

EXPLORATIONS IN THE STRUCTURE OF TASK SPACES

Thomas KLEINSORGE
Universität Dortmund, Germany

Starting with outlining some analogies between task-set reconfiguration on the one hand and motor programming on the other hand, in this paper a perspective on task shifting is delineated that highlights the importance of taking into account the representational structures individual task sets are embedded in. It is shown that the relative difficulty of identical transitions between individual tasks depends on the relations between all tasks that possibly have to be performed in a certain situation. Thus, when focusing on transitions between subsequent trials only, discrepant findings are to be expected that can only be resolved by taking into account the context in which these transitions take place.

Introduction

When experimental psychologists try to understand the processes and structures that underlie their participants' performance in one of their reaction time experiments, they traditionally tend to neglect two important aspects. One aspect relates to the instruction given to the participants. Although it is evident that without this particular instruction it would be highly improbable that a participant would ever do the things an experimenter asks her to do, the question how instructions work has not received much attention in reaction time research (cf. Prinz, 1997). Somehow, participants must be willing and able to form an effective intention that guides their behavior according to the instruction. However, measurement takes place only after this has been done, and the resulting performance provides only rather indirect evidence for these processes. The second aspect largely neglected concerns the action that the participant takes to respond to a given stimulus. Although it might seem that (re-) actions are what reaction time research is about, in most cases only the time at which this action occurs, and whether it is in line with the instruction, is registered, but not the characteristics of the action itself (cf. Prinz, 1998).

From the perspective of linear stage theory (e.g., Sanders, 1980; Sternberg, 1969), it might be argued that the neglect of instructions and

The research reported in this paper was supported by grant KI 1205/1 of the Deutsche Forschungsgemeinschaft.

Correspondence concerning this article should be addressed to Thomas Kleinsorge, Institut für Arbeitsphysiologie an der Universität Dortmund, Ardeystraße 67, D-44139 Dortmund, Germany. Electronic mail may be sent to kleinsor@arb-phys.uni-dortmund.de

motor actions merely cuts something from the start and the end of the chain of events while leaving the middle part intact, the part that starts with the presentation of the stimulus and ends with the registration that a response has occurred. However, it becomes increasingly clear that both instructions and actions must be taken into account for a complete account of performance. The study of task shifting deals with the processes that transform the information conveyed by the instruction into an effective intention. As will be pointed out in the following, this interest in the poorly understood 'front part' of information processing somewhat ironically turns out to be closely related to questions regarding the 'end part', that is, the execution of motor acts.

Task-Set Reconfiguration and Motor Programming

The present paper delineates a particular perspective on the processes and structures¹ underlying the performance of shifts between cognitive tasks. The structures that enable the performance of a particular task are often described as 'task sets', and the processes involved in shifting from one task to another are usually referred to by the term 'task-set reconfiguration'. Thus, a task set is the result of transforming an instruction into an effective intention, and task-set reconfiguration captures at least some of the processes 'online', that is, while measuring performance, that traditionally proceed before any measurement takes place. Currently, most approaches to investigate task shifting are focused on the processes that are engaged in task-set reconfiguration. To itemize just a few examples, it is asked to what extent the processes that accomplish a shift are under endogenous control of the performer and how long these processes take (e.g., Rogers & Monsell, 1995; Meiran, 1996), whether the difficulty of task shifting is determined by the control requirements of the to-be abandoned or the forthcoming task set (e.g., Allport, Styles, & Hsieh, 1994), whether processes of episodic retrieval are a major determinant of shift costs (e.g., Pösse & Hommel, 1999), and in how far task shifting relies on inhibitory processes (Mayr & Keele, 2000). In contrast, questions regarding the structure of the representations involved in task shifting have received much less attention.

