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Dual Tasking From a Goal Perspective

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In many if not all situations humans are engaged in more than one activity at the same time, that is, they multitask. In laboratory situations, even the combination of two simple motor tasks generally yields performance decrements in one or both tasks, compared with corresponding single task conditions. In contemporary models of dual tasking, these dual task costs are attributed to a capacity-limited stage of mentally specifying required responses. Ideomotor theory suggests that the generation of responses is a process of specifying goals, that is, desired future perceptual states (= *effect anticipation*). Based on this, we argue that effect anticipation is the process responsible for dual task costs. We substantiate this suggestion with results from several lines of research, showing that (a) effect anticipation coincides with a capacity-limited process in dual task experiments, (b) no dual task costs arise if no effects are to be anticipated in one of the tasks, (c) dual task costs vary as a function of a how well effects from two tasks fit together, and (d) monitoring the occurrence of effects also adds additional costs. These results are discussed in a common framework and in relation to other observations and fields.

Keywords: action goals, dual task, ideomotor theory, interference, PRP

Doing two things at the same time is inevitable.[1] When looking at behavior in sufficient detail, it is obvious that dual tasking is the rule rather than the exception, and this is true from early childhood on (Courage, Bakhtiar, Fitzpatrick, Kenny, & Brandeau, 2015): We walk while speaking, speak while gesturing, gesture while mimicking, and so on. Interestingly, not all such activities would be construed as dual tasking, for reasons described later. Yet, they will appear as dual tasks, if at least two such activities are evaluated independently, that is, if the actor tries to pursue two separable goals and evaluates behavior against these two goal states.

Much of the previous research on multitasking has focused on the costs that occur when two separated tasks have to be done in a given time interval, as compared with doing only one task in the same interval. And indeed, several such costs occur. For example, costs in terms of increased response times (RT) occur when stimuli for two tasks are presented concurrently, as compared with presenting only one stimulus (dual task costs proper; Pashler, 1998). Even when one of the stimuli is presented briefly after the first stimulus, at least responding to this second stimulus is delayed while the first stimulus is still being processed (the Psychological Refractory Period [PRP] effect; Telford, 1931). Finally, performing two different tasks in a given time interval comes with so-called mixing costs, as compared with doing the same task over and over again (Allport, Styles, & Hsieh, 1994; Koch, Prinz, & Allport, 2005; Los, 1996), and with switching costs at the specific moment when it comes to move from one task to another (Rogers & Monsell, 1995).[2] Such costs are typically attributed to a limited capacity that has to be shared by two tasks; sometimes in such a way that only one task can use this capacity at any given moment in time. The respective models will be briefly sketched below in the Models Explaining Dual Task Costs section.

The point of origin for the present article is the observation that almost all situations incurring dual task costs require the generation of at least one overt (and sometimes covert) efferent activity. Indeed, even generating a simple motor response, without choosing between alternatives, typically creates large dual task costs

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[1] To be precise, we usually do even more than only two things at the same time. Psychological research has, however, focused on studies involving two different tasks, and we thus use the term *dual tasking* to refer to this situation in the remainder.

[2] The term *cost* suggests that, for example, dual tasking is somehow inefficient and should therefore be avoided at best. However, this depends on the standard to which dual task performance is compared. For example, it is true that RTs in the second of two tasks in a PRP setup increases when there is a short stimulus onset asynchrony (SOA) compared with doing this second task alone. However, the processing time between presentation of the first stimulus and the response of the second task (i.e., SOA + RT2) is typically shorter than is the sum of RT1 + RT2 if both task were processed serially. So, although performance in one of the tasks deteriorates, dual tasking in this scenario is still time-saving and thus efficient, as compared with doing two tasks in a row (see also, e.g., Reissland & Manzey, 2016).

(e.g., Karlin & Kestenbaum, 1968; Kunde, Landgraf, Paelecke, & Kiesel, 2007; Levy, Pashler, & Boer, 2006; Maslovat et al., 2015). In other words, a key component of dual task costs seems to be bound to the limits of generating a simple motor response. This is not a novel insight, but has in fact been incorporated in models of dual tasking (de Jong, 1993; Keele, 1973). However, although the role of action production processes has been acknowledged, it remained elusive what specifically makes these processes so limited. Therefore, to understand these constraints, a closer look at these action production processes is essential.

Dual tasking methodology is also used in other fields such as in research on working memory which we cannot cover here in detail (see Baddeley, 2012). We note, however, that the processes of generating motor activities has played a substantial role in these fields as well. Typically, people are asked here to memorize certain types of information (e.g., easily verbalized material or a sequence of spatial locations) while carrying out certain types of motor activities (such as repeatedly uttering words or tracking a moving object). This research has revealed memory systems for storing different kinds of material (but see, e.g., Cowan, 1988). Goal oriented actions have been suggested to be crucially involved in encoding and storing this material, such as subvocalizing for storing verbal material (Baddeley, Thomson, & Buchanan, 1975) or "inner scribe" or planning eye movements for storing spatial locations (Awh & Jonides, 2001).

We will present our arguments in the following steps. First, we explain that responses in dual task situations, except for very few cases, must be construed as goal-oriented actions (see also Prinz, 1998). Next, we argue that action goals are perceptually represented, that is, in terms of perceptible changes including those at the own body. Then we argue that the internal activation of goal representations is the key limitation of dual tasking and we review empirical evidence for this assumption. We conjecture that similar constraints that apply to stimulus representations in perception apply to the representation of action goals and thus to action production. Finally, we suggest some lines of research that might follow from this perspective.

Making the Body Move

How do we generate body movements? Already William James was apparently concerned with this question and he must have spent hours observing himself while carrying out simple acts such as bending a finger. Eventually he came to conclude that he could sense nothing else in his mind prior to actually bending the finger than an image of the perceptual consequences that would, according to previous experience, occur if he would carry out that motor activity. Consequently, he suggested that bodily movements can only be selected and initiated by recollecting "the memory-images of the movement's distinctive peripheral effects, whether resident or remote" (James, 1890/1981, p. 497) as sufficient "mental cues." This was the basis of what has become known as *ideomotor theory*.[3] Of course, introspection must be viewed with caution when it comes to derive models of human behavior. Yet, in this case, James seems to have been right.

Principles of Ideomotor Theory

Goal-oriented motor activities can occur only as a consequence of learning. Early on, during ontogenetic development, associations between efferent activities and their resulting perceptual consequences—their *action effects*—develop. These consequences certainly comprise the proprioceptive and tactile feedback from moving a body part when, for example, bending the finger to press a response key (the *resident effects*; sometimes also termed proximal or body-related effects; Pfister, 2019), but also visual and auditory consequences of this movement, including the visual impression from bending the finger and hearing the click when the response button is pressed (the *remote effects*; sometimes also termed distal or environment-related effects). Later on, recollecting the memories of these action effects serves to select and initiate the corresponding movement to bring about the desired perceptual consequence. In other words, recollecting certain effects primes those bodily movements that bring these effects about. As a consequence, bodily movements can be termed "actions" proper, (a) after links between movements and their perceptual consequences have been acquired and (b) a person aims to produce some of these consequences. This is in agreement with Wittgenstein's (1953) popular definition: action = body movement + intention.

There are various reviews on experimental work inspired by ideomotor theory, which we do not want to repeat here (e.g., Badets, Koch, & Philipp, 2016; Shin, Proctor, & Capaldi, 2010). Altogether, there is increasing evidence showing that humans—and possibly other species—readily acquire links between their motor activities and the perceivable changes induced by these activities. Most of this research relies on the observation that the encounter of, mostly distal, events that had previously been experienced to result from certain body movements, reactivate exactly these body movements (e.g., Elsner & Hommel, 2001). Further, codes of such perceivable changes seem to be involved when it comes to generate these motor activities. Most of this research relies on the observation that features of distal events that a bodily movement foreseeably produces, do impact the efficiency of generating that bodily movement. For example, the generation of a movement is slightly delayed when it predictably produces a temporally delayed rather than undelayed visual or auditory event (e.g., Dignath, Pfister, Eder, Kiesel, & Kunde, 2014), or when the predictable remote and resident effects of a motor pattern are incompatible to each other, for instance, when a left response predictably leads to a right visual effect and a right response leads to a left effect compared with when responses and effects are compatible and are thus located on the same side in action-effect compatibility (AEC) tasks (the AEC effect; e.g., Janczyk, Durst, & Ulrich, 2017; Koch & Kunde, 2002; Kunde, 2001; Pfister & Kunde, 2013).

