CHAPTER TEN

The role of task space in action control: Evidence from research on instructions

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Abstract

The ability to use instructions to prepare for upcoming events is a characteristic that humans uniquely developed. This cornerstone ability is evident in abundant prior studies, yet the exact role that instructions play in action control is unclear. We start with a survey of literature on instructions and action control, as well as the role that instructions play in action control. The review suggests that although the concept of *task set* based on task-relevant information is widely emphasized, the more critical concept is that of *task space*, which includes task-irrelevant information in a multidimensional representation and allows hierarchical switching between tasks. Within both concepts, *stimulus-response relations* are at the core, revealing the procedural nature of action control. Moreover, we use research on password generation to illustrate the application of task space to the area of cybersecurity and privacy. We argue that the task space framework captures the nature of the central processes of action control nested within a multidimensional representation from instructions, which can be extended to broader situations beyond laboratory settings.

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Both our instructions and cues reflected the dimensional organization of tasks, and may thus have supported a dimensional organization of task space.

Kleinsorge and Heuer (1999)

To perform an arbitrary task inside or outside of the laboratory, people must translate or encode the instructions into a structured cognitive representation that constrains and controls their actions. This control of action is accomplished relatively automatically (Hommel, 2000), but how this is done remains what Monsell (1996) called an "unsolved mystery of the mind." The interaction between instructions and action control has long been tackled by psychologists (Gibson, 1941; Monsell & Driver, 2000; Proctor & Xiong, 2017). In the present chapter, we review relevant literature to examine this interaction from a perspective of *task space* and highlight the concept of task space as a mediating link from arbitrary *tasks* to complex *situations*.

Kleinsorge and Heuer (1999) introduced the concept of task space to signify a hierarchical mental representation of tasks in the task-switching paradigm (in which people must shift between two or more tasks). Although they made a strong case in several articles for the necessity of the task-space concept to account for multiple-task performance (Kleinsorge, 2000; Kleinsorge, Heuer, & Schmidtke, 2001, 2004), the concept and its components, which include *multidimensional representation* and *hierarchical switching*, have been underappreciated.

The main goal of this chapter therefore is to propose that task space is of critical relevance to understanding how instructed action control operates. We focus on research conducted on human action control in both basic and applied settings, with emphasis on factors related to the interaction between instructions and action control. The basic research emphasizes compatibility studies, but also includes investigations of mixed-task and task-switching performance. Applied studies in cybersecurity are described that center on password creation. We argue that task space should be a key concept in the theoretical toolbox of psychological researchers. Our assertion lies on the one hand in the demand for more ecologically oriented research in cognitive psychology, and on the other hand in the rising opportunities to examine the generalization of basic research findings in the emerging cyber-physical world.

The chapter has four parts. In Section 1, we briefly describe analyses of instructions and action control, respectively, and then outline historical and current views about the role of instructions in action control. In Section 2, we analyze exemplar studies in detail from the perspective of task space and clarify the nature of hierarchical and multidimensional cognitive representations of instructions and how they influence the human information processing of action control. In Section 3, we broaden our discussion to application, focusing on the role of instructions in password generation. Section 4 concludes with a discussion of the theoretical implications of task space.

1. Role of instructions in action control

1.1 Instructions

In daily life, people face situations in which they need to perform tasks that they have not experienced previously. Instructions are often provided to guide people to act appropriately to achieve their goal. For instance, instructions (text and pictures) on a paper packet of seeds for planting provide the executable steps for sowing the seeds outdoors at different times of the year and in different regions and conditions. In laboratory experiments, participants seated in front of a display screen comply with instructions to perform tasks. An example is instructions for a typical visual Simon task (Simon, 1990), in which stimulus location is irrelevant and another feature relevant (Lu & Proctor, 1995): *In this task, you will be presented a series of trials in which a colored square will be displayed on the left or right side of the screen. You are to press the left key with your left index finger if the square is green and the right key with your right index finger if the square is red. You should respond as quickly and as accurately as you can.*

Generally speaking, instructions specify the end states to be achieved, describe the rules and regularities governing the task, focus on particular steps to be performed in given situations, and sometimes provide examples. There are fields of research concerning various types of instructions (e.g., Eiriksdottir & Catrambone, 2011; LeFevre & Dixon, 1986; Nussbaum, Kardash, & Graham, 2005), the steps in using instructions (e.g., Simon & Hayes, 1976), and how to design the layout and graphical implementation of instructions (e.g., Lowe, 1993). Our emphasis, though, is on verbal instructions used during laboratory experiments investigating choice-reaction tasks. Specifically, we focus on the mental representation of a plan for carrying out the task by using the instructed information.

Meyer and Kieras (1997) observed that task-analysis, which is regarded as an essential initial step in applied research (Chipman, Schraagen, & Shalin, 2000), is also needed for basic research. They stressed the value of "examining carefully the goals of the task and the instructions that people receive about how to achieve them" (p. 19). Fitting with our emphasis on various compatibility effects, we conducted a task-analysis of six classic studies of stimulus-response compatibility (SRC) effects for task relevant and irrelevant information that reported the detailed instructions: Fitts and Seeger (1953), Geissler (1912), Hedge and Marsh (1975), Hommel (1993), Langfeld (1910), and Simon (1969) (see Table 1). We organized the task-analysis around two types of information contained in the instructions, *declarative* and *procedural* (Anderson, 1983). Monsell and Driver (2000) noted that the representations of these two types of information are crucial to cognitive control in what they called the working memory theme, "recognizing that goal-appropriate processing requires short-term maintenance both of procedural 'instructions' and of the information operated on" (p. 12; see also Oberauer, 2009).

The analysis of declarative information includes the task goals and explicit dimensions for stimuli and responses described in instructions (Table 1, Declarative columns). Representations of the declarative information are within the range of objects or things to which participants can have conscious awareness, such as the location or color of an object. When performing the instructed task, those representations are accessible in long-term memory and more readily in short-term, working memory. The analyses of procedural information are comprised of the relations between stimulus and response (Table 1, Procedural columns). Specific examples are used infrequently in the instructions, primarily to clarify a procedure described in general terms (Table 1, first row) or to convey a common mapping-rule governing responding (Table 1, second row). There are explicit stimulus-response (S-R) relations that govern the mapping between conditions and actions, e.g., "if x is the case, do this; if y is the case, do that" (i.e., if-then decision rules, Anderson, 1983, 1992). Procedural representations also involve S-R relations that are not yet fully specified in the task environment. Of particular interest, when the conditions/stimuli (e.g., color) and actions/responses (e.g., spatial) described in the task procedures vary in dimensions, extra implicit S-R relations (e.g., stimulus location—response location, stimulus color—response color) may also be activated (Table 1, Procedural column, implicit part). Those task-irrelevant stimulus-response (S-R) relations may or may not be mentioned in the instructions but are not part of the explicit task that the participant is instructed to perform.

By identifying the sequences of actions from declarative and procedural aspects within the task analyses, it can be seen that the declarative information in the instructions provides a multi-dimensional representation of the task. For example, in Hommel's (1993) study, the tone stimuli varied in a

Table 1 Task analysis of instruction examples.