Our own approach started with considering possible analogies between task shifting on the one hand and motor programming on the other hand (cf. Kleinsorge & Heuer, 1999). Three general considerations led us to assume that such analogies might be fruitful to exploit. First, one of the most basic

¹ The term 'structure' is used in this article in a rather general sense as denoting an organized pattern of relations within a set of elements, for example, processes or processing modules.

observations in motor programming is that with dimensionally organized movements, the time needed to specify a certain movement characteristic generally reflects the dimensional structure of all movements that are possibly required in a certain situation (e.g., Rosenbaum, 1980). We wondered whether this might be true for the preparation of cognitive task features also. A second basic observation that is related to the first one consists of the finding that the difficulty of programming a certain movement depends on the structural relations between this movement and a movement that has been performed (or merely prepared) just before (e.g., Heuer, Spijkers, Kleinsorge, van der Loo, & Steglich, 1998; Spijkers, Heuer, Steglich, & Kleinsorge, 2000). Both issues converge upon the question whether the costs for shifting between cognitive tasks would reflect an eventual dimensional organization of these tasks and if so, whether specific dimensional relations between successive tasks would be associated with specific costs. Empirically, only few relevant observations were available, and the evidence seemed to be contradictory. On the one hand, Allport et al. (1994, Exp. 1) reported no difference in shift costs whether two successive tasks differed on one or two task features. On the other hand, Kluwe (1997) reported shift costs that depended on the number of task features on which a change took place, but in an underadditive manner. As outlined below, much of our work was devoted to investigate the conditions that determine the relations between shift costs and the structural relations between successive tasks.

A third consideration that led us to believe that there might be intimate links between motor programming and task set reconfiguration was based on observations reported by Rogers and Monsell (1995). In their experiments, they found consistently that a task shift went along with a response alternation benefit, whereas in task repetition trials the usual response alternation costs (e.g., Kirby, 1980) were observed. This interaction of sequential effects on 'higher' cognitive and 'lower' motor levels suggests that there might be intimate links between these levels which are often thought to be rather far apart from each other.

Before describing the way in which we tackled these issues empirically, a few general remarks about sequential effects might be in place.

Sequential Effects

Any behavior can be described on an (almost infinite) number of levels which all suggest their own units of description. When it comes to describing the psychological processes that are assumed to underlie a certain kind of behavior, choosing a level of description becomes an especially intricate problem. One problem relates to the question of how much context should

be taken into consideration to account for the performance of a particular task.

In experimental psychology, in particular in those areas that deal with choice reaction times, it has long been usual to treat a single experimental trial as a quasi-natural unit of description and to trace the processes that are assumed to underlie the performance of an (idealized) experimental subject as a chain of events (or a succession of stages) that starts from the processing of a ('the') stimulus and ends with motor act called ('the') response.

The well-known existence of sequential effects such as repetition effects proves that single trials are not independent from each other in that performance in one trial is substantially influenced by what happened in the preceding trial. Thus, sequential effects show that treating single trials as a unitary whole is problematic theoretically. Pragmatically, in most analyses of sequential effects the relation between the actually analyzed trial and its precursor is captured in terms of additional discrete variables (mostly in terms of (un)equality). This way, sequential dependencies are taken into account without ceasing to treat single trials as the unit of analysis. While this proceeding may suffice methodologically, there might be a danger to unwarrantedly incorporate this pragmatically grounded structure into assumptions regarding the cognitive structures underlying the performance of the task at hand (not to mention the possible neglect of potentially complex higher-order sequential dependencies).

Studies of task shifting are basically investigations of sequential effects. In most task-shifting experiments published so far, participants had to shift between two tasks, with task repetitions versus alternations being the contrast of central concern. This 'local' perspective may result in unwarranted conclusions because of not taking into account that the cognitive structures within which task shifting occurs may reflect relations between succeeding trials that are based on larger units, for example, an experimental block. To exemplify this point, consider the above mentioned finding, reported by Allport et al. (1994, Exp. 1), that task shifts involving a change of one or two task features result in shift costs of equal magnitude. In their experiment, the authors presented their participants Stroop-like stimuli that consisted of groups of one to nine identical digits. Participants had to attend to the numerical value of the digits or to the group size and to judge either whether the numerical value or the group size was odd or even or whether it was more or less than five. In separate blocks of trials, they had to judge repeatedly the same stimulus dimension, to alternate between the two stimulus dimensions, to alternate between the kinds of judgment, or to concurrently shift stimulus dimension and kind of judgment. While not shifting both judgment and stimulus dimension resulted in the fastest performance, concurrently shifting both judgment and stimulus dimension did not take longer