The core assumption that action goals are pivotal for motor performance is of course compatible with various theories beyond ideomotor theory. It is inherent to the model of posture-based movement planning (Rosenbaum, Meulenbroek, Vaughan, & Jansen, 2001), if we assume that postures are perceptible states. Also, research on the *focus of attention* hypothesis in motor control and learning has studied how attending to remote action effects

[3] William James was not the first with such ideas. Similar ideas were expressed earlier by Herbart (1825) and Harleß (1861), whereas the term *ideomotor* was first used by Carpenter (1852). More information on the history of ideomotor theory is provided in Stock and Stock (2004) and a translation and evaluation of Harleß' work is given by Pfister and Janczyk (2012).

changes motor learning as compared with a focus on resident effects (Wulf, 2007; Wulf & Prinz, 2001). However, ideomotor theory seems to set the most common ground for explaining dual task limitations, which is what we aim for here.

Summary

There is considerable evidence that the generation of a motor response is realized by retrieving to a sufficient degree memories of the perceptual consequences of that particular action. This, by definition, turns each voluntary bodily movement into goal-oriented behavior: an action that aims at producing certain perceptual feedback. This is an important insight, because it moves the focus of explanation to the process of goal activation rather than to that of stimulus-response assignments.

Dual Tasking

So far we have discussed research from single task settings, but as noted before, this laboratory approximation rarely if ever is true. In the following we turn to multitasking, that is, situations where two (or more) tasks have to be performed. Our focus here is on situations where two tasks are carried out with more or less time overlap, that is, on dual tasking. As an umbrella term, multitasking also covers situations where humans switch between two different tasks (*task switching*; Kiesel et al., 2010; Koch et al., 2018) and we make a few comments on task switching as well, though this is not the main topic of this review. In the following, we briefly introduce the standard research setups and results followed by a sketch of current models explaining these results.

Research Approaches and Results

In much work, dual task performance was assessed by comparing performance in single task conditions with that in dual task conditions (e.g., Hazeltine, Teague, & Ivry, 2002; Janczyk, Nolden, & Jolicoeur, 2015; Schumacher et al., 2001; Tombu & Jolicoeur, 2004). Accordingly, in some blocks, both tasks are presented in separation and only one response is required in each trial (homogenous single task blocks), whereas in other blocks, both stimuli are presented simultaneously and two responses are to be given (dual task blocks). In addition, sometimes blocks are realized where both tasks can in principle occur, but only one stimulus is presented on each given trial (heterogeneous single task blocks). Then, the RT increase from homogenous to heterogeneous single task blocks is sometimes referred to as mixing costs; the further increase in dual task blocks is an index of dual task costs.

A different approach to study dual tasking are *overlapping tasks experiments* (also known as PRP experiments). Here, the two stimuli are presented on all trials, but their temporal separation, that is, the SOA, is varied. With a short SOA, task overlap is high, but the longer the SOA, the less do tasks overlap. In this case, Task 1 RTs are often—though not always—largely unaffected by the SOA manipulation. In stark contrast, Task 2 RTs are longer the shorter the SOA, flattening out to an asymptotical level at sufficiently long SOAs. The difference between Task 2 RTs at a short and at a long SOA is sometimes called the *PRP effect* and is also an index of dual task costs.

Models Explaining Dual Task Costs

To account for the observation of dual task costs, and in particular for the PRP effect, cognitive psychologists came up with a variety of models which can—for convenience—be categorized under two broader classes: bottleneck models and resource/capacity sharing models. Regardless the exact conceptualization, these models share the assumption that task processing involves three stages: (a) a precentral stage usually associated with perceptual processing, (b) a central stage, and (c) a postcentral stage typically related to motor execution. Pre- and postcentral stages are assumed to not require shared capacities, thus being unaffected when running in parallel with all types of other concurrent stages. The central stage is usually labeled *response selection* in those models, and is in one or another way conceptualized as *capacity-limited* and hence responsible for dual task costs.

According to *bottleneck models* (see Figure 1a), response selection constitutes a bottleneck in the cognitive system, meaning that at any time only one response can be selected. As a consequence, response selection in Task 2 must await release of the bottleneck, what causes an idle time of processing sometimes referred to as the *cognitive slack*. The cognitive slack is what prolongs the corresponding Task 2 RTs, that is, what creates the PRP effect. There is some debate regarding the exact nature of the bottleneck, which is—according to some authors—immutable and structural (e.g., Pashler, 1994; Welford, 1952). For other authors, however, the bottleneck is implemented strategically in an attempt to avoid crosstalk between tasks and to enforce seriality of response selection (e.g., Meyer & Kieras, 1997; see also Miller, Ulrich, & Rolke, 2009). Also, it has been suggested that processes other than response selection can impose additional bottlenecks before or after selection of responses. Certain perceptual operations seem to do so (reviewed in Pashler & Johnston, 1998), and there is also quite some evidence that dual task costs occur when one of the tasks requires no selection between responses at all, that is in simple response tasks where only one predefined response is to be executed whenever a stimulus occurs (Maslovat et al., 2015; Schubert,

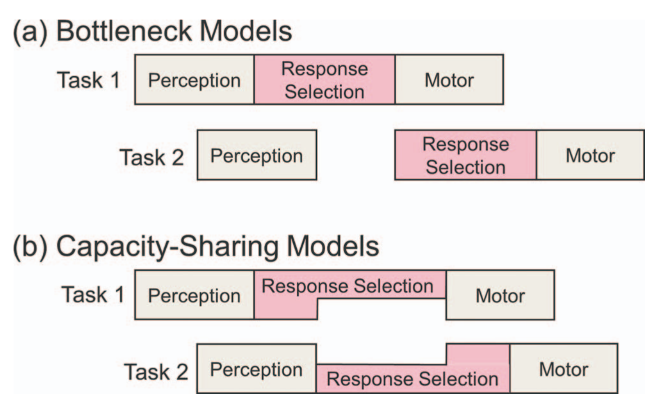

Figure 1. Illustration of the two standard models to explain dual task costs. (a) Bottleneck models allow only one response selection stage to run at the same time (e.g., Meyer & Kieras, 1997; Pashler, 1994; Welford, 1952). (b) Capacity sharing models allow response selection to proceed in parallel, but at the cost of sharing a common capacity and thus losing efficiency (e.g., Navon & Miller, 2002; Tombu & Jolicoeur, 2003). See the online article for the color version of this figure.

1999; Welford, 1952; see also Janczyk, Pfister, Wallmeier, & Kunde, 2014, Exp. 1). Thus, the selection between response alternatives is unlikely to be the sole cause of dual task costs. Some models therefore assume a bottleneck stage in response initiation instead of (Keele, 1973) or in addition to response selection (de Jong, 1993).

In contrast, *capacity-sharing models* (see Figure 1b) assume that two response selection stages can in fact run in parallel, but at the cost of less efficiency (Navon & Miller, 2002; Tombu & Jolicoeur, 2003). The rate of this sharing needs not be fixed but can vary depending on certain task characteristics. If one assumes that all available capacity is first allocated to Task 1 and only subsequently to Task 2, capacity-sharing models mimic the response selection bottleneck model. The degree to which capacities have to be shared among tasks might depend on the nature of tasks as suggested in the multiple resource model by Wickens (2008), such that two tasks share resources when they both rely on visual-spatial codes. The multiple resource model has turned out to be very helpful in engineering psychology, because it captures tasks beyond those employed in mental chronometry on which stage-oriented models typically rely. It is notoriously difficult, though, to scrutinize which sort of codes eventually exist and determine capacity sharing (e.g., only *spatial* and *verbal* codes, or also codes such as *numerical*, *temporal*, *symbolic*, *affective* etc.?).

Summary

We have briefly reviewed the most important approaches to study dual tasking, which was followed by the presentation of the two prevalent classes of models that were advanced to explain dual task costs. The important insight from these sections is that dual task costs are attributed to a capacity-limited stage that includes response selection, which is concerned with the selection of a response from various alternatives. Possibly, also the initiation of a selected response can be done for only one response at a time.

Goal Activation as the Crucial Determinant of Dual Tasking

The studies reviewed in the Making the Body Move section made clear that anticipation of action effects can be construed as a crucial process in generating motor activities following the premises of ideomotor theory. The models of dual tasking reviewed in the Dual Tasking section have in common that a stage invoked in response generation is the capacity-limited one that causes the problems associated with dual tasking and the related dual tasks costs. What we essentially contend here is that (a) generating a motor pattern (a "response") is better described as anticipation of intended effects and that (b) the limitation in activating representations of two distinct action effects at the same time is a cause for the observed dual task performance detriments. In the following, we present evidence for this view from four different lines of research we pursued throughout the recent years.