		Declarative		Procedural	
Source	**Instruction**	**Goal**	**Dimension**	**Action sequence**	**S-R relation (*R*)**
Langfeld (1910)/ Geissler (1912)	Shortly after you hear the word "now" a picture will be exposed in the square opening. You are to speak the first word suggested to you by the object in the picture, unless it is the name of this object. You are not to name the object, but you may describe it or name any of its parts. For example, if it is a cow you may say small, old, head, etc. After the word is spoken you are to give the results of a careful introspection. Pay particular attention to the processes of suppression and association and to the imagery	Speak the first word suggested by the object in the picture but not the object name	*Explicit:* *Stimulus dimension*: Object in the picture *Response dimension*: Word of the object name, words describing the object, and its parts	1. Hear the word "now" 2. View a picture in the square opening 3. Be aware of the first word that comes to mind 4. Recognize the object 5. Compare the first word with the object name 6. Find another word if step 5's results are "same"	***R*** (object, word) *Explicit:* Object → word but not object name *Implicit:* Object → object name

Continued

Table 1 Task analysis of instruction examples.—cont'd

Source	Instruction	Declarative: Goal	Declarative: Dimension	Procedural: Action sequence	Procedural: S-R relation (*R*)
Fitts and Seeger (1953)	Here is a stimulus panel of eight lights and a response panel in which you can move this stylus to one of eight places. Hold the stylus in your right hand. When I say "center" place it on this center disc. I shall then say "ready" and a few seconds later one of the lights will come on. If this light (point) should come on, move the stylus straight up. If this light should come on, move the stylus quickly to this position (indicate upper-right corner). If you start in the wrong direction, correct your movement as soon as possible. Do not try to guess which light will come on as they will be presented in a random order. Work for both speed and accuracy since both reaction time and errors will be recorded	Work for both speed and accuracy	*Explicit:* *Stimulus dimension*: Spatial *Response dimension*: Spatial	1. Hold the stylus in your right hand 2. Center the stylus after hear "center" 3. Notice "Ready" 4. Be aware of which light is on 5. Move stylus to position of the light 6. Correct the direction if start with wrong direction	***R*** (light position, stylus-movement direction) *Explicit:* Light position → stylus move to the same direction Light position → stylus move to a different direction

Continued

Table 1 Task analysis of instruction examples.—cont'd

		Declarative		Procedural	
Source	**Instruction**	**Goal**	**Dimension**	**Action sequence**	**S-R relation (*R*)**
Simon (1969)	This is a test to see how quickly you can react and move in response to a tone which you will hear either in your right ear or left ear…. Move the control handle *away* from the side of the ear stimulated. In other words, when you hear the tone in your left ear, move the control handle to the right as quickly as possible, and when you hear the tone in your right ear, move the control handle to the left as quickly as possible	React and move in response to a tone as quickly as possible	*Explicit:* *Stimulus dimension*: Tone location (left/ right) *Response dimension*: Control handle movement direction (left/right)	1. Hear a tone in left or right ear 2. Move control handle away from the side of the ear stimulated	***R*** (tone location, handle direction) *Explicit:* Tone location → handle move to the opposite direction *Implicit:* Tone location → handle move to the same direction
Hedge and Marsh (1975)	[Scenario: *Red* or *green* light can occur in left or right location; hand on start button on table must move to button labeled *red* or *green*, located toward upper right or upper left on the table.] Same-color condition: … regardless of where a light appears, when you see a *red* light move and press the *red* button; when you see a *green* light move and press the *green* button. Alternate-color condition: … regardless of where a light appears, when you see a *red* light move and press the *green* button; when you see a *green* light move and press the *red* button	Strike response button as quickly as possible; errors should be avoided [Described in Procedure]	*Explicit:* *Stimulus dimension*: Light color (red/ green) Button location (left/right) *Response dimension*: Button color (red/ green) Button location (left/right)	1. See a red/green light 2. Move to the same or alternate color key from the center key 3. Press the key	***R*** (light color, button color) Same-color condition: *Explicit:* Key color → same light color Alternate-color condition: *Explicit:* Key color → alternate light color *Implicit:* Key color → same light color ***R*** (light location, button location) *Implicit:* Light location → button location

Continued

Table 1 Task analysis of instruction examples.—cont'd

		Declarative		Procedural	
Source	**Instruction**	**Goal**	**Dimension**	**Action sequence**	**S-R relation (*R*)**
Hommel (1993)	[Scenario: High or low pitch tone can occur in left or right speaker; press left or right key with appropriate index finger in response to pitch; key-press turns on left or right light as an action effect.] Experiment 1: Key instruction (KI): … to "press the left-hand key" after hearing the low-pitched tone and to "press the right-hand key" in response to the high-pitched tone. Light instruction (LI): … to "produce the right-hand light" following the low-pitched tone and to "produce the left-hand light" in response to the high-pitched tone	KI: Press designated key after hearing high- or low-pitch tone LI: Produce designated light following high- or low-pitch tone	KI *Explicit:* *Stimulus dimension*: Tone pitch (high/low) tone location (left/right) *Response dimension*: Response location (left/right) LI: *Explicit:* *Stimulus dimension*: Tone pitch (high/low) Tone location (left/right) *Response effect dimension*: Light location (left/right) Response location (left/right)	1. Hear a tone of high or low pitch 2. Press the key or produce the light assigned to the tone pitch	KI ***R*** (tone, response key) *Explicit:* Tone pitch → response location *Implicit:* Tone location → response location LI ***R*** (tone, light) *Explicit:* Tone pitch → light location Tone pitch → response location *Implicit:* Tone location → light location Tone location → response location Response location → light location

Note: Stimulus-response Relation [S-R Relation (***R***)], which can be Explicit (Clearly Defined S-R Relations in Instructions) or Implicit (Embedded S-R Relations due to the Explicit Stimulus and Response Dimensions).

pitch dimension and a left-right spatial dimension. Critically, such multidimensional representations embed implicit action routes that may facilitate or impede responding as a function of whether they correspond or not with the explicit response criteria. This nesting of implicit routes is due to the cross-dimensional facets of task-relevant stimulus and response dimensions. When considering task performance, researchers should attend not only to the information specified in the explicit S-R relations but also to the multidimensional representation nested within the instructions (see, e.g., the later discussions of Dreisbach & Haider, 2008, 2009).

1.2 Action control

Action control has been studied in psychology for many years. Topics include executive ignorance [of how one executes actions] by Lotze (1886) (see Turvey, 1977), ideomotor theory by James (1890/1950), and psychomotor control by Woodworth (1899). With the rise of contemporary cognitive psychology, control of action began to be seen as a function of cognitive representations. As characterized by Miller, Galanter, and Pribram (1960), "The problem is to describe how actions are controlled by an organism's internal representation of its universe" (p. 12). Action selection and control has been studied within the human information-processing framework, the central tenet of which is that humans can be characterized as communication systems involving stages of perception, cognition, and action (Proctor & Van Zandt, 2018; Xiong & Proctor, 2018), each of which can be decomposed further. Over the past 25 years, increased interest in action and its relation with information-processing functions including perception, attention, intention, and motor control have surfaced in a number of approaches (e.g., Gollwitzer, 1999; Hommel, Müsseler, Aschersleben, & Prinz, 2001; Rosenbaum, 2010; Schneider, 1995). A common claim of those approaches is that action control is at the center of the science of mind and behavior.

Given agreement with this general claim, precisely how information-processing functions are linked for action control is still under debate. On the one hand, researchers in cognitive and social psychology have shown considerable interest in the association or direct coupling between perception and action (e.g., Dijksterhuis & Bargh, 2001; Hommel et al., 2001; Prinz, 1997). For example, Brass, Bekkering, Wohlschläger, and Prinz (2000) had participants perform a two-choice task in which they were to lift the index or middle finger of their right hand in response to the visual stimulus "1" or "2." During the trial, a task-irrelevant mirror image of the hand could show a lift of the corresponding or noncorresponding finger. Movement onset was faster when the irrelevant image movement corresponded with that of the required response, leading Brass et al. to conclude, "This finding supports the idea that movement observation exerts an automatic influence on movement execution" (p. 139). As another example, Chartrand and Bargh (1999) instructed participant to describe photographs, in alternation with another person (a confederate) who described different photographs. Participants shook their foot more frequently when the confederate shook her/his foot, and rubbed their face more frequently when the confederate engaged in face rubbing. Based on these and other data, Dijksterhuis and Bargh (2001) stated, "We argue that social perception, defined here as the activation of a perceptual representation, has a direct effect on social behavior. Perceptual inputs are translated automatically into corresponding behavioral outputs" (p. 1).

On the other hand, hierarchical approaches argue that planning and control of goal-directed movements depend on prior expectations related to achieving a particular outcome (e.g., Koban, Jepma, Geuter, & Wager, 2017; Wolpert, Doya, & Kawato, 2003). Grafton and de Hamilton (2007) provided behavioral and neurophysiological evidence for a hierarchy of action selection and control that includes levels of conceptual intention ("actions are performed to achieve a desired goal and to solve a problem," p. 592), specific movement goal, motor commands, and body kinematics. Wolpert et al. (2003) go so far as to say, "Hierarchy plays a key role in human motor control" (p. 599). Crucially, they identified the hierarchical structure as a way of integrating top-down plans and bottom-up constraints of bi-directional information processing. Behavioral evidence has been gathered as well for hierarchical control through chunking of words as a basis for skilled typing (Yamaguchi & Logan, 2016).