than shifting between stimulus dimensions or kinds of judgment alone. (Indeed, from their figure it seems that concurrent shifts actually took less time, although this was not statistically significant.) This observation led Allport et al. (1994, p. 431f) to draw strong conclusions about the processes underlying a task shift. The nature of their conclusions does not matter here. Rather, it is the premise that the costs for a switch between two particular tasks can be accounted for by considering only these two tasks that will be questioned. If, for example, it could be shown that a comparison of one- versus two-dimensional shifts depends on whether both kinds of shifts occur in the same versus in different blocks of trials, this would point to the importance of considering the representations underlying task-shifting in more detail.

The 'Task Space'

As mentioned above, the time needed to specify a certain movement depends on the relations between this movement and a preceding movement, with these relations being defined in terms of the dimensional relations among all movements that are possibly called for in a certain situation. Analogously, we introduced the term 'task space' as denoting the organized set of representations of all tasks the performance of which can be called for in a given situation (Kleinsorge & Heuer, 1999). Our basic assumption was that the whole task space must be taken into account for a complete explanation of the (relative) magnitude of shift costs. For example, we supposed that whether one- versus two-dimensional shifts result in equivalent or different costs would depend on the whole task space and not only on the relation between two isolated trials.

Our explorations in the structure of task spaces started with employing an experimental paradigm in which the tasks our participants had to shift between resulted from an orthogonal combination of three binary, hierarchically ordered task dimensions. On the top of the hierarchy, the required type of judgment was represented. In our earlier studies (Kleinsorge & Heuer, 1999; Kleinsorge, Heuer, & Schmidtke, in press a; Kleinsorge, Heuer, & Schmidtke, *subm.*; Heuer, Schmidtke, & Kleinsorge, in press), participants had to perform either a numerical judgment regarding the magnitude of a digit or a spatial judgment regarding the position of a digit. On the intermediate level of the hierarchy, the judgment-to-response mapping was represented. This could be either compatible or incompatible. On the bottom level were the responses, which could be a right or left button press. Thus, there were four tasks with an overlapping response set: numerical/compatible, numerical/incompatible, spatial/compatible, and spatial/incompatible.

Our basic observations with this set of tasks can be summarized as follows. First, a shift of the type of judgment always resulted in a cost. Second, a shift of the judgment-to-response mapping resulted in a cost when no shift of judgment was required. In contrast, whenever the type of judgment changed as well, shifting the judgment-to-response mapping actually resulted in faster responses than when only the type of judgment but not the mapping had to be shifted. Third, and in line with the observations reported by Rogers and Monsell (1995), response alternations were always accompanied by shorter response times whenever either the type of judgment or the judgment-to-response mapping changed but led to costs when there was no such change.

In the meantime, we were able to replicate this pattern of shift costs several times, demonstrating that it is robust against variations of

- the way in which the task features 'type of judgment' and 'judgment-to-response mapping' are cued (Kleinsorge et al., in press a))
- the response-stimulus interval (Kleinsorge et al., *subm.*)
- the relative frequency of shifts (Kleinsorge et al., *subm.*)
- the specific types of judgment (Kleinsorge, Heuer, & Schmidtke, in press b)).

Therefore, we are quite confident that our basic observations are not brought about by subtle methodological artifacts but can be replicated under a wide range of experimental conditions.

We explained this pattern of results on the basis of one structural and three processing assumptions. On the structural side, we assumed that our participants indeed represented the hierarchical structure of the three task dimensions. This structured representation constitutes the task space. Shifting within such a hierarchically organized task space proceeds in such a way that a switching operation applied to a hierarchically higher task dimension inadvertently generalizes to all hierarchically lower task dimensions (1st processing assumption). This necessitates corrective re-switches whenever a value on a lower task dimension remains the same across trials. These corrective re-switches do not generalize (2nd processing assumption). Generalizing switching operations and corrective re-switches serve to select the appropriate task-set. We assumed further that a selected task set needs to become implemented in order to be operative (3rd processing assumption).