The Locus of Effect Anticipation

It often takes more (response) time to initiate a bodily movement that is required to produce an intended distal event, when that intended event is predictably incompatible to the required bodily movement (or respectively to the resident effects of that movement) in AEC tasks. This delay is conceivably based on an anticipatory representation of the distal event, because that event is not yet physically present when RT is measured (Kunde, 2001; see also Janczyk & Lerche, 2019; Pfister, Janczyk, Gressmann, Fournier, & Kunde, 2014; and others). Influences of AEC are reasonably strong with continuous movements and effects such as joystick/mouse/lever/wheel responses and spatially (in)compatible object movements (e.g., Janczyk, Yamaguchi, Proctor, & Pfister, 2015; Janczyk, Pfister, & Kunde, 2012; Shin & Proctor, 2012; Yamaguchi & Proctor, 2011), force varying keypresses and effects of (in)compatible intensity (e.g., Kunde, Koch, & Hoffmann, 2004), or verbal responses and phonologically (in)compatible verbal effects (e.g., Földes, Philipp, Badets, & Koch, 2018). In contrast, they seem weaker, and sometimes not obtained, with discrete spatial responses and effects (e.g., Pfeuffer, Kiesel, & Huestegge, 2016; Weller, Pfister, & Kunde, 2019), in particular when action effects are unattended (Ansorge, 2002), or when the compatibility relation rests on a semantic level alone (Földes et al., 2018). Still, AEC effects in general provide a useful index of the effect anticipation process, which is the basis for intentionally generating a motor pattern according to ideomotor theory.

Two methods are described in the literature to identify the locus of this anticipation process within the stream of task-processing. For simplicity, we describe these methods for the case of bottleneck models but note that capacity-sharing models make in fact the same critical predictions (see Navon & Miller, 2002). The first approach is called the *locus of slack-logic* (Schweickert, 1978; for applications and further descriptions, see Janczyk, 2013; Janczyk, Augst, & Kunde, 2014; Miller & Reynolds, 2003) and allows to distinguish whether an RT effect has its source (a) before the bottleneck stage or (b) in or after it.

At first sight, asking the question at which stage effect anticipation occurs might seem odd, because ideomotor theory draws no sharp boundaries between perceptual and motor-related stages. Instead, it emphasizes that generating a motor activity relies on perceptual codes, and action generation is considered a continuous rise of effect code activation. Once an effect code activation threshold is reached, the motor pattern most closely linked to that effect code is emitted (Kunde et al., 2004; Shin & Proctor, 2012). Selecting a response thus represents an intermediate state of effect code activation, below an execution threshold, whereas response initiation describes the process of an effect code activation crossing the execution threshold. Still, at some point in time between presenting a stimulus and generating a motor response there obviously is a limitation for generating more than just one action. This limitation might *mimic* a stage, rather than *occurring within* a stage. Certainly, it is important to study when this limitation occurs, and whether anticipation of perceptual codes is involved in it. Moreover, this will help to build bridges between stage-oriented and ideomotor theorizing, as it allows to express processes considered in one type of model in the language of the respectively other type of model.

To utilize the locus of slack-logic, an AEC task, which indexes effect anticipation, is implemented as Task 2 in an overlapping tasks/PRP experiment. It is first predicted that the AEC effect should be observed with a long SOA. Of particular importance, however, is the size of the AEC effect with a short SOA: If the AEC effect results from the bottleneck stage or later, the AEC effect should be of the same size as with the long SOA. This is predicted, because the effect code activation that gives rise to the AEC in Task 2 cannot occur without limitations concurrently with the effect code activation needed to generate another distinct action in Task 1. In other words, AEC and SOA should combine additively. In contrast, if the AEC has its source prior to the bottleneck, the prolongation should stretch into the cognitive slack, be absorbed, and thus not be observable in Task 2 RTs. Statistically, an underadditive interaction of AEC and SOA is expected.

The available empirical evidence clearly supports the first prediction. For example, Paelecke and Kunde (2007) implemented AEC with spoken color words as responses and color patches as effects (Exp. 1) and with soft and hard key presses followed by quiet and loud tones (Exp. 2) in Task 2 of a PRP experiment. In both cases, the AEC and SOA manipulations combined additively. A further manipulation of AEC that requires continuous movements is a one-pivot lever (Janczyk et al., 2012; Kunde, Müsseler, & Heuer, 2007; Müsseler, Kunde, Gausepohl, & Heuer, 2008). Typically, moving the hand into one direction results in the lever to move into the opposite (i.e., spatially incompatible) direction, yielding longer RTs compared with a condition in which the direction of hand and tool is compatible. Importantly, using such tasks yielded the same results as described already (Kunde, Pfister, & Janczyk, 2012, Exp. 1 and 2).

In all these experiments, AEC was manipulated block-wise, and thus any results may be subject to strategic adaptations as well. However, in one further study, we manipulated AEC trial-wise in an experiment using mouse movements, and again AEC and SOA combined additively (Wirth, Pfister, Janczyk, & Kunde, 2015, Exp. 1). Finally, also another behavioral influence that indicates effect code activation, namely the delayed action production with delayed as compared with immediate action effects (Dignath & Janczyk, 2017; Dignath et al., 2014), combines additively with the SOA (Wirth et al., 2015, Exp. 3).

Having excluded a prebottleneck stage, the *effect propagation-logic* can be used to further investigate whether the AEC effect results from the bottleneck stage or a subsequent stage (e.g., Durst & Janczyk, 2018; Janczyk, Humphreys, & Sui, 2019; Miller & Reynolds, 2003; see also Smith, 1969). Typically, the task order is reversed and analyses focus on the short SOA condition. Obviously, Task 1 RTs should be affected by AEC now with longer RTs in incompatible than in compatible conditions. If the AEC effect results from a stage after the bottleneck stage, however, Task 2 RTs should be unaffected, because the Task 1 motor stage runs in parallel to other Task 2 processes. In contrast, if the AEC effect results from any stage prior to motor execution, the capacity-limited process of Task 2 is delayed accordingly, and thus the Task 1 effect should propagate into Task 2 RTs. The results from available experiments are in accordance with this latter prediction (Kunde et al., 2012, Exp. 3; Paelecke & Kunde, 2007, Exp. 3; Wirth et al., 2015, Exp. 2 and 4; Schwarz, Pfister, Wirth, & Kunde, 2018).

However, it should be noted that we have consistently observed overpropagation of manipulations of AEC in Task 1 into Task 2, that is, larger RT effects in Task 2 as compared with Task 1 (Kunde et al., 2012; Paelecke & Kunde, 2007; Wirth et al., 2015). This may suggest that another capacity-limited process is invoked by manipulations of action effects after Task 1 RTs had been registered. As explained below, we assume that this process is monitoring of action effects.

Combining these results suggests that effect anticipation coincides in time with what models of dual tasking refer to as response selection—quite in line with the basic assumption of the ideomotor theory (see also Janczyk & Lerche, 2019). Two further aspects are noteworthy, however. First, it should be acknowledged that an additional contribution to AEC may result from motor execution and become visible in continuous movements only (see also Kunde et al., 2004). In particular, when using mouse movements as responses, not only RTs but also the trajectories were affected by an AEC manipulation (e.g., Pfister, Janczyk, Wirth, Dignath, & Kunde, 2014).

Second, Paelecke and Kunde (2007, Exp. 4 and 5) also employed a task in which stimuli either resembled the predictable distal effects of the motor pattern requested by that stimulus, or resembled the distal effects of a not requested motor pattern. As observed previously, responding was faster when the stimuli did match the distal sensory effects of the requested motor patterns rather when stimuli and effects did not match. The explanation for this observation is that at least some of the effect anticipation otherwise needed to generate an effect-related motor pattern is spared by directly perceiving these effects (Elsner & Hommel, 2001). Notably, this manipulation yielded an underadditive combination of compatibility with SOA. Accordingly, only internal generation of goal codes causes a limitation, whereas external stimulation of goal codes (driven by stimuli prior to responding) does not, or at least, to a lesser extent.

In sum, these studies point to effect anticipation as being at least involved in, and maybe coinciding with, the process that causes dual task costs. We will continue by considering what happens if one task requires a response that cannot be conceived as an action and thus does not involve effect anticipation.

