Predictability improves dual-task performance:

The effects of explicit and implicit learning

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Doctoral dissertation by

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List of Articles

This thesis is based on three published articles. I am the lead author on Article 1-3, meaning I was mainly responsible for data collection, data-analyses and writing. I had a smaller role in the conception of the experiments, which was mainly done by Stefan Künzell, Rita F. de Oliveira and Markus Raab, as I was not involved in the writing of the grant that contained the original ideas for this project. I am a co-author of Article 4, a theoretical paper for which I did part of the literature research and writing.

Article 1: Ewolds, H., Broeker, L., de Oliveira, R. F., Raab, M., & Künzell, S. (2017). Implicit and Explicit Knowledge Both Improve Dual Task Performance in a Continuous Pursuit Tracking Task. *Frontiers in psychology*, *8*, 2241. https://doi.org/10.3389/fpsyg.2017.02241

Article 2: Ewolds, H., Broeker, L., de Oliveira, R. F., Raab, M., & Künzell, S. (2021b). Ways to Improve Multitasking: Effects of Predictability after Single- and Dual-Task Training. *Journal of Cognition*, *4*(1), 4. https://doi.org/10.5334/joc.142

Article 3: Ewolds, H., Broeker, L., de Oliveira, R. F., Raab, M., & Künzell, S. (2021a). No impact of instructions and feedback on task integration in motor learning. *Memory & Cognition, 49*(2), 340–349. https://doi.org/10.3758/s13421-020-01094-6

Article 4: Künzell, S., Broeker, L., Dignath, D., Ewolds, H., Raab, M., & Thomaschke, R. (2018). What is a task? An ideomotor perspective. *Psychological Research, 82*, 4–11. https://doi.org/10.1007/s00426-017-0942-y

Summary

Predictability is increasingly recognized as an important principle in perception and motor learning. The pursuit of increased predictability seems to one of the main goals that the human system pursues. Therefore, providing predictability in one of the most challenging situations that humans face, namely multitasking, a promising line of research. In this thesis the impact of predictability was systematically investigated in five experiments. In the first four experiments predictability was achieved by implementing a repeating pattern in one task, or both tasks. Participants acquired knowledge of these patterns either explicitly or implicitly in several training sessions, under single-task or dual-task conditions. We tested whether this increased predictability helped dual-task performance after the training sessions. The results suggest that predictability is helpful for dual-task performance, although the benefits are confined to the predictable task itself. In a fifth experiment we focused on providing between task predictability, which led to a large performance improvement in both tasks, prompting the discussion about what constitutes a task, in the sense of when can two tasks be perceived as a single task comprising both, a theoretical problem we tried to tackle in one of the articles.

Explanations for the findings, theoretical implications, methodological issues and suggestions for future research are given in the general discussion.

List of abbreviations

CT-task	Continuous Tracking task
DT	Dual task
FMRI	Functional Magnetic Resonance Imaging
PRP	Psychological Refractory Period
RT(s)	Reaction Times(s)
RT-task	Reaction Time task
ST	Single task

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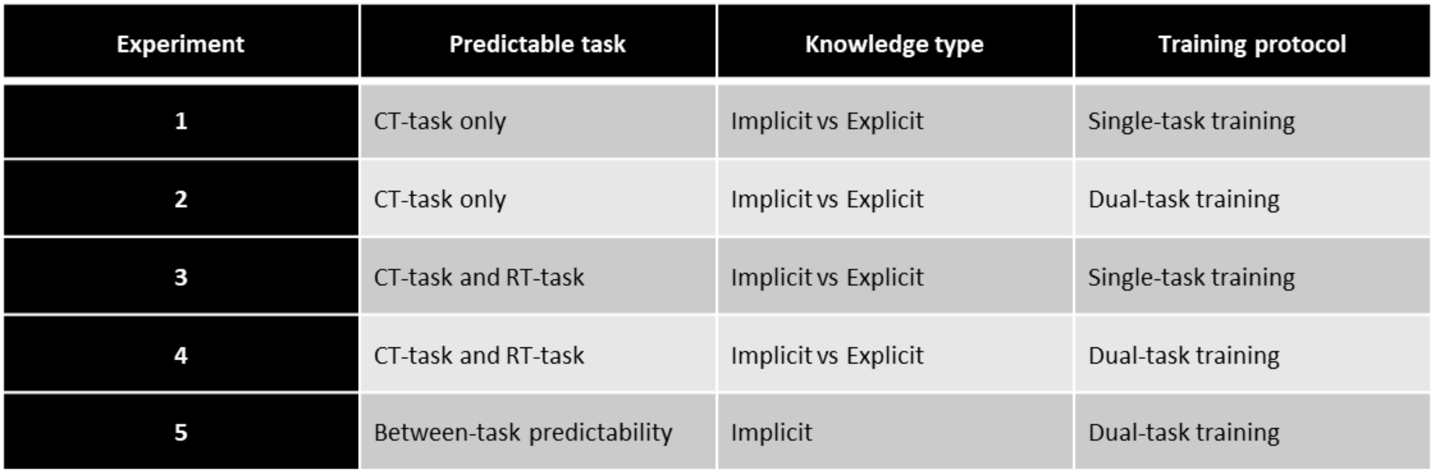
Introduction

Aristotle provided maybe the first quote capturing the apparent difficulty we have in doing multiple tasks at once when he wrote: “when we are lost in thought, afraid or pulled toward a loud noise, we may fail to see the things right in front of us” (Bekker, 1831, as cited in Neumann, 1996, p. 396). Modern theorizing about multitasking may have started as the result of (introspective) experiments on attention by James (1890) and Wundt (1903), and the subject is of great interest to behavioral scientists and broader society to this day. With the increasing prevalence of attention demanding digital devices, busy work environments, hectic traffic and general abundance of distractions in our daily lives, the need for adequate solutions to multitasking problems seems more relevant than ever (Gazzaley & Rosen, 2016; Newport, 2016).

