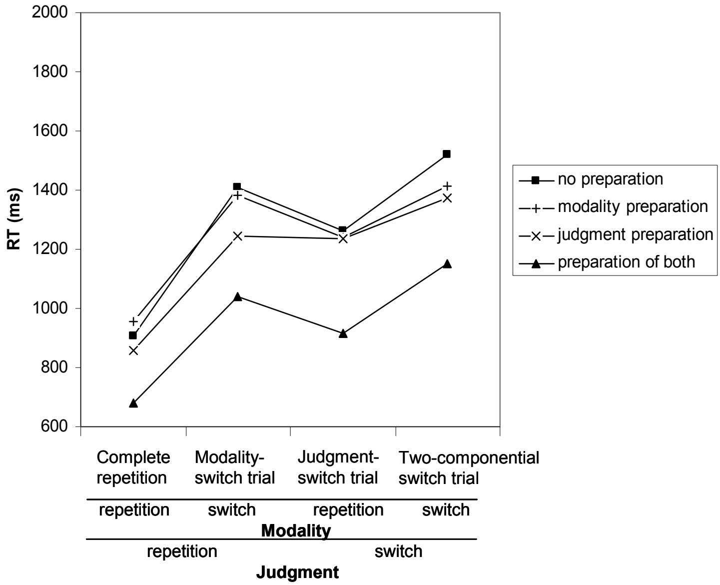

Figure 3
Experiment 3. Reaction times (RTs) as a function of judgment transition (judgment repetition vs. judgment switch), modality transition (modality repetition vs. modality switch), and cuing condition (no preparation vs. preparation of modality vs. preparation of judgment vs. preparation of both components)

nential switch trials was significant ($t(15) = 4.1$; $p = .001$). Taken together, the shift-cost pattern clearly resembles the under-additive pattern found in the previous experiments.

The focus of Experiment 3, however, was on task preparation. Here, the analysis yielded significant main effects of judgment preparation and modality preparation as well as an interaction between judgment preparation and modality preparation. To specify the interaction of judgment preparation and modality preparation, the RTs of no-preparation trials (1272), modality-preparation trials (1248 ms), judgment-preparation trials (1117 ms), and preparation for both components trials (948 ms) were compared with paired samples t-tests (2-tailed, alpha = 0.008). Trials in which both components could be prepared differed significantly from all other trials (*t*s > 8.4; *p*s < .001), the differences between the remaining cuing conditions were not significant ($t(15) = 1.1$; $p = .270$ for the comparison of no preparation and modality preparation; $t(15) = 1.7$; $p = .270$ for the comparison of modality preparation and judgment preparation; and $t(15) = 3.8$; $p = .002$ for the comparison of no preparation and judgment preparation, note that this effect was not significant due to the corrected alpha-level).

As regards an influence of preparation time on the shift cost pattern, the results can be summarised by stating that preparation for one specific task-set component did not reduce the corresponding shift cost (the interaction of judgment transition and judgment preparation and of modality transition and modality preparation were not significant, see Table 3). Additionally, the four-way interaction of judgment transition, modality transition, judgment preparation and modality preparation was also not significant so that we did not observe an influence of the cuing condition on the general shift-cost pattern.

Error analysis

The analysis revealed significant main effects of judgment transition and of modality transition as well as a significant interaction between judgment transition and modality transition. The interaction between judgment preparation and modality preparation was not significant. No further main effect or interaction was significant (see Table 3).

Discussion

We observed that the general reduction in the RT level was substantially larger when both task-set components could be prepared as compared with trials in which only one task-set component (i.e., the judgment or the response modality) could be prepared prior to the onset of the imperative stimulus. Furthermore, the effect was not additive but we found a strong interaction of judgment preparation and modality preparation. Thus, we conclude that subjects had a specific benefit from knowing both task-set components in advance that was more than the sum of benefits from knowing each task-set component individually. We suggest that this specific benefit was based on the possibility to start task-set integration during the CSI.