Given these assumptions, it becomes quite clear that the question whether it is easier to perform a one- or a two-dimensional shift is rather intricate. Without knowing how the task dimensions are represented, including the hierarchical relations embodied in this representation, this question cannot be answered. Neglecting the response level, a shift of the type of judgment only or a shift of the judgment-to-response mapping only are both one-dimensional shifts. Nevertheless, whereas a shift of only the mapping is rel-

atively easy, a shift of only the type of judgment is much harder because this shift generalizes to the mapping level and necessitates an additional re-switch because the mapping actually remains unchanged. Averaging over both types of one-dimensional shifts would yield estimates of shift costs that are approximately the same as the shift costs for a two-dimensional shift. Of course, such an averaging would dismiss all the information that makes it possible to draw conclusions about the representational structure underlying shifting performance.

Shifting Within a Hierarchically Organized Multidimensional Task Space

Statistically, the above-mentioned pattern of shift costs gives rise to a complex pattern of interactions. However, given the theoretical considerations outlined in the preceding section, this complex pattern can be translated into a simple additive model of shift costs. This model can be expressed by the equation

$$RT_i = RT_0 + k_1 \cdot S + k_2 \cdot I_M + k_3 \cdot I_J$$

with RT_0 as the baseline RT for task repetitions including response repetitions, S as the duration of a switch, I_M as the duration of implementing a new mapping, and I_J as the duration of implementing a new type of judgment plus a mapping. In Table 1, the values for k_1 , k_2 , and k_3 are given for all eight possible transitions between trial n and trial $n-1$.

Table 1. Number of postulated Switching Operations and Implementation Operations as a Function of the Relation to the Preceding Trial (Judgment same or different, Mapping same or different, Response same or different)

J	Relation		Number of operations		
	M	R	k_1	k_2	k_3
=	=	=	0	0	0
=	=	≠	1	0	0
=	≠	=	2	1	0
=	≠	≠	1	1	0
≠	=	=	3	0	1
≠	=	≠	2	0	1
≠	≠	=	2	0	1
≠	≠	≠	1	0	1

The number of switching operations k_1 is given by our 1st and 2nd processing assumptions: Any switch on a hierarchically higher level generalizes to all lower levels (one switching operation) and necessitates corrective reswitches on all dimensions on which the feature of the previous trial is

repeated (one switching operation per repeated feature). For example, when only the type of judgment has to be shifted from one trial to the next (5th row in Table 1), this results in three switching operations. First, there is a switch on the judgment level that generalizes to the mapping level and the response level. Second, because the features on these two levels actually are repeated two corrective reswitches are needed, resulting in a total of three switching operations.

The parameters k_2 and k_3 that specify the number of implementation operations follow from our 3rd processing assumption: Any feature that has been switched must become (re-) implemented in order to be operative².

This simple additive model provides a formal statement of the theoretical notion of a generalizing switching mechanism that operates upon a hierarchically organized task space. When applied to real data, estimates of the duration of a switching operation (S) are consistently in the range of 23 to 43 milliseconds, whereas the estimates of the duration of the implementation operations are more variable under different experimental conditions (cf. Kleinsorge & Heuer, 1999; Kleinsorge et al., *subm.*). A reason for this seems to be that a substantial part of the implementation requirements depends not on the relation to the preceding task but on the difficulty of the new task (cf. Kleinsorge et al., *subm.*), whereas switching operations are conceptualized as operating upon abstract representations that do not reflect the difficulty of the represented.

The distinction between a selection process that deals with task representations which abstract from the actual information processing requirements of a task and an implementation process that (partly) reflects these requirements can also be found in a recent model of task shifting proposed by Rubinstein, Meyer and Evans (*in press*), where these processes are termed 'goal shifting' and 'rule activation'. More generally, there seems to be a tendency to address action schemata at the most abstract level of description applicable under the respective conditions without specifying the details of their execution (cf. Vallacher & Wegner, 1987). Thus, there is converging evidence that renders the distinction between selection and implementation a viable one.