One potential method to improve human dual-task performance is the introduction of predictability whenever one is faced with multiple tasks. The question this research project tries to answer is how predictability influences dual-task performance. One potential effect of predictability is that it can provide a degree of automatization to a task so that more attention can be paid to another task (Neumann, 1984). Theoretically, this formulation of the effect of predictability assumes that multitasking performance is dependent on the availability of a certain quantity of attentional resources, a popular metaphor to describe limits in dual-task performance. Several other metaphors and associated theories have arisen in the quest to explain the limits of human information processing. Even though the goal of this thesis was not to pit one theory of multitasking versus another, a thesis on multitasking should probably nevertheless contain a description of the most popular multitasking theories. Therefore, these theories will be described next. Thereafter, I describe the way predictability was operationalized in the current experiments, namely through implicit and explicit knowledge, and the interaction between these knowledge bases and single- vs dual-task training. Then I outline the research questions and hypotheses, after which the four articles (three experimental studies and a theoretical perspective) will be presented. In total these articles describe 5 experiments in which we combined a continuous tracking task (CT-task) with an auditory reaction time task (RT-task). In this series of experiments, we systematically manipulated predictability, with explicit or implicit knowledge, and the training protocol (single-task vs dual-task training), see Table 1.



Experiment	Predictable task	Knowledge type	Training protocol
1	CT-task only	Implicit vs Explicit	Single-task training
2	CT-task only	Implicit vs Explicit	Dual-task training
3	CT-task and RT-task	Implicit vs Explicit	Single-task training
4	CT-task and RT-task	Implicit vs Explicit	Dual-task training
5	Between-task predictability	Implicit	Dual-task training

Table 1. Design of the research plan. In all experiments we used a continuous tracking task (CT-task) and a go/no-go reaction time task (RT-task). Knowledge type was only investigated in the tracking task, the sequence in the go/no-go reaction time task was so short it always became explicit.

The results of the five experiments are summarized in the general discussion, where I answer the research questions and discuss the limits and strengths of the methodology used in the experiments and possible future directions of research, at the end I formulate the main conclusion.

1.1 Multitasking Theories

Our ability to focus on certain things while ignoring others, our ability to pay attention, is an important function that helps goal-directed behavior. The selectiveness of attention also plays a role in most theories trying to explain limitations in multitasking behavior (Johnson & Proctor, 2004). One of the first popular theories regarding dual-tasking performance was derived from Broadbent's (1958) filter theory. The theory stated that the nervous system represents a single information processing channel that can only be used for one type of information at a time. Before sensory information can enter this channel, it is held in a temporary storage where it cannot be identified (sensory memory), or at least be given its full meaning yet. The function of this filter was the prevention of overloading the limited capacity processing channel. The exact location of this filter is still an area of debate, early-selection theories propose that information is identified after the filter, and before entering the bottleneck caused by the limited processing bottleneck, whereas the late-selection theory proposes that information is identified before entering the bottleneck (Broadbent, 1958; Deutsch & Deutsch, 1963; Treisman, 1960).

The bottleneck idea is still widely popular in dual-task research, mainly through the use of the paradigm which was named by the effect that it causes: the psychological refractory period (PRP) paradigm (Pashler, 1994). In this paradigm two stimuli are presented at varying intervals to each other, for example 700ms, 200ms and 0ms. The resulting responses showed that a slowing down occurred for the second response which was larger when the interval between stimuli was shorter. Using a stage model of information processing, where perceptual processes precede a response selection stage after which motor programming result in a response, researchers tried to locate the bottleneck by varying the difficulty of the various stages. If the stage is susceptible to a bottleneck the slowing down of the response to the first task should translate to a proportional slowing down in the following, second task[1]. Bottleneck theories are in line with the common opinion that 'true' multitasking is not possible, and that what seems to be

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[1] Whenever 'A second task' or 'secondary task' is mentioned in this thesis it simply refers to a task that is performed in addition to another task, without implying primacy or priority of either task.

multitasking on the surface is actually achieved by switching between both tasks very quickly or through a shortening of the stages in the information processing model (Ruthruff et al., 2006).

Kahneman (1973) proposes an alternative view to the bottleneck model: the theory of limited general resources. This theory proposes a pool of unspecific resources than can be distributed voluntarily to tasks. In this theory parallel processing is in principle possible, but the system has a limited amount of resources so that too much load, from both tasks combined, will cause competition for resources and ultimately interference. The bottleneck metaphor is rather unattractive if taken more literally since the lay-out of neurons throughout the nervous system is characterized by parallel pathways making it difficult to detect a bottleneck (but see Dux et al. (2006). In contrast, the resource model has a more plausible connection with human physiology, as resources have often been equated with effort or cognitive load, and can be measured independently from the behavioral measures it is intended to explain, for instance by assessing pupil dilation (Vogels et al., 2018).

In contrast to a limited general pool of resources, Wickens (2008) proposes that there are multiple pools of specific resources. The reason for this diversification of the resource pool comes from the observation that dual-task costs can be greatly reduced when two tasks do not overlap on any of three dimensions (Wickens, 2008, p. 450): the stages of processing dimension (selection vs execution resources), the codes of processing dimension (e.g. spatial activity vs. verbal/linguistic activity) and the modalities dimension (e.g. visual perception vs auditory perception). This theory predicts for instance that dual-task costs will be greater when both tasks involve a visual processing stage, compared to when only one task demands visual processing, and the other task demands auditory processing.