Relevant neural evidence comes from a functional magnetic resonance imaging (fMRI) experiment of hierarchical planning by Koechlin and Jubault (2006), in which participants executed a series of responses by pressing a left or right button, or both. Two conditions were tested in which baseline trials switched periodically with trials of prelearned-chunks. In the simple condition the chunk was a sequence of button presses: Left&Right/Left&Right/Right/Right/Left; in the superordinate condition the superordinate chunk, C1/C1/C2/C2/C3, was composed of three categories (C1, C2, C3) for which the mappings of three stimuli to the left and right responses differed. The posterior prefrontal cortex

(PFC) regions showed increased activity at the beginning and end of simple chunk sequences and at the transitions between categories within the superordinate condition, implying that these regions control starting and stopping of component motor acts at chunk boundaries. In contrast, the start and end of the superordinate chunk sequence were associated with increased activity in the anterior PFC, which involves higher-level planning processes. Based on these results, Koechlin and Jubault concluded that contextual control can be considered to be a set of selection processes operating on the hierarchical structure of action plans.

To address the opposing character of the associative-perceptual and hierarchical conceptual approaches to action control (bottom-up vs. top-down), Ondobaka and Bekkering (2012) proposed that conceptually guided action is higher in the hierarchy than perception-guided movement. Their view is that action control involves generating expectancies at both an abstract level of intention and the physical level of movements. They based this view in part on a study by Ondobaka, de Lange, Newman-Norlund, Wiemers, and Bekkering (2012) in which participants moved to the higher or lower of two numbers based on the observed similar action of a confederate coactor. Results showed a correspondence effect for movement direction of the participant with that of the coactor when intending to select an action congruent with that of the coactor but not when intending to select an incongruent action. Ondobaka and Bekkering (2012) suggested an idea-guided action at a higher hierarchical level than perception-guided movement, which they argued "play[s] a fundamental role in shaping perception and action" (p. 4). This action hierarchy "fulfills conceptually guided proprioceptive and visual expectations without the necessity of an intermediate cognitive process" (p. 4), implying a vital function of structure. Thus, the role that the conceptual level plays at facilitating perception-action association seems to be a consequence of its high-level representation within the hierarchical structure, which is mainly determined by the specific instructions that are given.

1.3 Relation between instructions and action control

Studies examining the influence of instructions on action control date to the early 1900s. Psychologists became aware that outcomes of psychological experiments, including reactions, associations, and judgments, were determined in part by instructions. Külpe (1904) (described in Humphrey, 1951, p. 268), leader of the Würzburg school, reported results of an experiment in which four nonsense syllables were displayed visually for 125 ms. The syllables were colored differently and arrayed to form distinct figures. Instructions were to observe (a) the number of letters, (b) the letters and their locations, (c) the colors and their locations, or (d) the emergent figure. Participants were able to perform the instructed tasks relatively accurately, showing little ability to report unattended features.

Watt (1904/1906), a student of Külpe's, reported a similar demonstration for presentation of single printed words with instructions to (a) classify the object that was specified, (b) name the whole object, (c) name part of the object, or (d) name an example. He explained it as an "*Einstellung*" (set) that people create in constituting an "*Aufgabe*" (task) prior to the stimulus presentation due to the instructions. Ach (1905/1964) provided one of the best demonstrations: The numbers 6 and 2 displayed to participants yielded a response of 8, 4 or 12 depending on whether the instructed *Aufgabe* was to add, subtract, or multiply.

Building off the work of the Würzburg psychologists, Langfeld (1910) and Geissler (1912) reported experiments, described in Table 1, using a "method of negative instruction" (see Proctor & Xiong, 2017). With this method, pictures of objects were presented one at a time, and participants were instructed to say the first word that came to mind unless it was the name of the object, in which case they were to say a different name. After each response, the participant introspected about the processes of suppression, association, and the imagery involved. The introspections often mentioned that the participant first covertly named the object and then inhibited that name. On this basis, Langfeld concluded, "There are a positive and negative '*Aufgabe*,' both of which are carried out. The negative '*Aufgabe*' has acted as a block, cutting out a definite association" (p. 208). Geissler's more detailed investigation also included introspections of the foreperiod, which led him to place emphasis on the function of the exact instructions in generating the determining tendencies of the set to perform the task.

The functions that instructions play in action control are well-illustrated by the research of Külpe, Watt, Ach, Langfeld, and Geissler. People can transform action intentions into actions as a function of instructions even without being given specific stimulus conditions. Instructions provide an explicit *task set*, which is the mental representation of the task that is to be performed. The instructions also activate a broader context, the *task space*, within which the explicit task set and implicit tasks are nested (e.g., negative and positive *Aufgabe* in Langfeld, 1910). The implicit tasks are activated from the implicit *S-R relations*, which are nested within the multi-dimensional representation but are task-irrelevant or unspecified as part of the task to complete.

Despite the three levels of concepts (task set, task space, and S-R relations), investigations of the relation between instructions and action control have mainly focused on task set and S-R relations. We consider those two levels in this section, but delay discussion of the broader context of task space to Section 2, for which it is the focus.

1.3.1 Task set

The concept of task set—which is used to specify the task-relevant stimulus dimension, the required response, and the mappings from stimuli to responses—has been mainly used to explain the representation for action control induced by the instructions (Gibson, 1941; Monsell, 1996; Schneider & Logan, 2014; Selz, 1924/1981). In his critical review of the set concept, Gibson (1941) conducted a survey of the experiments on reaction time, association, learning, perception, and conditioning to discover the concept's underlying meaning. He concluded that although the use of the term *set* varied greatly across different psychologists (e.g., task set, mental set, goal set), and the definition was not generally formulated, certain features were common to the various uses. Those terms imply a state of preparedness and a readiness to respond selectively to a restricted range of stimulus material, all of which function in directing and determining associations specific to the task (i.e., explicit S-R relations).

For single- and multi-step tasks, Monsell (1996) provided a list of control functions, the foremost of which is task set. Monsell indicated that task set is often specified by verbal instructions and retrieved from memory later. SRC effects investigated by Fitts and Seeger (1953) and Simon (1969) provide simple illustrations (see Table 1 for analysis of their instructions). In Simon's two-choice reaction task, the task set included left-right tones and left-right responses, with conditions differing in whether the S-R mapping in the set was to make the compatible or incompatible response to the stimulus. As in most studies in which S-R mapping is varied block-wise, the compatible mapping yielded shorter RT than the incompatible one.

Although this result occurs for blocked presentations of compatible and incompatible mappings, the benefit of a spatially compatible mapping does not occur when trials with both mappings are intermixed (Shaffer, 1965; Vu & Proctor, 2004). This outcome implies that when two S-R relations are mapped to the same stimulus and response sets, the representations of the compatible and incompatible mappings are the same, and selection of the specific response is processed with minimal differences. Thus, the benefit of the compatible mapping in block-wise conditions is likely due to bypassing the cognitive transformation processes that have to be engaged for the incompatible mapping and for the compatible mapping when it is intermixed with the incompatible mapping. Such bypassing explains why the two-choice spatial SRC effect persists through more than 2000 practice trials (Dutta & Proctor, 1992).

A classic study by Fitts and Switzer (1962) provides another good illustration of the role of task set in performance. They gave participants sets of 2, 4, or 8 digits or letters from which the presented one was to be named as quickly as possible. Responses were faster with the smaller set sizes than the larger ones if the stimuli were from a familiar subset (e.g., *1* and *2*, or *A* and *B*) but not if they were from an unfamiliar subset (*2* and 7, or *E* and *P*). Fitts and Switzer attributed these results to differences in what they called cognitive set, the establishment of which is like transferring a portion of the total stored information to working memory, which allows rapid comparisons to incoming stimuli. Allport (2009) replicated the lack of effect size on performance with briefly exposed arrays of 4, 8, and 12 consonants for which participants were to report the letters in their respective positions. Although he used sequential groupings (e.g., JKLMQRST for the 8 consonant set), it is likely that the groupings were not sufficiently familiar for participants to restrict their task set to only the specific 4, 8, or 12 consonants that were possible.