No Goal—No Dual Task Costs

If effect anticipation is the capacity-limited process leading to dual task costs, this implies that no dual task costs should be observed if one task does not involve an action and thus no effect anticipation. To investigate this, we made use of a behavioral response that can occur for varying reasons, namely eye blinking. Eye blinking can occur intentionally, for example, if one wishes to cheer up a communication partner. In this case, eye blinking clearly can be conceived as an action. However, eye blinking is also part of an unconditioned reflex when an air puff is applied just below an eye—perhaps the most obvious form of simple behavior. Finally, an eyeblink can also be the required response to the onset of an auditory or visual stimulus; although admittedly, this may be restricted to the oddness of a psychological experiment. However, even though simple responses as in the latter case were sometimes conceptualized as *prepared reflexes* (Hommel, 2000; Woodworth, 1938), they are still examples of actions and thus should involve effect anticipation. We implemented an eyeblink task as Task 2 in an overlapping task/PRP experiment (Janczyk, Pfister, Wallmeier, et al., 2014). When eye blinking was the required response to an auditory stimulus in this task, dual task costs in terms of a PRP effect were observed (Exp. 1). Thus, even such simple (and certainly well practiced) motor behavior, possibly even responses to startling stimuli (Maslovat et al., 2015), incurs effect anticipation and thus becomes susceptible to dual task costs. In contrast, when eye blinking was triggered as an unconditioned reflex, no signs of dual task costs were observed at all (Exp. 2 and 3). Thus, the generation of the very same movement may or may not suffer from simultaneous processing of another task—dependent on whether it involves effect anticipation or not. Note also that in these studies participants had not to select between different responses, which questions that it is the selection between actions that causes dual task interference (e.g., Klapp, Maslovat, & Jagacinski, 2019).

Effect-Based Between-Task Crosstalk

The results reviewed so far suggest that the process responsible for dual task costs may be better described as effect anticipation rather than response selection. If this were true, another straightforward prediction follows: Between-task crosstalk effects should not be determined by features of the effectors, but rather of the perceptual effects produced with these effectors. To start with, we briefly summarize results from single task experiments speaking to this point.

One of the most well-known effects in cognitive psychology is the Simon effect (Simon & Rudell, 1967): Responses to a (relevant) stimulus feature are faster when the (irrelevant) stimulus location matches the response location (see Hommel, 2011, for a review). Against the background of ideomotor theory, however, the response location can be reinterpreted as the location of the current goal, that is, the depressed response button with all its action effects including the visual impression and the proprioceptive feedback from bending the finger. Hommel (1993) had his participants switch on left and right effect lights. When a response button press switched on the spatially corresponding light (in a sense an action-effect compatible condition), a standard Simon effect was observed. However, if a left button press switched on the right light and vice versa (in a sense then an action-effect incompatible condition), the Simon effect was reversed, if participants were instructed to switch on lights, but not if they were instructed toward pressing the buttons. Taken together, these results suggest that the compatibility relation is rather based on overlap between stimulus and goal location, even though contributions from the motor responses as such cannot be neglected entirely based on this study.

The same conclusion applies to bimanual movements, that is, those involving both hands at the same time. For example, responding with two homologous fingers (e.g., with both index- or both middle-fingers) is faster than using nonhomologous fingers (e.g., one index- and one middle-finger; see Rabbitt, Vyas, & Fearnley, 1975). The traditional explanation for this is that homologous brain areas are involved in the former cases that can mutually coactivate each other (e.g., Cohen, 1971). If, however, nonhomologous finger combinations result in similar visual effects and homologous finger-combinations result in dissimilar effects, the homology effect is reversed (Janczyk, Skirde, Weigelt, & Kunde, 2009). Similar observations were reported for more complex, continuous movements as well. Usually, two asymmetrical rotation movements with both hands are hard to execute, but this problem is solved if both movements produce symmetrical visual outcomes (Mechsner, Kerzel, Knoblich, & Prinz, 2001). Moreover, manipulating natural objects with both hands simultaneously is easier accomplished if both objects' end state is similar irrespective of whether the required movements are symmetrical or not (Kunde, Krauss, & Weigelt, 2009; Kunde & Weigelt, 2005). Further, the selection of responses in a free-choice task seems to be affected by similarity of action effects in addition to homology of fingers (Janczyk & Kunde, 2014). More generally, bimanual movements incur RT costs when both movements require asymmetric rather than symmetric trajectories (e.g., Diedrichsen, Hazeltine, Kennerley, & Ivry, 2001; Heuer & Klein, 2006). These costs are, however, heavily reduced when the goals of the two movements are cued directly instead of requiring a translation from symbolic cues (Diedrichsen, Grafton, Albert, Hazeltine, & Ivry, 2006; Diedrichsen et al., 2001). Similar to our contention on the importance of goal states, Oliveira and Ivry (2008) suggested that "response selection and online control of bimanual actions are minimally taxed when the actions are directly specified or conceptualized to focus on a simplified sensory goal" (p. 132). A similar conclusion was made by Franz, Zelaznik, Swinnen, and Walter (2001), who demonstrated that bimanual movements were easier to accomplish when their result can be conceptualized as a "common spatial representation" (p. 111). In sum, several studies using single or bimanual coordination tasks indeed point to a crucial role of goal states in creating interference in these examples. We now turn to dual tasks.

In addition to the unspecific and general dual task costs, content-specific interference occurs between tasks depending on certain response and/or stimulus features of both tasks. For example, Hommel's (1998) participants responded to a colored letter stimulus with a manual left/right response in Task 1 and a vocal utterance of "left" or "right" in Task 2. If both responses were compatible regarding spatial features (e.g., pressing the left key and saying "left"), RTs even in Task 1 were shorter in comparison with incompatible trials (e.g., pressing the left key and saying "right"). This phenomenon has thus been termed the (compatibility-based) backward crosstalk effect (BCE). Such BCEs were replicated with different response modalities and different tasks (e.g., Durst & Janczyk, 2019; Ellenbogen & Meiran, 2008, 2011; Hommel & Eglau, 2002; Janczyk, 2016; Janczyk, Renas, & Durst, 2018; Lien & Proctor, 2000; Naefgen, Caissie, & Janczyk, 2017; Watter & Logan, 2006; and many others) and in children and older adults as well (Janczyk, Büschelberger, & Herbort, 2017; Janczyk, Mittelstädt, & Wienrich, 2018).

In these experiments, the compatibility relation was usually defined based on (relative) response locations. However, similar to the above reviewed single task studies, this confounds response with goal locations: Pressing a left response key also results in a left visual impression of the moving finger, in a left sound from pressing the button, and in a left proprioceptive feedback from bending the finger. Even worse, all these aspects are action effects and are likely anticipated to emit the bodily movement. Thus, it may also be the case that compatibility is better described as being determined on the basis of the effects' locations.

To identify the crucial determinant, Janczyk, Pfister, Hommel, and Kunde (2014) equipped participants with visual effects in one or both tasks in BCE experiments. For example, in Experiment 1, the Task 2 response resulted in a left or right visual effect with a manipulation similar to the one used by Hommel (1993): When the Task 2 response and the resulting effect were spatially compatible, a standard BCE was observed for this group. Of course, all compatibility relations were confounded in this case, and more interesting is thus the performance of a group for which the relation between response and effect in Task 2 was reversed and thus incompatible. If the action effects do not matter at all, the BCE should just be the same as in the first group. In contrast, the BCE was reversed in this group, that is, RTs in Task 1 were shorter when effects were compatible, irrespective of the fact that in this case the key locations were incompatible. This result was generalized in two further experiments using continuous movements with the lever device described above (Exp. 2) and even with nonspatial action effects that could be similar or not (Exp. 3).[4] To corroborate the general conclusion, Renas, Durst, and Janczyk (2018) employed a crossed-hands manipulation in two BCE experiments (Wallace, 1971; see also Kunde & Wühr, 2004; Pfister & Kunde, 2013). While with uncrossed hands, the left response key was operated with the left hand and the right response key was operated with the right hand, in the crossed-hands condition the left response key was operated with the right hand and vice versa. The size of the BCE was similar in both conditions, however, irrespective of whether the manipulation was implemented in Task 1 or 2, and irrespective of whether the other response was given with the feet or vocally. Thus, this study rules further out that the side of the anatomical connection of the effector with the body is important, but rather emphasizes again the location of the consequences of a bodily movement.

In these studies, two overt motor behaviors were involved. But what about the interplay of overt motor behavior and mental operations which are deemed to involve covert motor activity? Several studies have shown that mental rotation (Shepard & Metzler, 1971) is facilitated by preceding or simultaneous manual rotations into the same direction (Wexler, Kosslyn, & Berthoz, 1998; Wohlschläger & Wohlschläger, 1998). Now, manually rotating something in a clock-wise direction brings about visual effects and proprioceptive impressions rotating into the same direction as well, and thus response and goal rotation directions are again confounded. We used rotations of a steering wheel that resulted in rotating effects into the same or the opposite direction[5] in combination with a mental rotation task to de-confound these aspects (Janczyk, Pfister, Crognale, & Kunde, 2012). Again, we observed evidence that a subsequent mental rotation is facilitated if the resulting effect rotation goes into the same direction, but this was also true when the manual rotation went into the opposite direction. Thus, even the interplay of overt behavior and mental operations like mental rotations appears to be driven by action effects rather than by the effectors producing these effects.