Both bottleneck and resource theories propose there is a limit in attention that prohibits the execution of two tasks at the same time without interference. Bottleneck theories propose that this is the case because during a certain stage in information process, usually the response selection stage, the information processing pipeline can only handle one task at a time. Resource theories propose that the limitation is indeed there but not because there is a bottleneck, but because there is a limit to resources available to process two tasks simultaneously. Both types of theories are compatible in many ways and researchers have indeed combined them. For instance, Tombu and Jolicœur (2003) asked the question what the ‘bottleneck’ consist of and put forward that at the very least the processing bottleneck, in line with an actual bottleneck, must have a certain capacity. An important difference is that resource models propose that two tasks can occupy a bottleneck simultaneously. Backward crosstalk effects in PRP studies (Janczyk et al., 2014; Janczyk, 2016), where the second stimulus in a PRP paradigm influences the reaction time (RT) to the first stimulus, even though the first stimulus should have been in the bottleneck solitarily and processed before the second stimulus, show that it may be difficult to let only one task occupy the bottleneck at a time. It seems unlikely that the human processing system is so neatly organized it can put information related to one task through a processing bottleneck without any information related to a different task (or distracting information for that matter) contaminating it. This phenomenon is also described as crosstalk. Crosstalk challenges the idea of a bottleneck and contrary to resource accounts, does not reflect how much neural processing can be devoted to a task, but explains dual-task costs by proposing that there is interference between simultaneously active neural pathways (Schacherer & Hazeltine, 2021). According to the crosstalk idea dual-task costs arise because of confusion about which task features belong to which task and shares the same principle of multiple resources theories that the more task are separable, or use different resources, the less interference occurs.

An important difference between bottleneck theories and resource theories is that the former state that only serial processing is possible, while the latter also allow for the possibility of parallel processing. Researchers using fMRI during a PRP-experiment found indication that the bottleneck is caused by a network in the frontal lobes only being able to process one task at a time (Dux et al., 2006). However, the standard PRP-paradigm is arguably biased towards a serial processing mode, but under certain conditions parallel processing has been demonstrated as well (Fischer & Plessow, 2015; Sigman & Dehaene, 2008; Yildiz & Beste, 2015). We therefore favor resource theories in some of the articles presented later, and one of the findings in the experiments is consistent with a multiple resource account of dual-task performance. Crosstalk may play a role in our experiments as well, but since the design of our experiments is not sufficiently set up to test interference caused by crosstalk we do not extensively elaborate on potential dual-task costs caused by crosstalk. In the next section I describe the phenomenon of predictability and how it may aid dual-task performance

1.2 Predictability

We perform two tasks at the same time often, but we don't always experience this as detrimental to performance, even though combining laboratory tasks almost always leads to dual-task costs (Koch et al., 2018). A possible reason for these contrasting findings could be that many tasks in real life are predictable. For example, descending a familiar set of steps in your hometown while showing something on your phone to a friend might not be a challenging task, while doing the same on set of stairs you have never seen before might require your full attention, and you refrain from showing your friend the funny photo on your phone until you are at the bottom. The difference between the two situations is that the former situation is predictable. Prediction allows us to exploit predictability in the environment by foreseeing future event states and anticipated action consequences within the human system (Broeker et al., 2017). Neumann (1990, 1996) argued that in predictable situations direct parameter specification is made possible, which means that the processes between the acquisition of information and motor output are (largely) eliminated. Neumann called these processes ‘perception’, which must not be confused with the perception stage in information processing theory, rather in Neumann’s conception perceptions also includes awareness of incoming information and processes that in stages of information processing theory would belong to the response selection stage. The consequences for dual-tasking are that processes limited by a response selection bottleneck, or processes that require resources, can skip this bottleneck or resource intensive process, as long as the task is predictable, theoretically improving dual-task performance by freeing up a bottleneck or resources.

Predictability could play a major role in dual-task performance according to both bottleneck and resource theories, with the caveat that the effects of predictability according to *multiple* resource theories are likely restricted to a specific resource pool. The freeing up of resource in one resource pool does not necessarily mean that those resources can be deployed for a task that uses a different resource pool. The effect predictability has on crosstalk is less clear. Crosstalk might be reduced if predictability eliminates processes that make use of neural pathways that cause interference, but it is also possible that remaining pathways, according to Neumann those pathways involved in information acquisition and motor output, still cause crosstalk.

Increasingly, the view of the brain as a ‘prediction machine’, that seeks increased predictability continually, has gained support from (cognitive) neuroscience, where it was shown that cortical columns of cells, and even the structure of neurons themselves, are set up to interact with the world in a predictive manner (Clark, 2013; Hawkins et al., 2017; Hutchinson & Barrett, 2019). The human brain can be seen as an organ that continually predicts what it will encounter next and updates its models based on whether these predictions were correct or incorrect, which will ultimately reduce the computational cost of action selection (Clark, 2013; Pezzulo et al., 2018). In contrast to the view that the brain merely tries to construct a workable model of the world, as in standard stages of processing theory, the view that prediction is one of the main functions of the brain also means that the brain continuously tries to predict the world (Feldman & Friston, 2010). Predictive models have been used in robotics and data processing techniques such as the JPEG to reduce processing bandwidth. For example, in the JPEG format not every pixel needs to be coded. Instead, the value (or color) of one pixel can often be predicted by the value of the pixels surrounding it. Only prediction errors, or unexpected variation, which occurs for instance at the boundary of objects, needs to be encoded to program an accurate representation of a picture (Clark, 2013). This is more economical for storage and processing than having to encode every single pixel. Retinal ganglion cells in animals process visual information in a similarly predictive fashion as the JPEG processing (Hosoya et al., 2005), and there is now considerable evidence that the brain uses predictive coding in many situations where perception and action serve to detect and reduce prediction errors (Friston, 2010; Hawkins et al., 2017; Hutchinson & Barrett, 2019). One of the reasons why the role of prediction might be so prominent is that it increases efficiency, not just on the level of the neuron, but also on larger scale neural networks. Indeed, it has been found that the cortical activation after exposure to a predictable sequence of stimuli is reduced with repeating presentations (Eagleman et al., 2009).