More important from the perspective of action control, studies revealed that instructions can modulate the manner in which stimuli activate their corresponding responses. For example, in a study by Cho and Proctor (2007), participants made left and right keypresses to Arabic numerals (3, 4, 8, and 9) or number words (*three*, *four*, *eight*, and *nine*). In one experiment the instructions were to use an odd vs. even parity rule, whereas in another they were to use a multiple-of-3 or not rule. For both stimulus modes, an RT advantage for the mapping of odd to left response and even to right response was obtained with the odd–even rule. But this mapping effect tended to reverse with the multiple-of-3 rule, even though the mapping of digits to responses is the same for the two rules.

Similar results were obtained for a task in which the action was pouring water into a glass. Caljouw and van Wijck (2014) showed participants a reference glass and a jug containing 1.5 L of water. Instructions were to fill an experimental glass with an amount equal to that of the reference glass or that left an empty space for an amount that could be contained from the reference glass. With the fill-glass instructions, participants poured less water into a tall narrow glass than to a short wide glass that held the same volume, but with the empty-space instructions this outcome reversed such that participants poured more water into the tall narrow glass. The authors suggested that the fill-glass instructions caused participants to attend to the water region, whereas the empty-space instructions caused them to attend to the unfilled region.

1.3.2 S-R relations

Task set helps narrow down the associations that are related to the current task or action. However, those associations are not adequate to fulfill the tasks (Selz, 1924/1981). Thus, encoding the relations between events during instructions is not just formation of links between event representations but also of specific ways in which the events are related (directed associations; Hazeltine & Schumacher, 2016; Mitchell, De Houwer, & Lovibond, 2009).

Based on Ach's and Watt's concepts of the *Aufgabe* and directed association, Selz (1924/1981) proposed a concept of schematic anticipation (Humphrey, 1951; Simon, 1981): Presentation of a stimulus together with an *Aufgabe* causes the participant to create a relational structure that is like an equation with an unknown element: Stimulus–*Aufgabe*–(Response?) (Simon, 1981, p. 155). Finding the designated response that satisfies this relation would complete this total *Aufgabe*. For problem-solving, Selz also proposed a specific method of abstraction of means (Humphrey, 1951), according to which a starting state and a goal, together with a set of operators, may be used to transform the starting state into the goal state by a sequence of successive applications. Thus, the task-conditioned information processing involves a continuous sequence of general (set) and specific partial operations (particular stimulus condition) accumulating over time in a stepwise fashion. The sequential order of task set and stimulus condition in information processing allows interaction between instructional action control and stimulus-driven action control.

Humphrey (1951) criticized Selz's abstraction of means as being too general to provide the specific psychological functions required by the theory. But Duncker (1945) understood that schematic anticipation enables transformation of the task such that "the substitution for the task of another task, through whose solution the original problem is also to be solved" (Selz, 1913, p. 41), whereby a series of transformations might gradually approach the problem solution. Simon (1981) discussed whether such transformation is sufficient to fulfill the task. He first analyzed it from a means-ends perspective (reducing the difference between current state and goal state), and argued that the transformation makes the difference between goal and the present state explicit. Simon then described the similarity of Selz's equation to the condition-action production rules (i.e., procedures that "fire" when their conditions are met) in Newell and Simon's (1972) information-processing theory of problem-solving. In addition, Simon argued that task completion and human actions do not stop after specifying the condition-action production rules, and he pinpointed that Selz did not provide a solution for the conflict in situations in which the conditions of more than one production rule are satisfied at the same time. So, Simon proposed that a control mechanism is needed to solve the conflict problem by defining priority rules, thus determining the ultimate production.

The control mechanism suggested by Simon indicates that besides the predefined relations from the task instructions, a stimulus can activate various task-irrelevant associations in an unrestricted manner. Thus, some task-irrelevant S-R relations (e.g., similarity or same dimension) can interact in an automatic fashion with the predefined relations that are already prepared (conditional automatic). This interaction allows interference or facilitation on choice-reaction trials in which the relevant and irrelevant relations are incongruent or congruent (e.g., the Stroop color-naming effect; Stroop, 1935).

Anderson et al. (2004) also emphasized the importance of S-R relations and developed a set of production rules in the ACT-R (Adaptive Control of Thought—Rational) architecture to explain how people interpret instructions. The system forms a declarative representation of the task instructions, which is interpreted initially by a set of production rules. With minimal experience like that usually provided in the warm-up trials at the beginning of an experiment, a task-specific set of production rules is developed that does not depend on the declarative representation. Anderson et al. described this generation of production rules as accounting for "one of the mysteries of experimental psychology, which is how a set of experimental instructions causes a participant to behave according to the experimenter's wishes" (p. 1046). Besides ACT-R, other popular cognitive architectures, such as SOAR (States, Operators, And Results; Lehman, Laird, & Rosenbloom, 1998), and EPIC (Executive Process Interactive Control; Meyer & Kieras, 1997), are production systems in that they are based on production rules. Despite the distributed representation of task-related stimuli and responses, production rules can detect patterns between these representations and take coordinated actions, suggesting some fundamental truth about human cognition (Anderson et al., 2004).

Together, the above findings imply that instructions not only specify a group of component operations needed to perform a particular task but also describe a state of preparation for the task with if-then production rules. After configuration, the state of preparation to perform the instructed task somehow provides opportunities for the S-R relations associated with the critical task dimensions to execute, even contrary to the task intention (e.g., Simon task, Stroop task, and negative instructions). Thus, to understand the role that instructions play during action control, it is necessary to place the investigation into a broader context.

2. Understanding human action control within task space

Kleinsorge and Heuer (1999) introduced the concept of task space to signify a hierarchical mental representation of tasks in the task-switching paradigm, with different tasks being represented at a lower level of representation but integrated at a higher level. They based their argument on results from an experiment in which the tasks differed in whether the judgment was numerical magnitude of a centered digit or left-right location of another digit presented peripherally, and in whether the judgment-to-response mapping for each task was compatible (e.g., small digit, left response, or left location, left response) or incompatible (e.g., small digit, right response, or left location, right response). Reaction times were longer for switch trials than repetition trials when the type of judgment (magnitude or location) remained unchanged, but shorter for switches than repetitions when the type of judgment was also changed. The pattern of switch costs is consistent with the hypothesis of a dimensionally organized task space in which switching processes are performed that affect the highest-level task dimension requiring a change. A switch of the task at the highest level activates a switch of the response at the lower-level, which then has to be switched back, resulting in a delay on trials for which the response is to be repeated. Thus, multidimensional representation and hierarchical switching are two critical components of task space.

Kleinsorge and Heuer (1999) proposed task space within the context of the task-switching paradigm, but Kleinsorge et al. (2004, p. 39) underscored that the task-space concept is essential for theorizing about action control in general:

> *A task space is a means of integrating and coordinating behavior in terms of a representational structure that covers a range of situational demands in a way that abstracts from the particularities of individual stimulus-response pairings. In a sense, such a representation seems to be trivially necessary to account for the fact that participants are able, without much learning and practice, to follow the instructions given to them in experiments of the type described above. It is inconceivable that this would be possible on the basis of representations whose structure encompasses only the elements of individual trials. However, the notion of a task space does not only hold that a representation of the situational demands as a whole does exist, but that this representation also affects the way in which shifts between individual tasks are accomplished.*

Our view is that the concept of task space implies that much more information than that regarded as task-relevant defines the boundaries of the task context, and is crucial to human action control. Thus, task space is applicable as well to control and coordination of components of a single task. Next, we discuss the two components, multidimensional representation and hierarchical control, using examples from single and mixed tasks to illustrate the importance of the task-space concept for understanding human action control.

2.1 Multidimensional representation

Kleinsorge et al. (2004, p. 31) referred to the structures of the task space as "global representational structures," and emphasized that "shift costs do not only depend on the local transitions between successive tasks, but also on the global representation of the whole set of tasks" (p. 33).