² Because an implementation of a new type of judgment always goes along with an implementation of a new judgment-to-response mapping both processes are captured by the single parameter I_j . Therefore, whenever $k_1 = 1$, then $k_2 = 0$. Alternatively it would have been possible to set k_2 to 1 whenever $k_1 = 1$. In this case, I_j would capture the additional time needed to implement a new type of judgment in addition to a new mapping. Furthermore, there is some dependency of k_2 and k_3 from k_1 in that whenever $k_1 > 1$, either $k_2 = 1$ or $k_3 = 1$. This results from the fact that whenever $k_1 > 1$ there must be a switch on either the judgment level or the mapping level which, according to the 3rd processing assumption, necessitates a reimplementation. Similarly, when no switch occurs at all ($k_1 = 0$), nothing has to be implemented.

Generalizing switching operations result in a presetting of a task representation that may or may not correspond to the task representation that is actually needed. This generalization appears to proceed completely unintentionally. Nevertheless, it is certainly dependent on intentions, at least on the very intention to comply with the request to shift the task. In addition, there are certain other factors that set the stage for generalizing switches to occur.

Boundary Conditions for Generalizing Switching Operations

As mentioned above, we observed the pattern of shift costs indicative of generalizing switching operations under a variety of experimental conditions. Nevertheless, there are surely boundary conditions for their occurrence. Perhaps the most important one relates to the hierarchical structure of the task space. Although a hierarchical structure within the set of tasks does not guarantee that the representation of these tasks, that is, the task space, is hierarchically structured itself, it is highly improbable that a hierarchical structure will emerge in the task space when the set of tasks has no hierarchical structure.

Another boundary condition results from the fact that generalized switches should lead to a presetting of specific values on the hierarchically lower task dimensions on which they take place. With binary task dimensions, a generalized switch is a switch towards the other value on any lower dimension. But what happens if there are two rather than only one other features present? Recently, we (Kleinsorge et al., *in press b*) employed an extension of our original paradigm in which we orthogonally combined three types of judgment, three judgment-to-response mappings, and three responses. With this combination of tasks, at least on the mapping dimension no generalized switching took place. Instead, shift costs grew monotonically with the number of dimensions on which a change actually occurred. Thus, whereas with binary task dimensions it is easier to shift the mapping together with the type of judgment than to shift only the type of judgment, the reverse is true for three-valued task dimensions. This is true despite the fact that the same transitions from trial $n-1$ to trial n are involved. For the response dimension our findings were somewhat ambiguous, probably because it is possible to prepare for two responses simultaneously (cf. Heuer, 1982). In contrast, it seems to be impossible to prepare two different judgment-to-response mappings concurrently. Theoretically, it would be possible to prepare one of the two alternative mappings, but this does not happen. In fact, because this would lead to a wrong presetting in one third of the trials, such a mechanism would be very uneconomically, whereas with binary dimensions cognitive expenses are equal whether generalized switches take place or not. This is

true for our balanced experiments, whereas in ecologically more valid settings generalized switches may be a rather efficient mechanism for cognitive re-orientation.

Preliminary observations from our laboratory suggest that even with binary task dimensions generalized switches do not occur when participants just before extensively practiced shifting with three-valued task dimensions that included the binary values. This again points to the above-mentioned importance of considering larger time scales than only an experimental block or even a single trial. When participants established a task space in which three possible values are represented on each task dimension, this representation seems to govern their shifting processes also when the actual set of tasks is reduced to a combination of binary task dimensions.

Conclusions

When participants shift among a set of simple cognitive tasks, the processes by which these shifts are accomplished depend not only on the to-be performed task and the task that had to be performed one trial ago. Instead, the nature of the processes that underlie a shift depends on the structural relations between all tasks the performance of which can potentially be required in a certain situation. This means that the relative difficulty of identical transitions from a task in trial $n-1$ to another task in trial n can vary greatly and even reverse in sign, depending on all other shifts that would have been possible. Thus, to be complete, theories of task-set reconfiguration should focus not only on local relations between individual tasks but also on the more global representational structures single task sets are embedded in.