Predictability also plays an important role in sensorimotor control (Wolpert et al., 2011). Predictive control is essential for the production of elegant movements, together with reactive control and impedance control. The main advantage of predictive control is its speed, delays in feedback loops make reactive control often too slow, a predictive model ensures timely responses to events in fast paced environments. For instance, in the above “familiar stairs” example, the muscles of the foot and legs are activated in a certain way and prepared to receive a certain feedback from touching the stairs at a certain moment. These sensory consequences are predicted by a forward model with the use of a copy of the motor command (efference copy). Predicted sensory consequences are compared with actual sensory consequences, if there is a mismatch, for instance the arrival of sensory feedback through your foot as a consequence of touching the stairs is taking longer than predicted, because there is a gap in the stairs, the system quickly sends a signal that predictive control is no longer sufficient. You will stop showing your phone and focus on not falling (too badly). Similarly, to the ideas by Neumann discussed earlier, as long as the predicted consequences match the actual consequences predictive control can control action and slower reactive based control is not necessary. The involvement of these slower control mechanisms may be detrimental for dual-task performance, but it’s also useful for learning and making future situations more predictable by updating the forward model.

Taken together the research on predictability point towards predictability being fundamental to how we perceive our environment, how we move efficiently, and how our cognition functions (Broeker et al., 2017). Therefore, predictability is a promising candidate in the quest to reduce dual-task interference. Tasks can be made predictable in multiple ways, for instance by offering cues (Broeker et al., 2021) or sequential knowledge. In our experiments we made tasks predictable by allowing participants to learn about a repeating segment[2] in a

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[2] A predictable pattern in tracking tasks is referred to as a “repeating segment”, it might also be called a “constant segment”. In serial reaction time (SRT) tasks this pattern is referred to as a “repeating sequence”. In this thesis we usually use “repeating segment” but in the articles “constant segment” is used in the figures sometimes as well. All these term refer to a predictable pattern in the task.

continuous tracking task and/or a repeating sequence in an auditory go/no-go reaction time task, either explicitly or implicitly.

1.3 Explicit vs implicit learning

In all five experiment we manipulated explicit and implicit knowledge. With the discovery that amnesia patients were still able to learn new skills, without being able to report knowledge (Cohen & Squire, 1980), a distinction between explicit and implicit learning was made, where before learning was defined as a unitary process (Loonis et al., 2017). The distinction between explicit and implicit knowledge can also be described as “knowing that” and “knowing how”. Explicit learning is done with awareness, with the help of instructions and with attention being directed to relevant information. Explicit learning has been succinctly defined as “hypothesis testing”, and can be divided into rule-application and rule-discovery learning (Abrahamse et al., 2010; Green & Flowers, 2003). With-rule application learning an explicit instruction about the contents to be learned is given, for instance a specific movement pattern is described or shown. Rule-discovery learning does not reveal the specific contents to be learned, rather instructions mention the existence of a certain pattern, the discovery of this pattern is still to be discovered. In the experiments of this thesis rule-discovery based learning was used to contrast explicit learning with implicit learning.

Implicit learning happens without awareness and is presumed to also result in knowledge that one is not aware of (implicit knowledge). Furthermore, implicit learning improvements are driven by correct responses only, in contrast to the hypothesis testing in explicit learning where the corrections after a wrong response enable the formation of explicit knowledge. Amnesia patients benefit from errorless learning more than non-errorless learning protocols (Loonis et al., 2017; Maxwell et al., 2001; Roberts et al., 2018), characterizing implicit learning as a nondiscerning type of learning. Implicit learning seems to function like a sponge, soaking up regularities in the environment uncritically. A problem with defining implicit learning is that it is defined by negatives, no awareness of the fact that learning took place nor of the resulting knowledge, and a negative can be hard to prove (Shanks & St John, 1994), see the General Discussion for more. Nevertheless, for the experiments in the current thesis we used the most common characterizations of implicit learning: no awareness of what is to be learned and no awareness of the resulting knowledge.

The explicit vs implicit knowledge distinction is of special relevance to dual-task performance. The acquisition and the employment of implicit knowledge is presumably more automatic than explicit knowledge and is therefore not limited by a bottleneck or scarce resources, theoretically pointing towards an advantage of implicit knowledge in dual-task situations.

The most popular paradigm to investigate implicit learning, and therefore the most fruitful in providing theory on explicit learning and implicit learning and how they relate to attention, is the serial reaction time (SRT) task. Many real-life behaviours require sequencing of movements by using task-relevant information, one can think of driving through a hectic city, typing an email or playing a musical instrument. It is therefore no wonder that a rich scientific literature has developed that investigates how humans (and even other animals) successfully accomplish sequencing of movements in a task like the SRT-task. In the original SRT task each trial consists of participants pressing one of four buttons as indicated by a cue, shortly after which the next cue appears, leading to a quick succession of movements over numerous trials (Nissen & Bullemer, 1987). Typically, a repeating sequence of stimuli is introduced on which participants, often unknowingly, perform better than on a random sequence of stimuli, as indicated by faster reactions and/or less errors. The exact content of what is learned in this type of task is still under debate but evidence has been found for the formation of associations from trial to trial between successive responses, between successive stimulus features and between successive stimulus-response compounds, revealing an extraordinary ability of humans to make use of, either implicitly or explicitly, predictable patterns in the environment (Abrahamse, 2010).