2.1.1 Evidence from single tasks

Earlier, we described typical instructions for a visual Simon task in which left-right stimulus location is irrelevant and a left or right keypress is to be made in response to a relevant non-spatial feature such as color. The Simon effect obtained in this and related tasks is that responses are faster when the stimulus location corresponds with the response location than when it does not (Simon, 1990). Note that the stimulus location is not part of the instructed task set, which is to respond to the relevant dimension with a left or right response. The essential factor is that the required response discrimination makes the spatial response dimension relevant (Ansorge & Wühr, 2004), activating the spatial stimulus dimension and the links between the two as part of the task space.

More than just the long-term, corresponding spatial links can be activated in a Simon task. Fewer than 100 trials of practice responding to stimulus location with an incompatible spatial mapping prior to Simon-task trials can eliminate or reverse the Simon effect immediately or 1-week later (Luo & Proctor, 2016; Tagliabue, Zorzi, Umiltà, & Bassignani, 2000). Tagliabue et al. distinguished short-term memory links from long-term ones to explain the reversal. Whereas the long-term memory links are the task-irrelevant natural spatial correspondences between stimulus and response locations that produce the typical Simon effect, the short-term memory links are those between the task-relevant dimension of the stimuli and the left and right responses, based on instructions. The observed transfer indicates that the short-term links from the initial spatial mapping task continue to be activated as part of the task space when stimulus location is no longer relevant, even 1-week later. Thus, the so-called "short-term" links are not short-lived in the typical sense of short-term memory, and the spatially incompatible mapping from practice becomes part of the long-term memory. Those states of preparation outside of the current task set are essential to understanding action control of a particular task.

2.1.2 Evidence from mixed tasks

A similar modulation of the Simon effect is induced by including a compatibly or incompatibly mapped location-relevant task on half the trials (Marble & Proctor, 2000; Proctor & Vu, 2002). Marble and Proctor's Experiment 4 included a mixed-compatible condition in which the location-relevant trials were compatibly mapped to the responses, and a mixed-incompatible condition in which they were incompatibly mapped. Thus, across tasks, the percentages of trials in which S-R locations corresponded or not were 75/25 and 25/75, respectively, for the mixed-compatible and incompatible conditions. The experiment also included a baseline condition in which all trials were of the Simon task. For both mixed-task conditions, the overall RTs were lengthened relative to the baseline condition, as expected on the basis of the enlarged task space that included another task set. From the hierarchical perspective, for these mixed-task conditions, the initial decision should be which task is signaled, followed by selection of the specific response.

More important, the Simon effect was reversed for the mixed-incompatible condition, whereas the mixed compatible condition did not show a significantly larger Simon effect than the baseline condition. Therefore, beyond adding another task set, when the mapping for the location-relevant trials was incompatible, it also influenced the spatially compatible

S-R association for the Simon-task trials. That is, from the task-space perspective, in the mixed-incompatible condition, on the location-irrelevant trials the activated opposite S-R mapping was counter to the typical corresponding relation. Because the explicit opposite S-R relation needed to be maintained, it overrode the spatially corresponding S-R relation, reversing the Simon effect. However, when the mapping for the location-relevant trials was compatible, the S-R relation was consistent with the spatially corresponding S-R relation for the Simon-task trials. The lack of influence on the Simon effect of the compatible location mapping may be due to the activated spatial mapping being the same as that of the long-term S-R links activated by the Simon task alone.

Theeuwes, Liefooghe, and De Houwer (2014) showed a qualitatively similar pattern of results on the Simon effect when a visual Simon task (the diagnostic task) was performed after instructions for a spatial inducer task but prior to its execution. The inducer task was a compatible or incompatible mapping of left/right stimulus locations to left/right key-press responses, whereas the diagnostic task was to respond to the colors (green or blue) of the same stimuli with the same left/right key-presses. Regardless of spatial mapping, the enlarged task space when the inducer task set was added increased overall RT, and the Simon effect was eliminated if the instructed S-R mapping was spatially incompatible but unaffected when it was spatially compatible. Thus, Theeuwes et al.'s results also suggest that the representations of instructed compatible S-R mappings and the long-term spatial congruent S-R associations may be the same.

Furthermore, the modulation of Simon effect size is evident when the differential frequency is for the Simon-task trials themselves. Marble and Proctor (2000) varied the frequency of corresponding and noncorresponding trials in a pure Simon task (75% corresponding or 75% noncorresponding). The Simon effect was reversed when 75% of the trials were noncorresponding, but increased when 75% were corresponding. The increase of the Simon effect in this latter case implies that the increased frequency of corresponding trials superimposes a response bias on the effect obtained in the baseline condition, which is similar to the bypass described earlier for the block-wise compatible SRC task. The Simon effect RT-distribution functions for all three relative frequencies showed a similar decreasing pattern, indicating a similar but opposite direction superimposition when 75% of the trials were incongruent. For the mixed-task conditions, the Simon effect distributions were relatively flat across RT bins. Thus, although the Simon effect was reversed for both the mixed-incompatible condition and the 75% incongruent Simon-task condition, the reversal for the former seems mainly due to an opposite S-R relation being activated in task space, whereas that for the latter condition is likely a criterion shift as a consequence of learning the frequencies.

Also relevant is a study by Proctor, Yamaguchi, Dutt, and Gonzalez (2013), which examined a mixing task in which trials of a Simon task for red/green color were intermixed with an SRC task for which some trials were spatially compatible and others incompatible. Thus, in total, participants were required to maintain two types of tasks and four S-R task-defined relations. Across two experiments, the percentages of trials for the Simon and SRC tasks were varied, with the two tasks being equally likely or one task being more frequent. In another experiment, the Simon and SRC tasks occurred with equal frequency but the congruent or incongruent S-R mapping predominated for the SRC task. For all experiments, the SRC effect was absent overall (as in Shaffer's, 1965, study in which compatible and incompatible mappings were mixed), irrespective of whether SRC or Simon trials predominated, suggesting that participants were selecting a mapping rule before proceeding with selection of a specific response. Regardless of which task was most frequent, the Simon effect was evident and of similar size, contrary to the positive and negative effects found when only compatibly or incompatibly mapped SRC trials, respectively, are mixed with Simon-task trials (Proctor & Vu, 2002). The two types of S-R mappings activated by the location-relevant trials are mutually exclusive, thus people had difficulty maintaining one explicit spatial S-R mapping in the task space. Without the influence of an explicit compatible or incompatible S-R relation within the task space, the Simon effects obtained in the subtask set were similar to those of the pure Simon tasks. In general, the results reveal the importance of a task space afforded by S-R relations but not of task-type expectations.

Many results of the prior studies suggest a two-step process for selecting responses when compatible and incompatible mappings are mixed: (1) selection of mapping rule; (2) selection of response. If a two-step process is executed, an SRC effect should occur for the initial mapping decision. Evidence for such an effect comes from studies in which stimuli of positive or negative valence (depictions of favorite or rival sports team; flowers or spiders) signal whether the spatial mapping on a trial is compatible or incompatible (Conde et al., 2011; Proctor, 2013; Yamaguchi, Chen, Mishler, & Proctor, 2017). In such cases, there is no benefit for the spatially compatible S-R mapping, but RT is shorter when positive valence signals compatible mapping and negative valence signals incompatible mapping than for the opposite relation. That is, positive valence is compatible with "corresponding response" and negative valence with "opposite response."

Arrington, Altmann, and Carr (2003) noted that the relations between specific task sets can be more or less similar in a multidimensional task space. They examined the influence of task-set similarity by varying the number of component processes (perceptual, decision, and response) that the tasks had in common. In two task-switching experiments, Arrington et al. found that task-switch costs were smaller when the tasks shared what they called an attentional control setting (e.g., height and width form judgments) or response modality (e.g., manual responses for both tasks) than when they did not (e.g., height and color judgments, or manual responses for one task and vocal responses for the other). These results suggest that similarity in terms of component processes is a factor in defining the characteristics of the multidimensional task space.