Yet, as regards the effect of a long preparation time, one also has to note that preparing for one task-set component did not reduce the corresponding shift cost. Rather, the RT data show that the shift cost concerning the other task-set component was reduced (see Table 3). That is, when subjects could prepare for the upcoming judgment, the modality-shift cost was reduced and vice versa. This finding appears to be counter intuitive and we currently cannot provide an explanation for it. However, one might speculate that the task-set component that was indicated 100 ms before the onset of the imperative stimulus received more attention because subjects were already awaiting its specification. Furthermore, the specification of the second task-set components was always combined with a perceptual change in the cue (a shape change for the judgment and a colour change for the response modality). This change might also have drawn the attention towards the later cued task-set component. Alternatively, one might also speculate that knowing one but not the other task-set component lead subjects to expect a change in the unknown task-set component.

In contrast to Experiment 2, the data pattern of Experiment 3 also showed that even when both task-set components could be prepared, preparation did not affect the shift-cost pattern. Certainly, this null-effect has to be treated cautiously, so that it appears to be difficult to draw any strong conclusions from this finding. Additionally, there were at least three differences between Experiment 2 and 3 that might have influenced preparation effects. First, Experiment 3 was more complex than Experiment 2 as subjects experienced four different cuing conditions and altogether nine different cues (including the neutral values). Second, the CSI was manipulated block-wise in Experiment 2, whereas cuing conditions were intermixed in each block in Experiment 3. Finally, in Experiment 2 the response modality was indicated by a tone, whereas the response modality was indicated by the colour of the cue frame in Experiment 3. Based on the results of Experiment 1, we are confident that this difference in the cue type did not affect the overall shift-cost pattern. Yet, it might have influenced preparation effects as it is known that a short cue presentation (i.e., the tone in Experiment 2 was presented for 50 ms only whereas the colour was presented until a response was given) influences advance preparation (Verbruggen, Liefooghe, Vandierendonck, & Demanet, 2007). Specifically, the study by Verbruggen et al. (2007) demonstrated that a short cue presentation further reduced the residual shift cost that was observable with a long cue presentation. In this way, the preparation following a short cue presentation of one of the task-set components could have equated the differences between the three types of shift trials that were still observable when a pertinent cue was used for both components.

However, one could even question whether subjects indeed engaged in task-set integration during a long preparatory interval or whether they simply failed to engage in preparation (cf. de Jong, 2000). Usually, the reduction of shift cost with a long preparation time is taken as evidence that preparation took place (Meiran, 1996; Rogers & Monsell, 1995). Yet, we believe that the preparatory-based reduction of the RT (and error) level is a more general but equally valuable indicator of preparation (see also Koch, 2005). In Experiment 3, we found such a general effect of preparation time – specifically when both task-set components were indicated 1000 ms before the onset of the imperative stimulus. Therefore, we are confident that subjects did use the preparatory interval.

We thus summarise that a long preparation time in which task-set components can be prepared has two effects. On the one hand, as demonstrated in Experiment 2, a long preparation time can result in the reduction of shift cost in a way that no difference between the different types of switch trials is found. On the other hand, the overall reduction of the RT level is substantially (i.e., over-additive) larger when both task-set components are indicated long before the stimulus than when only one task-set component is indicated. We take these findings as empirical evidence that the integration of task-set components is possible already during task preparation – as long as both task-set components were specified in advance.

General discussion

The present study examined the cognitive representation of tasks (i.e., task set). In three experiments, subjects switched between two judgments (magnitude judgment vs. parity judgment) and two response modalities (vocal vs. manual responses, vocal vs. foot responses, or manual vs. foot responses). All three experiments clearly showed an under-additive shift-cost pattern and, thus, provide evidence for the interaction of judgment switching and response-modality switching. We suggest that the interaction of judgment switching and response-modality switching results from an integration of the two task-set components into one cognitive task representation (e.g., a magnitude/vocal task). Our results further suggest that the integration of task-set components is not influenced by the type of cues (Experiment 1) or by preparation time (Experiments 2 and 3) as we observed the critical interaction of judgment transition and modality transition in each experiment, with each type of cues and each cuing condition.