Since learning in this task often occurs without awareness the next interesting question to ask might be if learning can also occur without attention. The method used to answer this question entails combining the SRT-task with a resource demanding second task, assuming that this forces the SRT-task to be done with only just enough resources to perform the task itself, with no resources being left for learning. Results of one of the first SRT-task studies indicated that diverting attention in this way prevents implicit sequence learning (Nissen & Bullemer, 1987), later studies found that learning is still possible but reduced, or only possible with unique sequences, where each stimulus perfectly predicts the next stimulus, and not with probabilistic sequences, where prediction is less reliable (Cohen et al., 1990; Frensch et al., 1994). Some authors suggest that learning itself is not reduced but the expression of knowledge is interfered with under dual-task conditions (Frensch et al., 1998), others argue that learning is interfered with, not because of a reduction in attentional resources, but because the uncritical implicit learning process codes events from the distraction task into the sequence that is to be learned in the SRT-task, complicating the sequence with randomly occurring events (Röttger et al., 2019; Röttger et al., 2021; Schmidtke & Heuer, 1997). A final possible reason that an added task interferes with implicit learning is that during the training process participants gain some awareness of the repeating sequence and develop a degree of explicit knowledge, the application of which demands attentional resources (Jiménez & Vázquez, 2005).

This last issue raises the question how explicit and implicit knowledge can be separated. Implicit learning can be implemented relatively easily by not giving explicit information about the to be learned pattern. The problem is ensuring that this also leads to exclusively implicit knowledge. Indeed, in many SRT-task studies it has been found that at least some participants do acquire explicit knowledge during the training (Abrahamse, 2010; Curran & Keele, 1993; Jiménez et al., 2006; Nissen & Bullemer, 1987; Röttger et al., 2019). On the other hand, it is well established that explicit learning will also involve implicit learning, implicit learning is involuntary and difficult to prevent. Furthermore, certain aspects of motor control can only be learned implicitly, explicit instructions can guide which information needs to be attended, but the actual coordination of muscle activity is largely out of conscious control and learned implicitly (Mechsner, 2004; Reber, 2013). Many studies have employed methodologies to separate implicit from explicit learning in the SRT-task. For instance, presenting a predictable sequence during a dual-task, or unpredictably offering repeating segments, would make it less likely that performance is influenced by explicit knowledge of these repeating segments. In the first case attentional resources necessary for the application of explicit knowledge are taken away, in the second case participants are uncertain whether explicit knowledge can be applied reliably, making it less likely they rely on explicit knowledge. In these studies explicitly instructed participants still tend to perform better on repeating segments than on random segments, leading to the hypothesis that explicit and implicit knowledge develop in parallel (Curran & Keele, 1993; Keele et al., 2003; Willingham & Goedert-Eschmann, 1999).

Arguably the most developed popular theory on explicit and implicit learning was put forward by Keele et al. (2003). In this theory a non-attentional dorsal system, comprising mostly the parietal cortex and supplementary motor cortex, is only capable of implicit learning. An attention-demanding ventral system, mainly located at the temporal and prefrontal cortex, is capable of both implicit learning and explicit learning. The systems operate fully independently from each other, they don’t share information. The combination of these two separate systems explains why implicit learning would be reduced under dual-task conditions, since the attention demanding ventral system will not operate optimally Furthermore, the dorsal system is characterized as uni-dimensional, meaning that learning of associations between stimuli happens automatically within a dimension (e.g., a visual dimension) and is not disturbed by stimuli belonging to a different dimension (e.g., stimuli from a distracting auditory task). The ventral system is multi-dimensional; it automatically forms associations between stimuli within dimensions, like the uni-dimensional system, but it can also form associations between stimuli of different dimensions, rendering it able to form more sophisticated knowledge representation of the outside world, but also making it more susceptible disturbances in learning when a second task introduces random events interspersed with the to be learned sequence in the task containing a repeating sequence (Röttger et al., 2021).

The implicit vs explicit knowledge distinction may be different in the continuous tracking task (CT-task) used in the current experiments, compared to the SRT-tasks discussed before. While discrete movements as in the SRT-task have a clearly defined beginning and end, continuous tasks do not. Some data from a paradigm that bridges the gap between the discrete SRT-task and the continuous tracking task is the Serial Interception Sequence Learning (SISL) task (Reber, 2013). In this task continuously vertically moving cues are responded to by a key press when the cue reaches a target area, similar to the popular computer game Guitar Hero. As with the CT-task, performance on the SISL-task is based on accuracy, not reaction times, and explicit knowledge may be hard to acquire in both tasks. Indeed, in the SISL-task learning seems to be largely implicit, as providing participants with explicit knowledge of the repeating sequence does not improve learning rate (Reber, 2013). In several other more motor focused tasks, explicit knowledge is also often found not to be helpful, such as mirror drawing (Gabrieli et al., 1993), rotor pursuit (Tranel et al., 1994), force field learning (Shadmehr et al., 1998) and a probabilistic catching task (Green & Flowers, 2003). Similar findings can be expected from the CT-task, explicit knowledge may not be easily translated into performance improvements because of the more continuous nature of tracking compared to the more easily explicitly storable discrete sequence of button presses in the SRT-task. For dual-task learning protocols, the hypotheses are less straight forward. Explicit instructions will demand more resources than no instructions, and both sequence learning and expression might be suppressed. However, this depends on the assumption that implicit processes are significantly reduced in the explicit group, compared to the implicit group, which depends on how much a second task and explicit instructions together negatively affect implicit learning processes.