All in all, the studies reviewed in this section so far strongly suggest that indeed codes of intended perceptual action effects (i.e., goals) determine to a large degree which actions go together easily and which do not.

Monitoring Produced Action Effects

So far we were concerned with anticipated action effects. Conceivably, however, effect codes are not immediately erased once an action is physically executed. Actors must retain effect codes beyond action initiation, as a reference to monitor that they actually achieved what they aimed for. In fact, Welford (1952) already argued that a second process termed response monitoring interferes with other tasks and is thus an individual source of dual task costs (see also Bratzke, Rolke, & Ulrich, 2009; Ulrich et al., 2006). Now, assuming that effect code activation cannot occur for two tasks at the same time, such codes, which remain active for monitoring should interfere with the generation of other actions. We have argued previously that such response monitoring may better be reinterpreted as monitoring of proprioceptive action effects, and thus as a special case of a more general effect monitoring process (Kunde, Wirth, & Janczyk, 2018). To test this idea we (Steinhauser, Wirth, Kunde, Janczyk, & Steinhauser, 2018; Wirth, Janczyk, & Kunde, 2018; Wirth, Steinhauser, Janczyk, Steinhauser, & Kunde, 2018) employed a variant of the overlapping tasks/PRP approach where we presented the Task 2 stimulus always 50 ms after the Task 1 response was given. This was done to avoid any overlap between response selection/effect anticipation stages (see also Bratzke et al., 2009, for an earlier use of this variant). The manipulation of AEC in Task 1 resulted, as one would expect, in a standard AEC effect in Task 1 (i.e., longer RTs in the incompatible compared with the compatible condition). We further assumed that monitoring action effects that are incompatible to the resident effects of the action takes longer than monitoring action effects that are compatible (Desantis, Roussel, & Waszak, 2014). This lengthened effect monitoring process in the incompatible Task 1 condition should then interfere with Task 2 performance more compared with the case of a compatible Task 1. In fact, Task 2 RTs were longer following an incompatible than following a compatible Task 1 action effect, even in this situation where the Task 2 stimulus occurred only after the Task 1 response was given. Similar Task 2 results were also observed when Task 1 AEC varied unpredictably from trial to trial. Thus, these recent results suggest that not only anticipating to-be-produced action effects, but also monitoring of eventually produced action effects can contribute to the occurrence of dual task costs (cf. also Kunde et al., 2018, for further evidence).

Summary

We have reviewed studies from four different lines of research showing that (a) conceiving response generation as action effect anticipation is a more realistic description of the source of the problems in dual tasking, (b) no dual task costs occur in case of simple non–goal-directed behavior not involving effect anticipation, (c) the amount of specific dual task costs is determined by action effects rather than the involved effectors, and (d) even monitoring the actual occurrence of desired effects is an additional source of costs in dual tasking. In other words, activating and

[4] It should be added here that the numerical size of the reversed BCE was smaller and nonsignificant in comparison with the standard BCE. This, however, is easily explained by recognizing that, in the condition with the reversed BCE, the action effects that are directly associated with the finger movement counteract the added visual action effect that occurs on the opposite side.

[5] More precisely, we employed a display similar to the attitude indicator in airplanes, an instrument that indicates the deviation from level flight. Of interest, two versions of this instrument are in use (see also Previc & Ercoline, 1999). In most Western aircrafts, an inside-out display is employed where the plane remains stable, but the horizon rotates. Notably, turning a plane counter-clock-wise then results in a clock-wise rotation of the horizon. In Russian aircrafts, in contrast, an outside-in display has been preferred, where the horizon remains stable, but the plane rotates. In our terminology, one can conceive the former as action-effect incompatible but the latter as action-effect compatible (see also Janczyk et al., 2015).

monitoring goal states appears to determine dual task costs and irreconcilableness of actions. Before we integrate these results, we briefly summarize further related studies involving ideomotor theory and dual tasking.

Ideomotor Compatibility and Dual Tasking

Ideomotor theory has in the past been invoked into dual task research from a slightly different point of view as well. In particular, it was argued that using *ideomotor compatible* tasks enables one to bypass any central and capacity-limited stage of processing and thus to eliminate dual task costs. According to Greenwald and Shulman (1973), ideomotor compatible tasks are ones in which the "stimulus resembles sensory feedback from the response" (p. 70). As an example, if one has to utter "cat" in response to hearing "cat"–this would qualify as ideomotor compatible, and so would be bending a right index finger as a response to an image of a bended right index finger. Because in such cases the requested action effect is actually presented and thus does not need to be endogenously activated, the capacity limited central stage is not heavily implicated and dual task costs shall be small.

The role of ideomotor-compatible S-R sets in dual tasking has repeatedly been studied over the last 40 years or so (Brebner, 1977; Greenwald & Shulman, 1973; Greenwald, 2003, 2004, 2005; Lien, Proctor, & Allen, 2002; Lien, McCann, Ruthruff, & Proctor, 2005; Lien, Proctor, & Ruthruff, 2003). This research can be summarized by saying, that dual task costs can be strongly reduced though not abolished by ideomotor compatible stimuli.

Halvorson, Ebner, and Hazeltine (2013) and Halvorson and Hazeltine (2015) have recently followed-up on these studies. Focusing on their simultaneous presentation experiments, they observed that dual task costs can be largely reduced when both tasks are *modality-compatible* (e.g., responding vocally to auditory-verbal stimuli, and manually to visual stimuli; Stephan & Koch, 2010, 2011), even though the mapping of individual stimuli and responses in each task need not be *ideomotor-compatible* (e.g., saying "dog" to the auditory stimulus "cat," and bending the middle finger when seeing the image of a bended index finger). The authors explain this by reduction of cross-talk between tasks when they operate on distinct codes (auditory-verbal and visuo-spatial codes, respectively). We come back to this issue when discussing modality-compatibility.

Altogether, it seems fair to summarize this debate by saying that ideomotor-compatible stimuli strongly reduce, but do perhaps not completely abolish, dual task costs. This debate has somehow come to a dead end for two reasons. First, it has, at least in the early days, focused on the *nonexistence* question, thus the question whether small (mostly nonsignificant) dual task costs are just small or absent. Second, ideomotor-compatibility is probably a theoretical ideal that can never be met empirically, because a stimulus can barely ever replace all sensory effects of a response, including its proprioceptive and tactile components, thus leaving open the possibility for at least small dual costs.

Elaboration

The review so far has shown that goal codes, that is, codes of to-be-produced perceptual events in the environment, including the own body, are key to understanding dual task constraints. In the following we want to elaborate this goal-oriented perspective and explain how it might account for key empirical observations in dual tasking.

Seemingly Simple Actions Require Goal Activation

Even simple, predetermined actions are emitted with a delay concurrently with another action, as compared with initiating this action alone. This cost occurs despite the absence of peripheral effector overlap or other obvious (e.g., spatial) overlap between actions, and without the necessity to select between actions. For example, pressing a brake pedal, eye blinking, or grasping an object are all delayed when another action has to be specified concurrently (Janczyk, Pfister, Wallmeier, et al., 2014; Kunde et al., 2007; Levy et al., 2006). Because no response selection is necessary here, it has been argued that there is a response initiation bottleneck instead of (Keele, 1973) or in addition to (de Jong, 1993) the traditional response selection bottleneck. Recently, this observation has also been taken as an argument for a response timing bottleneck (Klapp et al., 2019). We believe that such assumptions are not necessary. In fact, action production can be construed as a gradual increase of activation of codes of the actions' perceptual effects, with no sharp distinction between selection and initiation stages (Kunde et al., 2004). The rise of effect code activation, prior to reaching an execution threshold and thus the actual occurrence of a bodily movement, is subject to the same limitation as any other increase of effect code activation at a lower activation level.

Actions Are Perceptually Represented and Constrained

Assuming that actions are perceptually represented, namely by their perceptual effects, suggests that they are constrained in a similar way as percepts are. Two such constraints have been described by Fechner (1860) and Weber (1834). First, a percept arises only when its internal representation exceeds a certain minimal threshold. Second, two percepts are distinguishable only when there is a relative difference in their activation strength. We suggest that the same applies to the perceptual effect codes that mediate action production. Thus, a motor pattern is emitted only when its associated effect codes exceed a certain threshold (execution threshold), *and* when these codes are sufficiently distinguishable (relative threshold) from other concurrently active effect codes (see Figure 2).