2.2 Hierarchical control

In addition to multidimensional representation, the structure and consequent characteristics of the representation are important for action control. Miller (1956) famously illustrated the importance of hierarchical representation for absolute judgments and memory spans, "By organizing the stimulus input simultaneously into several dimensions and successively into a sequence of chunks, we manage to break (or at least stretch) this informational bottleneck" (p. 95). Kleinsorge and Heuer (1999) noted the similarity of their emphasis on hierarchical representation to the work on human memory, pointing out, "It is likely that the organization of task space will reflect the organization of tasks, similar to how the organization of memory reflects the organization of verbal material" (p. 310).

Recently, Korb, Jiang, King, and Egner (2017) provided evidence indicating how neural circuitry may mediate the hierarchical structure of superordinate task-set and subordinate response-set selection processes using fMRI and transcranial magnetic stimulation. Both methods showed that activation of the presupplementary motor area (preSMA) was closely related to task-set control costs, whereas supplementary motor area (SMA) activation was closely related to response-set control costs. Although activation in these areas echoed the distinct hierarchical areas, activity in the basal ganglia (BG) reflected an interaction between task- and response-set costs evident in participants' behavioral data. Balleine, Dezfouli, Ito and Doya (2015, p. 1) reached a similar conclusion about the neural basis of hierarchical control from reviewing a range of findings: "Hierarchical action control is implemented in a series of feedback loops integrating secondary motor areas with the basal ganglia."

2.2.1 Evidence from single tasks

We described results earlier showing that activation of the long-term S-R associations of corresponding stimulus and response locations in Simon tasks can be overridden by associations between noncorresponding locations established through practice or instructions. There is also evidence that the long-term associations can be overridden by a rule that is part of the task set established for responding to the relevant stimulus dimension.

Hedge-and-Marsh Reversal of the Simon Effect: Evidence of the relevant rule being applied to the irrelevant location dimension comes from a version of the Simon task introduced by Hedge and Marsh (1975) (see Table 1). In their study participants made binary choices to red or green stimuli in left and right locations by moving a finger from a start button to one of two response buttons located in left and right locations but colored red or green. In a *same color* condition the instructions were to press the red key in response to the red stimulus and the green key in response to the green stimulus. In an *opposite color* condition, the instructions were to press the green key in response to the red stimulus and the red key in response to the green stimulus. With the *same color* instructions, a standard Simon effect was obtained: Responses were faster when stimulus and response locations corresponded than when they did not. In contrast, with the *opposite color* instructions, responses were faster when the stimulus position and response location did not correspond than when they did.

Hedge and Marsh (1975) attributed this reversal of the Simon effect to participants applying an "opposite" rule not only to the task-relevant color dimension but also to the task-irrelevant spatial dimension, which is outside of the set defined for the task (i.e., the task set is in terms of stimulus and response-button colors). This explanation is similar to that of Kleinsorge and Heuer (1999) for the benefit of a response switch when the task also switched, according to which the switch at the task level produced a switch at the S-R level. In Hedge and Marsh's case, the "opposite" decision for the color mapping was applied as well to the location dimension.

De Jong, Liang, and Lauber (1994) conducted a version of the Hedge-and-Marsh task in which the designation of the colors of the response alternatives (red and blue in their study) varied from trial to trial, being cued 1 s in advance by onset of colored squares or color words above the response-key locations. In another condition, the left response was designated throughout the trial block as one color and the right response as the other, but both response labels were an uninformative yellow color, and task-mapping instructions were cued verbally (SAME or OPPO) at the middle of the display on each trial. Because the color labels in two conditions and the same/opposite mapping in the other condition were randomly varied from trial to trial, participants had to rely on the color coding of the responses in all cases. All three conditions yielded positive Simon effects when the task color mapping was compatible and reversed effects when it was incompatible, indicating that the result pattern obtained by Hedge and Marsh (1975) does not require a constant color mapping but an incompatible S-R relation.

Another critical feature of De Jong et al.'s (1994) results is as follows: Their data showed that the positive Simon effect was smaller overall and decreased to zero across the RT distribution for all three of their conditions, whereas the negative Simon effect was larger overall and differed in size across the three conditions. Consistent with many results we have described, their findings imply that a top-down selection rule is applied only for the incompatible mapping, with activation of the corresponding response solely responsible for the positive Simon effect obtained with the compatible color mapping. In other words, for the incompatible color mapping there is a hierarchical structure that also governs the spatial relations between the stimuli and responses.

Simon Effect Modification from an Extra Dimension: Metzker and Dreisbach (2009) contrasted the Simon effect in one-to-one (same number of stimulus features and responses) and many-to-one (more stimulus features than responses) mapping conditions. In their Experiments 1–3, three photographs of fruits were mapped to one keypress response (e.g., left) and three photographs of different fruits to the other response (e.g., right). Stimuli could occur in left, center, or right positions. In a condition with many-to-one mapping, the stimuli were each individually associated with the assigned response. In a one-to-one mapping condition participants were informed that the stimuli for each response differed by a single rule (e.g., fruit names that start with B in German to with the right response and those that do not with the left response). The Simon effect was evident only in the one-to-one mapping condition.

Because the one-to-one mapping was linked with rule usage, Metzker and Dreisbach (2009) conducted an Experiment 4 to eliminate application of the task rule itself as an influence on the Simon effect. Stimuli were eight photographs of fruits. In the one-to-one mapping condition, four fruits in one color (e.g., red) were mapped to a left response and the four fruits in another color (e.g., green) to a right response. In the many-to-one condition, two colors (e.g., two in red and two in green) were mapped to the left response and two other colors (e.g., two in yellow and two in blue) to the right response. Again, the Simon effect was evident in the one-to-one condition but not the many-to-one condition. Together, Metzker and Dreisbach's results imply that the automatic activation of spatial information depends on a high-level binary categorization of stimuli, which can be mapped onto the two horizontal responses in a similar manner as the default long-term spatially compatible mapping. Thus, the representational structure of the whole task space is crucial for performance.

The positive Simon effect can also be enlarged if an extra compatible relation is included. Experiments 4 and 5 of Proctor and Lu (1994) tested whether the relation of the color of a fixation circle to the color of a target or noise stimulus influenced the Simon effect for a task in which letter identity was the task-relevant dimension. In their Experiment 4, the fixation point (white) was always colored differently than the target (yellow) and the noise (yellow or blue). The Simon effect was increased when the noise and target were the same color and decreased when they were different colors. In Experiment 5, the fixation point could be one of three colors (blue, white, and yellow), and the target was white and noise was yellow, or vice versa. When the target stimulus's color was same as that of the fixation point, the reduction of the Simon effect in the presence of a different color noise stimulus was eliminated. These experiments show that correspondence or noncorrespondence of an extra irrelevant dimension, color, can influence the Simon effect produced by the spatial dimension, suggesting an impact from the higher level.

For Hommel's (1993) study, described in Table 1, in which participants made a left or right keypress to a high or low pitch tone presented to the left or right, the unique manipulation was that a keypress turned on a light on the opposite side. When instructions were to press the left or right key, a positive Simon effect occurred, but when instructions were to turn on the left or right light, the Simon effect was negative relative to the key location. Thus, introduction of a goal manipulation inverts the Simon effect, showing a significant impact on action control. From our view, a higher-level goal determines whether the lower-level representation is of the relation between the stimulus location and the location at which the keypress is made or the location at which the consequent light activation occurs.

2.2.2 Evidence from task switching

So far, the evidence suggests a hierarchical space representing the task. Although a hierarchy does not necessarily represent the entire structure of task space that people self-generate and maintain (Dreisbach & Haider, 2009; Kleinsorge et al., 2004; Weaver & Arrington, 2013), the behavioral evidence for a hierarchical structure during action control indicates that it is a representation that people prefer to use. Therefore, the transformation of intentions conveyed by instructions into actions without being given specific stimulus conditions is bounded by the structure of the task space, which is often hierarchical.