1.4 Single-task vs dual-task training

The final question we investigated in the current experiments is the relative benefits of single- vs dual-task training of predictable task(s). As described in the section above, dual-task training is thought to largely block the effects of explicit knowledge, and partially reduce implicit learning, at least in more discrete tasks. The effectiveness of single-task vs dual-task training in absence of any learning of a predictable pattern needs to be discussed as well. Ruthruff et al. (2006), posited that in the PRP-paradigm improvement in dual-task performance might be mediated by three different mechanisms: automatization, task-integration and/or stage shortening. Automatization refers to eliminating the need for attentional resources needed to perform a single task and can be achieved by single-task training. Task integration involves the improved coordination of processing two tasks simultaneously, by improved task scheduling, and crucially depends on dual-task training. Stage-shortening essentially entails improvements in single-task performance that should also improve dual-task performance by decreasing the amount of overlap (timewise) of the two tasks in the processing bottleneck but differs from automatization in the sense that it does not eliminate the requirement of resources. In the PRP paradigm Ruthruff and colleagues found mainly evidence for stage shortening. However, as discussed before, the typical PRP-paradigm may favor serial processing (Fischer & Plessow, 2015; Miller et al., 2009), while the continuous task employed in the current experiments might favor parallel processing. Serial processing implies pauses in the tracking task which would quickly result in observable increasing error, in real time. Think of completely stopping to drive a car to answer a phone call. In such a situation and in the CT-task, task-integration might be a more viable mechanism to reduce dual-task costs. So, while general dual-task performance might improve with a dual-task training protocol, acquisition of implicit and especially explicit knowledge might be reduced, mostly in the early stages. As training progresses, however, increased efficiency through task-integration might free up attentional resources which may at some point suffice for unhindered explicit and implicit learning.

To avoid confusion, it should be mentioned here that the task-integration investigated in Experiment 5 (Article 3), is slightly different than the task-integration proposed by Ruthruff et al. (2006), which might play a role in Experiment 2 (Article 1) and Experiment 4 (Article 2). While the mechanism might be similar in both conceptualizations, in our experiment task-integration is helped along greatly by providing between-task predictability: events in one task predict what happens in the other task. This is how task-integration is usually investigated, see for instance Schmidtke and Heuer (1997) for an example in the SRT-task and de Oliveira et al. (2017) in the CT-task. These types of task integration lead to massive improvements in dual-task performance, but it may be contentious whether this situation still represents a dual-task proper, or a single “super task” containing two subtasks (Kahneman, 1973), an issue we discuss in Article 4.

It should also be mentioned here that a large literature on motor-cognitive dual-task training, e.g., walking and talking, in patient populations (e.g., stroke, multiple sclerosis) shows dual-task training leads to better outcomes compared to single-task training (Fritz et al., 2015; Silsupadol et al., 2009; Veldkamp et al., 2019). In healthy younger and elderly populations, the intensity of a dual-task training program also seems to be one of the few known effective mechanisms for increasing neural plasticity, possible through increased release of norepinephrine (Tully & Bolshakov, 2010), allowing them to adapt better to multiple simultaneous task demands (Bherer et al., 2005; Pellecchia, 2005). Interestingly, application of explicit knowledge during dual-task training seems to be difficult for elderly, only younger adults benefit from this type of knowledge, pointing towards the possibility that a certain “cognitive reserve” is needed to apply explicit information to increase performance during dual tasking (Caljouw et al., 2016).

2. Research questions and hypotheses

The main aim of the five experiments is testing the effect of predictability on dual-task performance. Theoretically predictability should be very promising mechanism to improve not just task performance in general, but dual-task performance in particular. In a series of five experiments, we systematically varied how predictability within tasks, see Table 1. In the first two experiments (Article 1) we investigated the effects of making the CT-task predictable, in experiment three and four (Article 2) both the CT-task and the other task, an RT-task, were made predictable. Within each article the first experiment (experiment 1 and 3) followed a single-task training protocol and the second experiment (experiment 2 and 4) a dual-task training protocol. In all four of these experiments an implicit group was compared to an explicitly instructed group. Looking forward to the results, a major question regarding the results of the first two experiments is the extent to which resources freed up in one task are redistributable to another task, a possible explanation for this is the existence of multiple resource pools, but other issues such as prioritization might also have been a factor, which we tried to eliminate in Experiment 3 and 4, by making the RT-task predictable as well. Our contention was that both explicit and implicit knowledge should improve dual-task performance, with a possible advantage of implicit knowledge because explicit knowledge might be less applicable in dual-task situations. In the current paper explicit knowledge consisted of preliminary information about the existence of regularities in the stimuli, as in Curran (1997) and Frensch and Miner (1994). It has been shown that such information increases the difference in reaction times between repeated and random segments, but this effect may disappear for more difficult sequences (Stefaniak et al., 2008), it is unknown what the effect of this type of knowledge is on the CT-task.

Regarding the single-task vs dual-task training protocols we expected a possible reduction in learning performance under dual-task conditions, but possibly greater improvements in dual-task performance overall compared to single task training. In Experiment 5 (Paper 3) we investigated mainly between-task predictability, but also kept the predictability in the CT-task from the previous experiments, although this time only provided implicitly. The final article is a theoretical paper that discusses the problem with the definition of what a "task" really is, in the sense of whether multiple tasks might be integrated into a single super task (which we tried to do in Experiment 5), and if we can then still talk about dual tasking.