This assumption implies that, everything else being equal, a perceptual goal code needs a stronger activation to become sufficiently discriminable, when other goal codes are active as well, than when they are not. Assume that a motor pattern is emitted when its associated effect codes have an activation of more than 1,000 units (minimal threshold), and their activation exceeds that of other goal states by more than 33% (relative threshold). Further assume that goal states can rise by one unit per millisecond. With no other active goal codes, the minimal execution threshold is reached in 1,000 ms. With another goal state being concurrently at an activation level of 900 units, 1,200 units (and ms) would be required because of the relative threshold. Thus, for a motor pattern linked to this goal state, more time will be required to exceed the execution threshold

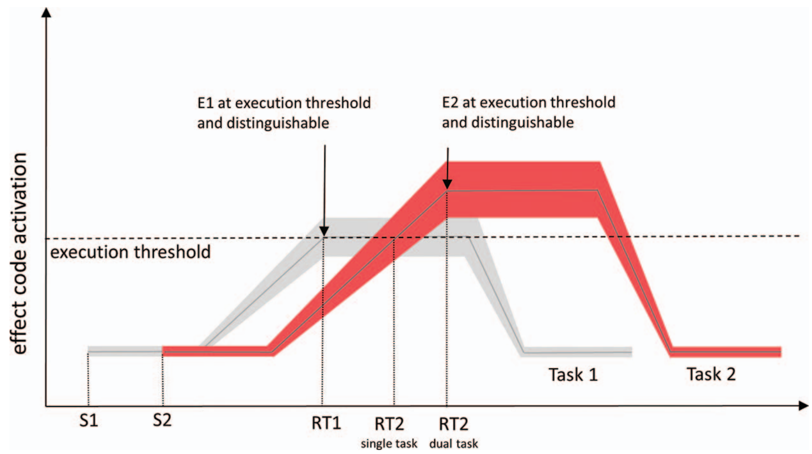

Figure 2. Illustration of hypothetical effect code activation of two motor actions in a PRP-like dual task situation. The colored areas depict the discrimination threshold which increases as effect code activation increases. A linear increase of threshold with activation strength is depicted here, but it might actually be an exponential increase according to Weber's law. If effect codes reach an execution threshold the corresponding motor pattern is emitted, provided these codes are sufficiently distinguishable from other, concurrently active, effect codes (no overlap of areas). Effect codes remain in an active state even after initiation of the corresponding motor pattern for the purpose of effect monitoring. Under dual task conditions, more activation of effect codes is necessary to become distinguishable from the effect codes of another task, and thus more time is required before a corresponding action can be emitted. RT = response times; PRP = Psychological Refractory Period. See the online article for the color version of this figure.

and to become discriminable from other effect codes. This is the reason for why responses take longer when more than one goal code is active, which is constitutive for dual tasking, as compared with pursuing only one goal, as in single tasking. Why does one goal state have to stand out among others? Assuming that actions are perceptually represented, the system would otherwise not "know" which motor pattern will eventually be executed because they were indistinguishable. However, the initiation of mentally indistinguishable actions obviously bears high risks, such as the possibility that a potentially threatening object is approached rather than avoided, or mutually irreconcilable motor patterns are emitted, such as grasping an object while leaning backward (Neumann, 1996). It is of course not the person trying to make a distinction between goal codes but rather the cognitive system controlling the person's motor activities has to do so.

If two or more goals are at a very high activation level, as is the case in multitasking proper, it might happen that neither goal code can make it to be relatively more active than another to a sufficient degree for a while, so that the system might appear temporarily blocked. Such periods of apparent inactivity are a common property of models that describe competition between options (Bogacz, 2007). These models typically assume that a behavioral option is chosen when the *difference* in evidence for this option relative to other options exceeds a certain threshold, rather than the evidence for this option as such. This is conceptually similar to the *relative* threshold described in the preceding paragraph. At the behavioral level, such periods of inactivity might correspond to hesitations that have been reported in dual task research (Netick & Klapp, 1994).

Compatibility of Effects and Effect Priming

The activation of codes of required effects depends on how these codes are linked to codes of other, currently not requested effects, and to the stimuli that remind of required effects, which explains various observations reviewed above. Motor patterns typically produce more than just one perceptual effect, such as tactile and visual effects. Codes of such multimodal effects are linked to each other, and prime each other, as a function of frequency and recency of previous concurrent encounters. Mutually compatible effect codes are those that have been encountered massively together. These encounters typically occur before a person enters the lab to participate in an experiment. For example, a left hand movement normally produces left visual and left tactile effects, and these effect codes are thus linked to each other. These links can thus be termed *long-term*. However, *short-term* links are established as well as a function of recency in an experiment, such as when a left tactile effect goes together with right visual effects. Facilitation occurs when the effects of a requested motor pattern are linked to each other by both, long-term and short-term links. This is the case, when a person aims to produce a left visual effect, such as flashing a light on the left or moving a tool to the left, with a left(ward) hand movement. In this case, there is mutual priming and thus faster rise of activation of mutually compatible visual (the intended flashing of the light) and body-related codes (the tactile effects from moving the left hand). Problems arise when two effect codes are mutually incompatible, such as when aiming to produce a visual tool movement to the left by means of a rightward movement of the hand (Müsseler et al., 2008). In this case, there would be no priming of a currently intended effect code. Together, this is the first reason for faster responding with compatible than incompatible action-effect mappings.

Additionally, with such an incompatible action-effect mapping the tactile codes—currently linked to an intended visual code—prime other, but currently not required visual goal codes via long-term links. For example, a right tactile code, which is currently linked to a required left visual code, would also activate a right visual goal code. This activation of currently not required visual effect codes makes it harder for a required visual goal code to stand out, and it might even require lateral inhibition of irrelevant effect codes (cf. Figure 3). This is the second reason for delayed responding with incompatible action-effect mappings.

The internal activation of effect codes can be externally supported by corresponding stimulation. The strongest support is provided by stimuli that closely resemble the currently intended effects, thus by ideomotor-compatible stimuli (Greenwald & Shulman, 1973; Diedrichsen et al., 2001; see Figure 3, lower part). Perfect ideomotor compatibility is a theoretical ideal, however. No stimulus can mimic all sensory effects of a required motor pattern completely, including all its tactile and proprioceptive components. As a consequence, even with ideomotor-compatible stimuli, some internal activation of effect codes likely remains necessary, and thus residual dual task costs occur (Lien et al., 2002).

Although external activation of effect codes is particularly strong with stimuli that resemble these effects, a certain amount of external effect code activation occurs as well with arbitrary stimuli because of previous encounters of stimulus-to-effect assignments (Hommel, 1998; Logan, 1988), or the intention to produce a specific effect to a certain stimulus (Gollwitzer, 1999; Kunde, Kiesel, & Hoffmann, 2003). Thus, a stimulus activates to some extent those effect codes to which it is linked by practice or instruction. This activation of effect codes impacts effect code activation in another task. First, an active effect code in a second task primes corresponding effect codes in another task. This gives rise to forward and backward effect-based cross-task compatibility influences (Janczyk, Pfister, Hommel, et al., 2014; Renas et al., 2018; Schwarz et al., 2018). Thus, when a red stimulus activates a "left" tactile effect code in Task 2 of a PRP experiment, this activates "left" effect codes in the first task as well. This is beneficial for the first task, in cases where this "left" code is linked to a motor pattern that is actually to be produced, as it supports the rise of these effect codes toward the execution threshold. In the same way, the activation of a left visual effect code in the first task supports the rise of the "left" tactile code in a secondary task toward the execution threshold. Priming of effect codes of a currently not requested motor pattern is detrimental, as the effect codes of the requested motor pattern need more activation to become discriminable from those being primed, but not being currently required.