The work of Dreisbach and colleagues has revealed the importance of a structural organization within the task space. Dreisbach and Haider (2008) had participants perform a choice-reaction task in which four words representing moving objects were assigned to a left keypress and four words representing non-moving objects to a right keypress. Half the words assigned to each response were presented in red and half in green. For an *S-R condition* the instructions were in terms of mappings of the individual words to the responses. In a *one task-set condition*, the instructions were to respond according to whether the word represented a moving object or not. In a *two task-set condition*, they were to categorize the red words as beginning with a consonant or vowel and the green words as animal or non-animal. Note that each stimulus was assigned to the same keypress response with the three instructions. Color repetition or change from the prior trial yielded a 30-ms switch cost for the two task-set condition, in which it signaled a task repetition/switch, but not the other conditions. The two task-set condition also showed the common finding that the cost of color change (task switch) was limited to trials on which the prior response repeated. The one task-set condition showed no effect of color repetition/change, consistent with having a single set of "moving" or "nonmoving," and the S-R condition showed an intermediate effect size. Despite the fact that participants in all three conditions were exposed to the same stimuli and responses, just those instructed in terms of task rules represented the action within a hierarchical task structure and showed a cost when switching between tasks.

Dreisbach and Haider (2009) conducted other experiments in which eight clothing words were assigned such that items that would cover the leg required a left response and items that would not do so required a right response. As in their prior study, participants in the S-R condition were not told of this rule, whereas those in the task-set condition were. The target word for a trial was presented in the context of an irrelevant line drawing.

For semantically related objects, the drawing depicted an object that was compatible or incompatible with the category of the target word. For semantically unrelated objects (animals), the object pointed in a direction compatible with the response (left pointing animal; left response to word) or incompatible with it. The S-R condition showed a compatibility effect for both the related and unrelated distractors, whereas the task-set condition showed a large compatibility effect for the related distractors but none for the unrelated ones. This result suggests that participants in the task-set condition coded the word according to category rather than left or right response, rendering pointing direction of the unrelated object inconsequential. In another experiment, Dreisbach and Haider showed that, for a larger group of participants tested with the S-R instructions, those who could identify the category distinction at the end showed results similar to the task-set condition, whereas the other participants did not show those results. That task rules cannot stop interference due to automatic activation of goal-related distractors provides further evidence for the hierarchical structure of the task space.

Weaver and Arrington (2013) examined the effect of hierarchical representation on action selection within free-choice multi-tasking environments. In Experiment 1, participants saw a series of multivalent stimuli and chose the specific task to perform on each trial. To establish a hierarchical representation, prior to the formal task, there was a practice phase, in which three different procedures were implemented to encourage participants to represent the task elements hierarchically as two aggregate tasks. Participants in a spatial-temporal group performed the two task elements of the first aggregate task in one screen location and the two task elements of the second aggregate task in different locations. There was also a short break between the first and second aggregate task. Participants in an aftereffects group viewed the stimulus moving to the left as an action effect for the completion of tasks in the first aggregate task and the stimulus moving to the right as the action effect for the completion of the second aggregate task. Finally, participants in a forced-choice group underwent all manipulations of the prior two groups and also encountered forced-choice trials. In the subsequent task phase, in which participants freely chose which task to perform on a given trial, only the participants who had to make forced choices on 10% of the trials showed evidence of hierarchical task representation. This experience with intermixed forced-choice trials was sufficient to induce hierarchical representation for the free choices even when the forced-choice trials were discontinued halfway through a second experiment.

Although hierarchical structure in behavioral data suggests hierarchical mental representation of the instructions, a non-hierarchically distributed connectionist network model can fit such data (Botvinick & Plaut, 2004). However, Schneider and Logan (2007) also obtained evidence for hierarchical mental representation from a task in which the behavioral data are not hierarchical. Specifically, participants switched between two memorized sequences of tasks in which they judged the referents of words as living/nonliving or small/large. On a given trial, participants were to perform the task from a designated location in the designated sequence. In one condition, only the sequence for a trial was cued in advance, whereas in another condition both the sequence and the position were cued. Their results showed sequence-repetition benefits, position repetition benefits only for sequence repetition, etc., in agreement with retrieval from a hierarchical representation.

Besides hierarchy, Kleinsorge and Heuer (1999) identified reference to the setting of the last trial as another ingredient to dimensional organization. Therefore, the task space that Kleinsorge and Heuer proposed can also be linked to the human information-processing system view, with the hierarchical structure decided by a top-down feedforward loop and a bottom-up feedback loop (Xiong & Proctor, 2018). The feedforward loop enables comparisons between actual and anticipated inputs, enabling a person to change her own internal organization based on predefined parameters in an automatic manner (Ashby, 1956; MacKay, 1956; Pribram, 1976). In contrast, the feedback loop is error-based, which enables the person to self-adjust in real-time (Pezzulo & Cisek, 2016). When the task switches, the feedforward loop is changed, causing a switch cost. However, when the type of judgment does not vary, the switch cost mainly comes from the local feedback, which will not impact the information processing activated by the feedforward loop.

3. An application of task space in cybersecurity decision-making

The generalization of any framework beyond controlled laboratory settings is essential for the scientific process. If task space matters, one could expect that the concept can also be applied to decision-making and action control in tasks that closely approximate those performed in everyday life. In this part, we focus on the role task space plays between instructions and decision-making/action selection by users in the area of cybersecurity and privacy. Tasks related to cybersecurity and privacy involve human-computer interaction, for which human information-processing comprises a subsystem of the entire interaction system (Proctor & Vu, 2016).

Cybersecurity is a major concern of both users and organizations because most aspects of everyday life have become interweaved into the Internet (Singer & Friedman, 2014). Each day, users make decisions and select actions online that impact their security and privacy, as well as those of other people and organizations. However, humans are considered to be the weakest link in cybersecurity (Nohlberg, 2009) because they perform security-related activities poorly. Consequently, there is considerable interest in improving human performance of security tasks (Proctor & Chen, 2015).

When interacting with the Internet, security is typically a secondary goal (West, 2008). Users want to purchase a product, obtain a reference on a particular topic, browse current news, pay a bill, etc. A likely reason why users' decision-making and action selection show minimal impact from security-related information is that security is not part of the initial task set (Dreisbach & Haider, 2008, 2009). Without security goals being activated as part of the task set, minimal attention and effort is allocated to security. Thus, the user's actions are primarily guided by the task set of accomplishing some objective such as purchasing a product or paying a bill.

The most obvious solution seems to be to add cybersecurity into the users' initial task set. Nevertheless, effort and attention are required for processing of task-relevant information. Thus, when given the option, people tend to choose actions that require less effort, such as dismissing the security warnings rather than processing their meaning (Egelman, Cranor, & Hong, 2008; Felt et al., 2015; Wu, Miller, & Garfinkel, 2006). Since effort is often designated as a negative attribute for risky decision-making (Wickens, 2014), one promising way to improve cybersecurity is to minimize the effort required for secure actions.

Using instructions to automatize the procedures required for safe behaviors offers promise to improve users' security performance. By using instructions in this manner, cybersecurity concerns are addressed implicitly as part of the larger task space, which requires minimal effort. In the following, we use password generation as an example illustrating this point.

Passwords have been used extensively as a user authentication mechanism and will continue to be used in the immediate future (Bonneau, Herley, Van Oorschot, & Stajano, 2012). The goal of requiring passwords for authentication is to have users generate secure passwords that cannot be cracked easily but that can be remembered (Sasse, Brostoff, & Weirich, 2001).

Although instructions are provided when people create passwords online, little research has systematically investigated the role of instructions and how they affect the security of generated passwords. Customarily, the instructions for password creation at a site include restrictions like the following: minimum number of characters (usually 6 or 8); contain both uppercase and lowercase letters; contain a digit and special character; not contain the user's name. It may seem that passwords generated to satisfy the instructed restrictions will be secure, but many of the passwords were not be secure and could easily be cracked (Vu et al., 2007). This lack of security arises because users will base the passwords on common words for which they capitalize the first letter and add a digit and special character at the beginning or end. That is, the user's primary goal is to create a password with little effort that can be remembered at a later time. As with other interactions on the Internet, security/privacy is at most a secondary goal that needs to be activated when creating passwords.