The cognitive representation of tasks

Based on the present experiments as well as on previous two-componential switching experiments (e.g., Hahn et al., 2003; Hübner et al., 2001; Hunt & Kingstone, 2004; Kleinsorge, 2004; Kleinsorge & Heuer, 1999; Murray et al., 2009; Vandierendonck et al., 2008) it can be concluded that two task-set components are integrated into one single task representation. The observed interaction of two task-set components clearly indicates such an integrated cognitive task representation rather than an independent linear organisation of task-set components. Furthermore, the present study extended previous studies in an important aspect. We were able to show that an interaction of task-set components is also observed when one task-set component has a more cognitive nature (i.e., the judgment or stimulus categorisation) and the other task-set component is motor-related (i.e., the response modality).

In this context, the idea of an integrated task representation does not necessarily imply that task-set components may not be organised within the task set. For example, Kleinsorge and Heuer (1999) propose a hierarchical task-space model in which task-set components are integrated but still organised hierarchically. As regards the shift-cost pattern, it was argued that a hierarchically higher component (e.g., judgment) influences hierarchically lower components (e.g., Sc-Rc mappings) in such a way that a switch on a higher component leads to the tendency to switch the lower component, too. Therefore, a repetition of the lower component would produce an additional cost of "switching back." In the data pattern, worse performance is expected for switching only the higher component than for switching both components. In contrast to the hierarchical organisation of a task set, Vandierendonck et al. (2008) suggest a flat organisation. A flat organisation means that all task-set components are represented on the same level and play the same functional role in the cognitive representation of tasks. One empirical signature of a flat organisation is the finding that performance in all types of switch trials is comparable.

When we compare the performance in the three types of switch trials in the present experiments, judgment switch trials yielded a better performance than modality switch trials and two-componential switch trials in Experiments 1 and 3 as well as in blocks with a short preparation time in Experiment 2. This observation is neither in line with a flat task-set organisation nor in line with a hierarchical task-set organisation, in which one would expect judgment as the hierarchically higher component so that switching the judgment alone should lead to a worse performance than switching both components. In contrast, the data pattern observed in blocks with a long preparation time (Experiment 2) clearly indicates a flat rather than a hierarchical task-set organisation. After a long preparation time, the performance in all types of switch trials (i.e., modality-switch trials, judgment-switch trials, and two-componential switch trials) was comparable (cf. Kleinsorge et al., 2002). We interpret this result as showing a "residual shift-cost pattern" that emerges when subjects had enough time to perform the task-set integration in the preparatory interval. This idea is supported by the finding that such a flat residual shift-cost pattern also emerges when the preparation time is "unlimited" (i.e., self-paced trials; Hübner et al., 2001).

Thus, our experiments also suggest that the duration of preparation time plays a critical role in this context. The critical role of the preparation time is further demonstrated by the finding that the preparation-based reduction in the overall RT was substantially larger when two instead of one task-set component could be prepared (Experiment 3). This finding suggests that task-set integration can be completed during a long preparatory interval, leading to a residual shift-cost pattern, in which the performance is similar in all types of switch trials (i.e., one- vs. two-componential switch trials). With a short preparation time or with cuing only one task-set component, task-set integration still has to be completed after the presentation of the imperative stimulus. Therefore, performance can differ, for example, between judgment-switch trials, modality-switch trials, and two-componential switch trials (i.e., faster responses in judgment-switch trials as compared to modality-switch trials and two-componential switch trials in the present study).

Task-set integration

The data pattern found in our experiments speaks in favour of an interaction and integration of task-set components. That is, individual specifications of task-set components (e.g., magnitude and manual) are integrated into a specific cognitive task representation (e.g., magnitude/manual task set). As a consequence, subjects in the present experiments switched among four tasks (e.g., magnitude/vocal, magnitude/manual, parity/vocal, and parity/manual).