Modality Compatibility

Visual stimuli resemble, and thus activate, the mostly visual effects of a manual action more than the auditory effects of a vocal action (although the visual-manual association is probably even weaker than the tactile-manual association; Stephan & Koch, 2015; see also Hoffmann, Pieczykolan, Koch, & Huestegge, 2019). Conversely, auditory stimuli resemble, and thus activate, the auditory effects of a vocal response more than the visual effects of a manual action (see Figure 4). Thus, when a visual stimulus requires the production of an auditory effect (a modality-incompatible mapping), the stimulus-supported activation of the not requested visual-manual effect-effector links requires a strong endogenous activation of the currently requested visual-vocal effect-effector link, and possibly lateral inhibition of the not requested visual-manual links. This inhibition of the currently not requested effect-links creates task switching costs, when these links are needed in a subsequent trial (Stephan & Koch, 2011), and dual task costs when trying to carry out actions concurrently (Halvorson & Hazeltine, 2015). By contrast, less lateral inhibition is necessary with modality-compatible mappings, leading to smaller dual task costs (e.g., Hazeltine & Ruthruff, 2006; Hazel-

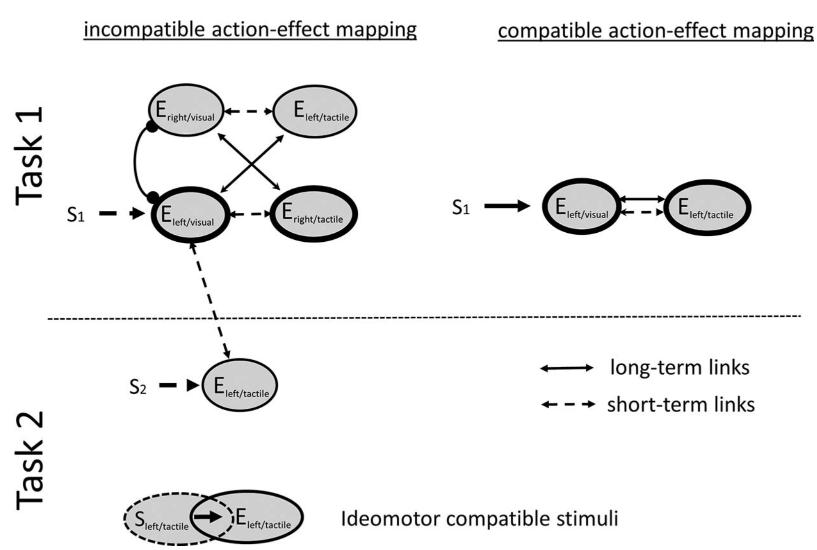

Figure 3. Different scenarios assuming multimodal effect codes in dual task-like situations. See text for description. S = stimuli; E = effect codes.

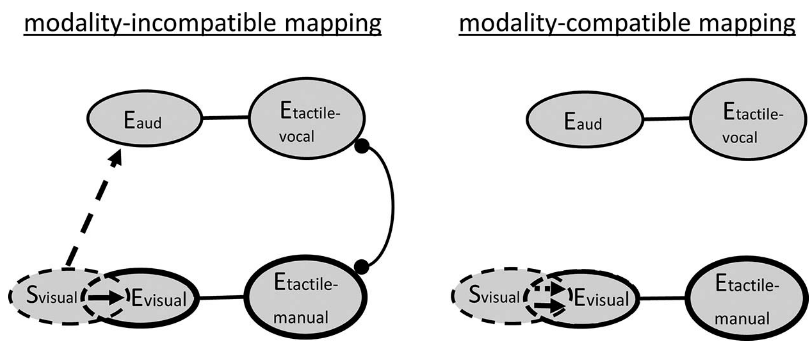

Figure 4. Assumed priming and lateral inhibition of effect codes in modality-incompatible and modality-compatible S-R mappings. Straight arrows represent activation according to preexperimentally established links between stimulus codes and effect codes (e.g., visual stimuli activate visual effects of manual actions). Dashed arrows represent activation according to instructed links between stimulus codes and required effect codes (e.g., visual stimuli are linked to the visual effects of manual actions in case of modality-compatible mappings, whereas visual stimuli are linked to the auditory effects of vocal actions in case of modality-incompatible mappings).

tine, Ruthruff, & Remington, 2006). Modality compatibility also seems to facilitate practice-related reduction of dual task costs, perhaps leading to the possibility of bypassing the bottleneck (Maquestiaux, Ruthruff, Defer, & Ibrahime, 2018). Interestingly, modality-compatible mappings facilitate performance in dual task conditions but barely, if at all, in single task conditions (Stephan & Koch, 2010). Possibly, the inhibition of a primed, but not requested effector system in case of modality-incompatibility is way more efficient in single task conditions as compared with dual task conditions, in which a currently inhibited effect system will be needed in the same trial (dual tasking proper) or briefly later (in task switching) and thus cannot be inhibited to the same extent.

It is also interesting that dual task costs are strongly reduced with modality-compatible mappings although the mapping of individual stimuli to actions is not ideomotor-compatible (e.g., saying "cat" to the auditory stimulus "dog," and responding with the middle finger to the image of an index finger). This might be explained by assuming that the auditory stimulus "cat" activates the code of the auditory effect "dog" still stronger and helps pushing it toward execution threshold more, than it does activate, for example, a visual code of a left finger response (as in case of a modality-incompatible mapping). In other words, the stimulus-induced activation of requested effect codes is probably still larger within the same rather than between modalities. From a goal perspective, it seems also possible that participants construe the task slightly differently with ideomotor-incompatible mappings. Because they cannot simply copy what they hear or see, they might aim at complementing stimuli to specific composita, such as "dog–cat" and "cat–dog." With half of the goal already being activated through the stimulus, even a superficially ideomotor-incompatible mapping can be construed as being rather compatible.

Conclusion

The main reason why dual tasking is difficult from a goal-oriented perspective is that a certain intended effect code needs to be relatively more active than other effect codes, and this takes longer with more than one effect code being active either in the same or another task at the same time. Stimuli that resemble currently not relevant effects increase the time for relevant effect codes to become sufficiently distinguishable from currently not required effect codes, which conceivably requires lateral inhibition of such irrelevant codes.

Implications and Relations to Other Observations

The goal-oriented perspective has several implications that we want to describe in the following.

Dual Tasking Is a Matter of Intended Effects (i.e., Goals), Not of Motor Patterns

The very same observable motor pattern can be carried out for different reasons. Both, the ease of producing a single motor pattern as well as the ease of combining two motor patterns more or less concurrently, is determined by the type of goals pursued, not muscles or responses. This general point can be illustrated in various ways. Consider a study by Klapp (2003). When participants were asked to produce either the three syllables "De" "Ka" "Bi" as compared with producing the two syllables "Du" "Co", RTs increased with the number of syllables. No increase with number of syllables was observed, when participants were asked to produce one of the two words "Dekabi" or "Duco." The reason for this is that three or only two goal codes, respectively, are activated sequentially with the syllable instruction, whereas only one integrated effect code is generated in the word instruction condition. Likewise, the same motor patterns are generated more quickly concurrently if they aim at the same body-external goals, rather than at different body-related goals (Kunde & Weigelt, 2005).

Representing different motor patterns in such a way that they are generated to produce one *joint* goal rather than two distinct goals can reduce or even eliminate dual task costs. For example, producing a 4:3 tapping ratio with the left and right hand is very hard, but producing a certain rhythm with both hands which is equivalent to that ratio is easy (Klapp, Nelson, & Jagacinski, 1998). Thus, integration of two action goals to one is a powerful means to overcome dual task costs. Although this point has been demonstrated with some dual task setups such as bimanual coordination

(Blinch & Jensen Kouts, 2018; Mechsner et al., 2001), it awaits to be tested with others such as in PRP experiments.

The Flexibility of Dual Tasking Is Determined by the Flexibility of Representing Perceptual Goals

What makes dual task costs so hard to describe in a unifying framework is that perceptible goals can exist at various levels beyond sensory features, a suggestion made earlier by Hommel, Müsseler, Aschersleben, and Prinz (2001). The term "perceptual" code does not mean "sensory" code. We can perceive features with respect to many more states than our sensors directly support (e.g., effort, convenience, symmetry, harmony, evenness, closeness, and so forth). All these states are mentally, and in most cases introspectively, distinguishable, and thus perceivable. There is no reason why such mentally distinguishable codes should not be linked to motor patterns and thus be used for action generation (Hommel & Wiers, 2017). Relaxing the idea of perceptible goal states to goals beyond immediate sensory feedback paves the way for explaining phenomena that are notoriously difficult to explain in terms of low-level sensory-motor processes.

Such phenomena become apparent when tasks involve overlapping sets of stimuli and responses, such as when asked to classify digits according to parity (odd or even) or numerical size (smaller or larger than five) with a left or right button press. Here, high accuracy cannot be achieved by linking individual stimuli to immediate perceptual effects (such as taking the digit "2" as a reminder to produce the tactile perception of a pressed left key). Therefore, people are forced to pursue more abstract goals, such as pressing the same left button to either signal (to the experimenter or computer) that the digit "2" is *even* or *small*. Typically, it is easier to press a left button to the digit "2" to classify that digit as *even* twice in a row, rather than having pressed the same button to classify the same digit as *small* in the trial before (Schuch & Koch, 2004). From a goal perspective, this happens because participants have to switch goals in the latter case, whereas the stimulus (the digit "2") provides no cue as to which goal to pursue. Moreover, the immediate resurfacing of a digit reactivates the goal to which it was linked a moment before, which facilitates activation of the same goal codes, while it lengthens the time for other goal codes to become sufficiently discriminable.