This text and the general discussion are written after the individual articles. Because of this some of the arguments and claims made in these individual articles does not completely fall in line with the reasoning in this introduction and general discussion. Whenever this is the case, please give more credence to texts written later, the introduction and general discussion, as those sections are based on later insights from both data and theory. The reference list of the introduction, discussion and conclusion can be found at the end of this document, the reference lists of the articles are found at the end of the respective articles themselves.

Article 1. Implicit and explicit knowledge both improve dual task performance in a continuous pursuit tracking task

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Abstract

The goal of this study was to investigate the effect of predictability on dual-task performance in a continuous tracking task. Participants practiced either informed (explicit group) or uninformed (implicit group) about a repeated segment in the curves they had to track. In Experiment 1 participants practices the tracking task only, dual-task performance was assessed after by combining the tracking task with an auditory reaction time task. Results showed both groups learned equally well and tracking performance on a predictable segment in the dual-task condition was better than on random segments. However, reaction times did not benefit from a predictable tracking segment. To investigate the effect of learning under dual-task situations participants in Experiment 2 practiced the tracking task while simultaneously performing the auditory reaction time task. No learning of the repeated segment could be demonstrated for either group during the training blocks, in contrast to the test-block and retention test, where participants performed better on the repeated segment in both dual-task and single-task conditions. Only the explicit group improved from test-block to retention test. As in Experiment 1, reaction times while tracking a predictable segment were no better than reaction times while tracking a random segment. We concluded that predictability has a positive effect only on the predictable task itself possibly because of a task-shielding mechanism. For dual-task training there seems to be an initial negative effect of explicit instructions, possibly because of fatigue, but the advantage of explicit instructions was demonstrated in a retention test. This might be due to the explicit memory system informing or aiding the implicit memory system.

Introduction

Dual-task studies reveal limitations in human behavior and are therefore an intriguing way to discover the functional properties of the cognitive and motor system. When two tasks are performed simultaneously a decrease in performance is usually observed. Several mechanisms have been proposed to explain this dual-task interference such as bottleneck theories (Welford, 1967; Pashler, 1994, Borst et al., 2010), capacity theories (Kahneman, 1973; Navon & Gopher, 1979; Wickens, 2008) and cross-talk models (Kinsbourne, 1981; Swinnen & Wenderoth, 2004). Bottleneck theories explain dual-task costs by proposing that certain processing stages (response selection and/or response execution) cannot be performed simultaneously. A bottleneck exists so that one task has to finish processing before the other may start, which causes a delay for the second task. Resource theories accept simultaneous processing but state that there is a finite resource (or resources) that put a limit on dual-task performance. Cross talk theories propose that dual-task costs mainly arise when the outcome of one task intervenes with the processing of another (Navon & Miller, 1987). So far these theories have not yielded practical solutions on how to improve dual-task performance (for an overview see Pashler, 1994). When casually observing motor behavior of humans in everyday situations however, it becomes apparent that seemingly successful dual-tasking is a common occurrence: walking down a busy street while talking, or driving a car while listening to the radio for instance. We argue that a key feature of such successful multi-tasking is the predictable nature of at least one of the tasks.

Another feature that theoretically reduces dual-task costs is automatic processing, since it leaves the bottleneck open (Ruthruff et al., 2006) or frees up limited resources, in order to be able to perform a different task. Neumann (1984) stated that automatic task processing depends on the fulfillment of two demands. According to Neumann there are three sources that specify the parameters that are sufficient to carry out an action: first, procedures stored in long term memory (skills), second, input information from the environment and third attentional mechanisms. As long as skills in conjunction with input information directly specify the parameters of the movement it can be completed without using attentional mechanisms and attentional capacity, and without leading to conscious awareness. Frith & Wolpert (2000) argue that this is exactly how the motor system, equipped with a forward model, seems to function. That is, as long as a situation is predictable, for instance going down a familiar set of stairs, and there is no mismatch between expected consequences and results, movements are largely automatic (they occur without awareness or attentional control). Indeed, it would be highly disadvantageous if we were aware of every eye movement or postural adjustment. Therefore, we hypothesize that automaticity and by extension dual-task performance is dependent on the predictability of a task.

One way to make a task predictable is through knowledge, either explicit or implicit. In the current paper implicit knowledge is defined as knowledge shown by performance in the absence of verbalizeable knowledge (Heuer & Schmidtke, 1996, Nissen & Bullemer, 1987). The role of implicit versus explicit knowledge in dual-task situations is controversial. In a review of serial reaction time tasks (SRT) and visuomotor adaptation tasks, Taylor and Ivry (2013) noted that explicit knowledge is mainly used in the planning of action goals while implicit processes are dominant in learning of the parameters of movement execution. Although the implicit and explicit knowledge systems can operate in parallel there is evidence that in dual-task conditions only implicit knowledge aids multitask performance (Curran & Keele, 1993). When participants in Curran and Keele’s study were explicitly informed about the sequence in an SRT task, they were much faster compared to non-informed participants, however, when a secondary task was introduced they performed equally to a group that learned the sequence implicitly. Curran and Keele argued that this meant that only the implicit component of knowledge obtained by the informed group was of use in the dual-task situation. The advantage of implicit knowledge has also been demonstrated in sports and motor-related contexts. For instance, novices who learnt a tennis forehand implicitly showed better performance while making complex decisions compared to novices who learnt the forehand explicitly (Masters et al., 2008). In contrast, Blischke et al.,

(2010) showed that no dual-task costs remained when a key sequence task was learned explicitly and under dual-task conditions. The role of implicit and explicit knowledge in dual-task performance therefore remains unclear. As outlined earlier, we would argue that predictability could be a crucial factor in facilitating optimal dual-task performance, and accepting that implicit and explicit knowledge constitute predictability, both should improve dual-task performance.