As regards the nature of the task-integration process, we assume that a short-term association of both task-set components occurs (Dehaene, Kerszberg, & Changeux, 1998). Task-set integration, thus, may depend on a simultaneous activation of two task-set components in working memory. This might lead to the binding of different task-set components for each task representation, resulting in task-specific action rules (cf. the idea of task-specific stimulus-response bindings by Allport & Wylie, 2000; Hommel, 2004).

That is, in each trial first the cognitive task representation has to be built. Secondly, task-specific action rules are selected and executed. Task-specific action rules depend on the integrated task set and are specific for both task-set components. Therefore, we use the term "task-specific action rules" to express that each integrated task (e.g., a magnitude/manual task) has specific action rules (e.g., "press a right key when the digit is smaller than 5") that differ from the rules in other tasks (e.g., "say right when the digit is odd" in a magnitude/vocal task).

The distinction between the processes of task-set integration and the activation of task-specific action rules is similar to the stage model of executive control (Rubinstein, Meyer, & Evans, 2001). The model assumes two stages termed "goal shifting" and "rule activation." In the goal-shifting stage, the goal of the previous trial is deleted from working memory and the goal of the actual task is implemented. Goal shifting can take place before or after stimulus presentation. In contrast, rule activation takes place only after stimulus onset (but before response selection). Likewise, Mayr and Kliegl (2003) propose a differentiation between a retrieval stage (i.e., retrieval of task-specific action rules from long-term memory) and an application stage. The idea of task-set integration contributes to these models by stating that the integration of two task-set components into a single task representation is an essential part of the goal-shifting or retrieval stage in two-componential switching conditions.

As to the question of when task-set integration takes place, it is interesting to note that according to additive-factors logic (Sternberg, 1969) an interaction of two variables indicates that the underlying processes affect the same processing stage. Thus, we assume that judgment switching and modality switching can be considered as being functionally similar and affecting the same processing stage in task performance. Response selection has already been shown as a relevant process in task switching (Philipp, Jolicoeur, Falkenstein, & Koch, 2007; Schuch & Koch, 2003; Verbruggen, Liefooghe, & Vandierendonck, 2006), and we likewise suppose that the integration of task-set components becomes relevant prior to response selection or at the response selection stage. That is, we suppose that the integration of judgments and response modalities is necessary to select the correct response. A similar idea was proposed by Mayr and Bryck (2005). These authors showed that Sc-Rc mapping rules and stimulus-response couplings were integrated in a task representation. Mayr and Bryck (2005) argued that this integration speaks against a linear processing in which rule selection precedes response selection. Similarly, we assume that the decision of which judgment to apply does not precede the decision of which response modality to use. Put differently, although one might associate the judgment with the response-selection stage and the response modality with the response-execution stage, the present data clearly demonstrate that both task set components are not organised in a linear fashion but interact.

It is important to note that task processing certainly can be understood as depending on different "stages" like stimulus encoding, response selection and response execution. Furthermore, we also assume that response selection necessarily takes place before response execution. However, our data speak against the assumption that those task-set components that distinguish between two tasks become relevant only at the corresponding "stage." Therefore response execution has to be decoupled from the task-set component "response modality."

Conclusion

The present study aimed to explore the cognitive representation of tasks with the task-switching paradigm. Based on the assumption that cognitive task representations consist of different task-set components we demonstrated that the response modality is a relevant component in the cognitive representation of tasks. Additionally, we demonstrate that different task-set components (i.e., judgments and response modalities) are represented in a functionally similar way and interact in a two-componential switching condition. All task-set components (e.g., judgments or response modalities) play a similar role in cognitive task representations. To perform a task, an integrated task representation is necessary. Thus, when two task-set components vary, both task-set components have to be integrated before response selection and execution can take place. In this way, the modality in which a response has to be executed becomes relevant long before the actual execution of the response and plays a crucial role in an integrated cognitive task representation.

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