Traditionally, such effects are ascribed to changing task representations. Schumacher and Hazeltine (2016) construe such task sets (or "task files") as an ensemble of representations of stimulus features, objects, abstract actions, motor units, responses, goals, and drives. These entities of task files are bidirectionally linked. Stimuli do not directly activate responses, rather links between stimuli and responses are biased by, for example, current drives, and goals, and conversely, drives and goals might bias stimulus uptake toward certain features. Dual task interference is attributed to the similarity of activation patterns of task files. Basically, this is consistent with the present idea of goal-based dual task interference. However, we suggest that various entities of the proposed task file (such as drives, task goals, abstract actions, responses) can equally be described as intended goal states, which are linked to a varying number of specific motor patterns. Contracting the muscles of the left index finger to the digit "2" in an experiment might be done to get a reward (drive), to indicate parity (task goal), to emit a manual action (abstract action), on the left side (response). These goal states jointly determine the most appropriate motor pattern in a given situation, whereas each goal state alone does not constrain the number of appropriate motor patterns to a sufficient degree. The number of motor patterns linked to these active goal states might still be high, such that the muscles of the left index finger might contract with varying degrees of force. But they all meet the currently active goal states.

Limitations From Memory Representation

Another source of limitation might result from the assumption that active goal states are likely represented in some form of (working) memory. It is well known that working memory is capacity-limited, and working memory and response selection have recently been described in a common framework (see Oberauer, Souza, Druey, & Gade, 2013). The question is: Where does the capacity-limitation result from? Several recent models suggest that it is an emergent feature of mutual interference between working memory items (e.g., Jonides et al., 2008; Nairne, 1990; Oberauer, Lewandowsky, Farrell, Jarrold, & Greaves, 2012; Saito & Miyake, 2004). Thus, with more items in working memory, an enhanced risk of feature overwriting results, leading to "less overall activation of the representation, and thus to a reduced probability of recalling the item, as well as slower processing" (Oberauer & Kliegl, 2006, p. 622). We conjecture that such limitations contribute to the capacity limitations observable in dual tasking. This conjecture has, of course, to be worked out further. However, preliminary evidence already suggests that the selection of working memory items for later report and the selection of actions interfere with each other, just as one would expect if they are subject to similar constraints (Janczyk, 2017; Janczyk & Berryhill, 2014).

Final Remarks and Future Research

Psychological phenomena typically do not have a single "true" cause. Rather they arise from various cognitive processes, which in turn contribute to various phenomena (Hommel & Colzato, 2017). This is likely true for dual task costs as well, which might have more causes than concurrently active goal codes. Moreover, one may argue that the goal-oriented approach to dual tasking is just a redescription of previous evidence. This may also be true. But we are convinced that this description comes with advantages over other approaches to dual tasking. First, it allows to discuss various dual task phenomena within the same framework. Second, it has already inspired research on empirical phenomena, which other approaches would barely have considered. For example, no other approach would have suggested the existence of goal-based across-task compatibility influences (Janczyk, Pfister, Hommel, et al., 2014; Schwarz et al., 2018). Third, this approach generates new questions, which empirical research might tackle.

The most interesting aspect of the goal-oriented approach is that it points to considerable flexibility of dual task performance. Depending on the goals pursued, two bodily movements can be easy or difficult to combine. Although it is difficult to directly observe goals, we can manipulate them, at least in humans, by instruction: This gives access to the study of such flexibility and has already been demonstrated. For example, mentally rotating an object clock-wise facilitates the concurrent production of clock-wise rather than counter-clockwise manual actions. However, if participants are instructed to manipulate a visual object that rotates into the opposite direction to the manual action, and receive performance feedback depending on the instructed object manipulation, counter-clock-wise manual rotations are facilitated (Janczyk, Pfister, Crognale, et al., 2012). We conjecture that many more such instruction-based variations of dual task performance exist.

Unification of Goals

The key problem to understand dual tasking, as we see it, is to explain why it is hard to aim at two goals at a time. Assuming that goals are perceptible states, the same constraints that apply to representing perceptual states should apply to multitasking. We have discussed one constraint, namely that these states need a relative activation difference to become discriminable. This assumption corresponds to the "mutual exclusivity" principle proposed by Klapp and Jagacinski (2011). These authors suggest, as we do, that actions are perceptually represented, namely in terms of Gestalten, and that thus the laws of Gestalt perception apply to motor control. One such Gestalt law is that of two possible interpretations of a stimulus, only one is perceived at a time (e.g., in the well-known Necker cube). Thus, for the same reasons that percepts are limited to one perceptual state at a time are motor actions constrained, which are based on such perceptual states. This is probably a kind of default mode. It is of low risk to pursue one goal that, according to previous experience, can actually be accomplished by associated efferent activity. By contrast, aiming at two mentally indistinguishable goals invokes potential problems, such as efferent activity that creates physical conflict of effectors. Such problems might be overcome by fusing two goals to one, which have then become linked to one efferent activity altogether. For example, participants might learn that acting correctly to, let's say, the letter "A" in one task and the digit "2" in another task of a PRP experiment can be achieved by pressing a left and right button in a row. Interestingly such grouping strategies are often considered as contamination of true dual tasking (Miller & Ulrich, 2008; Ulrich & Miller, 2008). In a sense they are, because dual tasking proper means to pursue two goals at a time. On the other hand, such fusion of initially distinct goals to one goal is a reasonable attempt to overcome dual task problems, and they might be the basis for practice-related declines of dual task costs. One consequence of fusing elements into Gestalten is that individual elements get lost. Along these lines, Huestegge, Pieczykolan, and Koch (2019) showed that performing a single task does not benefit from performing the apparently same task in a dual task setting in the preceding trial. This observation has been attributed to the absence of a repetition priming benefit if this task was previously performed in the context of performing it together with another task. Apparently doing two tasks formed a new Gestalt in which its original independent components got lost.

Perceptual Constraints

A more general constraint that arises from the proposal of a perceptual representation of goals is that things that are hard to perceive should be hard to be produced by corresponding motor activity. At the level of goals that relate to the own body this is trivial. We cannot perceive our right hand moving to the left and to the right at the same time and so cannot we move it. But in a more relaxed interpretation, this allows for interesting research questions. For example, two motor actions should more easily fuse to one action, and create no (or at least less) dual task costs, if their perceptual effects fuse easily. For example, research on multisensory integration has identified factors that support perceptual fusion (Odegaard, Wozny, & Shams, 2017), and it remains to be tested whether the same factors shape the fusion of actions that produce such multisensory effects as well.

Goal Levels

People can construe what they do at different levels of description (Vallacher & Wegner, 1987). For example, driving a car can be construed as a sequence of concurrent activities such as steering, pressing the clutch pedal, and shifting between gears. Yet, it might also be construed as the activity of driving from place A to place B. How humans construe an activity is probably a matter of instruction and of which aspects of the activity are independently evaluated and rewarded. Conceivably, the more an activity is evaluated on a superordinate level, the less likely will people decompose an activity into subordinate goals.

From the current perspective it is interesting to study in more detail whether, everything else being equal, performance suffers, if an activity is construed as pursuing various goals at a subordinate level, rather than pursuing one goal on a higher level. The *everything else being equal* condition might not be easily met though, because people tend to invest more effort when construing superficial identical activities as one where various goals have to pursued at the same time, rather than pursuing a superordinate goal (Srna, Schrift, & Zauberman, 2018).

Goal Awareness

Assuming that actions are perceptually represented might suggest that these effect codes are conscious. Obviously, after an action has been carried out, the perceptual changes that it produced are apparent or can be reconstructed, retrospectively, at a conscious level. However, effect codes are unlikely to become conscious during the entire course of generating a motor action. In fact, even effect codes that participants do not become aware of can at least prime their associated motor patterns (Kunde, 2004). Moreover, people often become aware of their goals only at the point in time they are asked about them. However, this does not logically exclude that factors that constrain conscious perceptual states apply to those that mediate action production as well (cf. Klapp & Jagacinski, 2011, for a discussion). In any case, the role of awareness of perceptual codes for action production needs to be considered empirically (Baars, 1988).

Conclusion

To conclude, multitasking is a multifaceted empirical phenomenon, and so multifaceted are probably its underlying mental processes. We believe that a new look at this phenomenon is needed which takes seriously the fact that human actions, which are insurmountable in multitasking, are generated through codes of perceptual goals. Understanding how these goals are mentally created, represented, and constrained is thus key to understand the possibilities and constraints of multitasking. Although we have focused mainly on situations where tasks more or less overlap in time (i.e., dual tasks), we are convinced that our approach can fruitfully be extended to other forms of multitasking, such as task switching, as well.

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