More important, small changes in instructions can affect the passwords that people generated. Choong and Greene (2016) and Greene and Choong (2017) evaluated participants' comprehension of various terms used in password generation rules requiring a "special character" (e.g., symbols, non-alphanumeric characters) with character-selection and compliance-checking tasks. Participants showed poor comprehension of the terms, with the respective terms triggering what Choong and Greene called different *character spaces* (characters available for use in password generation), which varied as a function of the specific words used in the instructions. When an exhaustive list of allowed characters was provided within the instructions, the error rate for character selection was lower than for all the other conditions. Also, in a compliance-checking task, the error rates for the passwords created when the instructions explicitly allowed special characters were lower than those when the special characters were not included in the instructions. Greene and Choong (2017) concluded that users' representation of character space will vary as a function of the exact terms used.

Even if the instructions for creating passwords are successful in getting users to consider the entire character space, from which they can select, the users will still tend to create insecure passwords because those passwords are easier to generate and more memorable than are more secure passwords (Morris & Thompson, 1979). Consequently, the security community has tried to develop strategies by which users can generate secure and usable passwords such that the security is guaranteed through users' compliance with the instructions (e.g., NIST guideline: Scarfone & Souppaya, 2009).

In other words, security of the generated passwords is implicitly included with the task space. A mnemonic strategy that has been suggested is to instruct the user to generate a sentence and then represent each word with a letter, digit, or non-alphanumeric character to create a password (e.g., Vu et al., 2007). But, even here, the specific instructions are crucial, as illustrated by research conducted by Yang, Li, Chowdhury, Xiong, and Proctor (2016).

Yang et al. (2016) assessed the security of passwords created by six mnemonic strategy variations in several online studies. These strategies varied with regard to specificity of instructions (e.g., general vs. personal) and/or inclusion of examples (e.g., general, personal, or mixed), which had a large impact on the frequencies with which the most common sentences, and the resulting passwords, were chosen. Generic instructions or commonly suggested examples resulted in high frequencies of the most widespread sentences and passwords, which reduces the entropy of the password set and, consequently, the security. For example, 22 of 864 participants chose the password "tbontbtitq," which was generated from "To be, or not to be, that is the question"; this introduces a regularity of which a hacker can take advantage. In contrast, instructions explicitly requesting users to choose personalized sentences that unlikely to be chosen by other people, along with an example ("I went to London four and a half years ago,") led to strong passwords. No sentence or password was selected more than once among 777 participants.

The previous two password studies show that how users represent the password rules and the consequent character or sentence space is decided by the exact terms and examples in the instructions. That performance is better with explicit requests and high-quality examples suggests the importance of clearly conveying how to use composition rules for carrying out each step and to illustrate the procedures for generating passwords. Furthermore, the explicitly specified procedures and examples are necessary to ensure users' secure decisions which are implicitly nested with the task space.

4. Discussion

The concept of task set, or mental set, has had a significant place in psychology from the early 20th century to the present. Dictionaries of psychology (e.g., VandenBos, 2007) include the terms *Aufgabe*, Determining Tendency, Mental Set, and Set, all of which refer to what we call a task set. In this chapter, starting from historical studies, we specified the function that task space plays for the interaction of instructions with action control for various tasks. Task space is a multi-dimensional structure that makes use of hierarchical representation in which the S-R relations are nested. The planning or the structural representation formed from instructions contributes to the control sequence and task performance. Besides explicit S-R relations within task sets, our review revealed that implicit S-R relations embedded within the task space also show a consistent influence on action control, sometimes in an effortless and automatic manner (e.g., the Simon effect).

Our distinction between task set and task space bears some similarities with Oberauer's (2009) proposed working memory system. Oberauer's emphasis is mainly on how information from long-term memory gets activated and coordinated in working memory. Our emphasis, though, is mainly on the roles that the different levels of activated information play in action selection. Oberauer regards the direct access region of procedural memory, which he calls *the bridge*, as the locus of the current task set. Task space in our terminology relates to the activated part of procedural memory in his terminology. He emphasizes that for anything within the activated procedural memory to affect reaction time, it must be established or retrieved in the bridge. In our view, inclusion of the task-irrelevant S-R relation in the task set (the bridge) is not necessary for that relation to influence performance. Oberauer (2009) built up his working-memory theory based on the structural representations; likewise, we emphasize the structural representation formed from instructions for action control. Oberauer only briefly mentioned the hierarchical link of procedures for action plans (2009, p. 57), but we highlight the hierarchical organization for action control within the task space.

Task space is analogous to the concept of problem space hypothesized for problem-solving (Newell & Simon, 1972). Newell and Simon proposed that an internal representation of an external task environment is the locus for problem-solving. Problem space thus includes possible operations, which enable achieving the goal state from the initial state. The two key constructs within the problem space are *state* and *operator*, corresponding to the declarative and procedural elements for instructions of tasks (discussed in Section 1). Simon (1978, p. 276) also made it clear that the relative ease of problem-solving depends on people's representing crucial elements of the task environment in the problem space. Thus, similar to task space, some operational relations are not explicit within the problem space.

Newell (1990, p. 122) proposed a time scale of human action that distinguishes different bands (see Table 2). From small to large time scale, Newell defined various systems, which are from Neuron to Task. Most of the tasks

Table 2 Newell's time scale of human action.

Scale (s)	Time units	System	World (theory)
10^7	Months	Situation	Social band
10^6	Weeks	Situation	
10^5	Days	Situation	
10^4	Hours	Task	Rational band
10^3	10 min	Task	
10^2	min	Task	
10^1	10 s	Unit task	Cognitive band
10^0	1 s	Operations	
10^{-1}	100 ms	Deliberate act	
10^{-2}	10 ms	Neural circuit	Biological band
10^{-3}	1 ms	Neuron	

Note: Adapted from figure 3-3 on p. 122 in Newell, A. (1990). *Unified theories of cognition*. Cambridge, MA: Harvard University Press.
The label "Situation" for the Social band added by the authors.

described in the present chapter fall in the cognitive band. Note that Newell also defined human problem-solving in the rational band as Task. Therefore, the problem space that Newell and Simon defined can also be regarded as a task space. That the task space for tasks in the cognitive band is similar to the problem space in the rational band is perhaps not too surprising since both have been the focus of detailed investigation using the human information-processing system approach since the 1950s (Xiong & Proctor, 2018).

Expanding the investigation of human action control into task space has two key implications. First, it is an intermediate step to extend our knowledge of human behavior within larger and more complex systems. There has been an increasing interest in understanding human action control from a social perspective (e.g., Atmaca, Sebanz, & Knoblich, 2011; Sebanz, Knoblich, & Prinz, 2003). Nevertheless, we argue that human action control should be placed within a broader system of *situation* (Proctor & Xiong, in press), which is the central idea behind the concept of situation awareness in human factors and ergonomics (Endsley, 2016). Our main point is that when the system is scaled up from task to situation, the information increases extensively. Similar to task space, there is also a multidimensional representation within the situation. Nevertheless, due to the uncertainty and large amounts of data involved, effective control of actions within a situation requires finding what is needed and when it is needed to satisfy specific goals. This idea resonates with the probabilistic functionalism and representative design of experiments proposed by Brunswik (1956), which integrate human information processing with ecological approaches.

Second, the understanding of task space also informs our understanding of heuristics, which have been defined as strategies with the intention to make accurate decisions through reduced effort by ignoring part of the information (Gigerenzer & Gaissmaier, 2011). Results of heuristic decision-making have been known as the less-is-more effect in that the reduced amount of information processed and time spent making the decision does not necessarily harm the decision accuracy. Although people have little awareness of how they arrive at an answer or solution correctly and quickly, we argue that this process could be based on people's prior experiences of similar situations such that implicit S-R relations are created in the task space. The conditional automaticity of those implicit S-R relations contributes to the "fast and frugal" nature of many heuristics (Gigerenzer & Todd, 1999).

Although current cognitive psychology research mainly focuses on what Newell (1990) called the cognitive and rational bands, understanding human action control within the social band may provide crucial knowledge about the dynamic aspects of human behavior across time, places, and interactions with technology and other people. To have a complete depiction of human behavior, it is necessary to place it into a broader system. Current and future technologies (such as health tracking systems and machine learning algorithms) provide unique opportunities to analyze human behavior within the ubiquitously connected cyber-physical world. Psychologists should take advantage of these opportunities and generalize the cognitive principles outside of the lab. Although the concept of task space only makes a small step for such extension, it may provide a crucial link between action control of laboratory tasks and that outside of the laboratory.

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