References

- Allport, D.A., Styles, E.A., & Hsieh, S (1994). Shifting intentional set: Exploring the dynamic control of tasks. In C. Umiltà & M. Moscovitch (Eds.), *Attention and performance XV* (pp. 421-452). Hillsdale, NJ: Erlbaum.
- Heuer, H. (1982). Binary choice reaction time as a criterion of motor equivalence: Further evidence. *Acta Psychologica*, 50, 48-60.
- Heuer, H., Schmidtke, V., & Kleinsorge, T. (in press) Implicit learning of sequences of tasks. *Journal of Experimental Psychology: Learning, Memory, and Cognition*.
- Heuer, H., Spijkers, W., Kleinsorge, T., van der Loo, H., & Steglich, C. (1998). The time course of cross-talk during the simultaneous specification of bimanual movement amplitudes. *Experimental Brain Research*, 118, 381-392.

- Kirby, N. (1980). Sequential effects in choice reaction time. In A.T. Welford (Ed.), *Reaction times* (pp. 129-172) New York: Academic Press.
- Kleinsorge, T., & Heuer, H. (1999). Hierarchical switching in a multi-dimensional task space. *Psychological Research*, 62, 300-312.
- Kleinsorge, T., Heuer, H., & Schmidtke, V. (in press-a) Hierarchical switching in a multi-dimensional task space is not induced by specific task cues. *Zeitschrift für Psychologie*.
- Kleinsorge, T., Heuer, H., & Schmidtke, V. (in press-b). Task-set reconfiguration with binary and three-valued task dimensions. *Psychological Research*.
- Kleinsorge, T., Heuer, H., & Schmidtke, V. (subm.). *Processes of task-set reconfiguration: switching operations and implementation operations*.
- Kluwe, R.H. (1997). Intentionale Steuerung kognitiver Prozesse. *Kognitionswissenschaft*, 6, 53-69.
- Mayr, U., & Keele, S.W. (2000). Changing internal constraints on action: The role of backward inhibition. *Journal of Experimental Psychology: General*, 129, 4-26.
- Meiran, N. (1996). The reconfiguration of processing mode prior to task performance. *Journal of Experimental Psychology: Learning, Memory and Cognition*, 22, 1423-1442.
- Pösse, B., & Hommel, B. (1999). The role of task relevant and irrelevant dimensions in task switching. In A. Vandierendonck, M. Brysbaert, & K. Van der Gooten (Eds.), *Eleventh Conference of the European Society for Cognitive Psychology: Proceedings* (p. 200). Gent: ESCoP/Academia Press.
- Prinz, W. (1997). Why Donders has led us astray. In B. Hommel & W. Prinz (Eds.), *Theoretical issues in stimulus-response compatibility* (pp. 247-268). Amsterdam: Elsevier.
- Prinz, W. (1998). Die Reaktion als Willenshandlung. *Psychologische Rundschau*, 49, 10-30.
- Rogers, R.D., & Monsell, S. (1995). The costs of a predictable switch between simple cognitive tasks. *Journal of Experimental Psychology: General*, 124, 207-231.
- Rosenbaum, D.A. (1980). Human movement initiation: Specification of arm, direction, and extent. *Journal of Experimental Psychology: General*, 109, 444-474.
- Rubinstein, J., Meyer, D.E., & Evans, J.E. (in press). Executive control of cognitive processes in task switching. *Journal of Experimental Psychology: Human Perception and Performance*.
- Sanders, A.F. (1980). Stage analysis of reaction processes. In G.E. Stelmach & J. Requin (Eds.), *Tutorials in motor behavior* (pp. 331-354). Amsterdam: North-Holland.
- Spijkers, W., Heuer, H., Steglich, C., & Kleinsorge, T. (2000). The specification of movement amplitudes for the left and right hand: Evidence for transient parametric coupling from overlapping-task performance. *Journal of Experimental Psychology: Human Perception and Performance*, 26, 1091-1105.
- Sternberg, S. (1969). The discovery of processing stages: Extensions of Donders' method. *Acta Psychologica*, 30, 276-315.
- Vallacher, R.R., & Wegner, D.M. (1987). What do people think they're doing? Action identification and human behavior. *Psychological Review*, 94, 3-15.