Predictability is well studied in serial reaction time studies which entail simple discrete movements (e.g. Nissen & Bullemer, 1987; Curran & Keele, 1993). Implicit sequence learning is a robust effect found when participants are allowed to practice on this task but equally, performance on the task is easily improved by explicitly pointing out the sequence. In the current study we use a pursuit tracking task that requires continuous movements to track sequences which has a less prominent explicit component than the serial reaction time task. The continuous nature of the pursuit tracking task makes it an interesting alternative to the more often used short discrete tasks. It captures performance of real-world tasks such as driving and walking which could be modelled as continuous tracking themselves (Raab et al., 2013). The pursuit tracking task requires participants to track a target moving on a screen. The target follows an invisible sinusoidal curve on the screen which consists of three segments (Pew, 1974). To investigate implicit learning, the middle segment remains constant throughout the trials, while the two outer segments vary. It has been demonstrated that this is a reliable manipulation to test for implicit learning, because participant’s performance on the repeating segment is better than on random segments after several practice blocks, even though they appear not to be aware of the repeating part (Künzell et al., 2016; De Oliveira et al., 2017; Pew, 1974; Wulf & Schmidt, 1997; Zhu et al., 2014).

In the current experiment we determined whether a repeated segment within the pursuit tracking task is learned under single task conditions, and if that results in better performance compared to random segments when a second task is introduced (an auditory go/no-go task). We expected better performance and even disappearance of dual-task costs for the repeated segment, which would confirm the hypothesis that tracking of the repeated segment is automatized. Whereas most studies investigating implicit learning in tracking have not tested the effect of explicit knowledge we added this condition to our experiment. Firstly this enables us to investigate the effect of explicit knowledge on a largely motoric task, secondly we are able to test the hypothesis that both types of knowledge would aid dual-task performance since both provide predictability.

Experiment 1

Materials and Methods

Participants

Participants were 37 university students that were divided into two groups: the *implicit group* had 20 participants (*M* = 25.0 years old, *SD* = 2.2) and the *explicit group* had 17 participants (*M* = 25.1 years old, *SD* = 2.8). All participants reported normal or corrected-to-normal vision and no reported neurological disorders. All participants gave informed consent prior to the start of the experiment and received remuneration of 20 € after completing the experiment. The research was approved by the local ethics committee.

Experimental setup

We asked participants to sit at a table in front of a joystick (Speedlink Dark Tornado) and a 24” computer screen (144 Hz, 1920 × 1080 pixel resolution) which were 40 cm apart. The tracking program ran on a Windows 7 computer and data was recorded at 120 Hz. The stimuli of the auditory go/no-go task were delivered via Sennheiser stereo headphones and we recorded responses with a foot pedal (f-pro USB-foot switch, 9 × 5 cm). To ensure that tracking performance was not influenced by moving the joystick through the resting zone, which causes an irregularity in resistance, we made sure that the motion required to position the cursor from the upper to the lower edge of the screen fell within the upper half of the range of motion of the joystick on the y-axis.

Tasks and display

The pursuit tracking task was replicated from Künzell et al. (2016). Random tracking segments were created from three segments *i* (left segment), *j* (middle segment) and *k* (right segment), with $j \neq i$, $k \neq i$, and $j \neq k$. The formula used to create the segments was taken from Wulf & Schmidt (1997):

$$f(x) = b_0 + \sum_{i=1}^{6} a_i \sin(i \cdot x) + b_i \cos(i \cdot x)$$

with a_i *and* b_i being a randomly generated number ranging from -4 to 4 and x in the range $[0, 2\pi]$. For this experiment 41 segments of similar length and number of extrema were selected. This is important to guarantee that learning is not attributed to difficulty of the segments (Chambaron et al., 2006). From the 41 segments available, the segment for each participant consisted of a (unique) middle repeated segment and two outer segments selected from the remaining 40. We chose the outer segments in such a way that each segment occurred an equal amount of time across and within participants. This meant that each participant would learn a different middle segment while the overall difficulty level was kept similar. For the tracking task, participants tracked a red target square along the invisible segment by controlling a cursor displayed as a white cross (both target and cursor fit in 19 × 22 pixels). Velocity of the target was constant along the curves, ensuring a uniform difficulty level across the trial. The velocity was the same as in Künzell et al. (2016) because they showed the most effective implicit learning at trial durations between 40 and 44 seconds.

The secondary task was an auditory go/no-go reaction time task, similar to studies investigating implicit sequence learning in SRTs (e.g. Heuer & Schmidtke, 1996). Participants pressed a pedal for high-pitched tones and ignored low-pitched tones (1086 Hz and 217 Hz, 75 ms). On each trial the number of target sounds was 19 or 20 and the number of distractor sounds varied between 13 and 20. The minimum duration between sounds was 1001 ms and no sounds were placed earlier than 500 ms after the start of the trial or 500 ms before the end of the trial.

Procedure

After signing the informed consent, participants sat at the table and adjusted their seat and pedal. We tested participants individually. We explained that the cursor and the target moved automatically from left to right along a sinusoidal curve, and the goal was to keep the cursor as accurately as possible on the target by moving the joystick forward and backward (along the x-axis cursor movement was coupled to the target). Every five trials feedback about performance appeared on the screen.

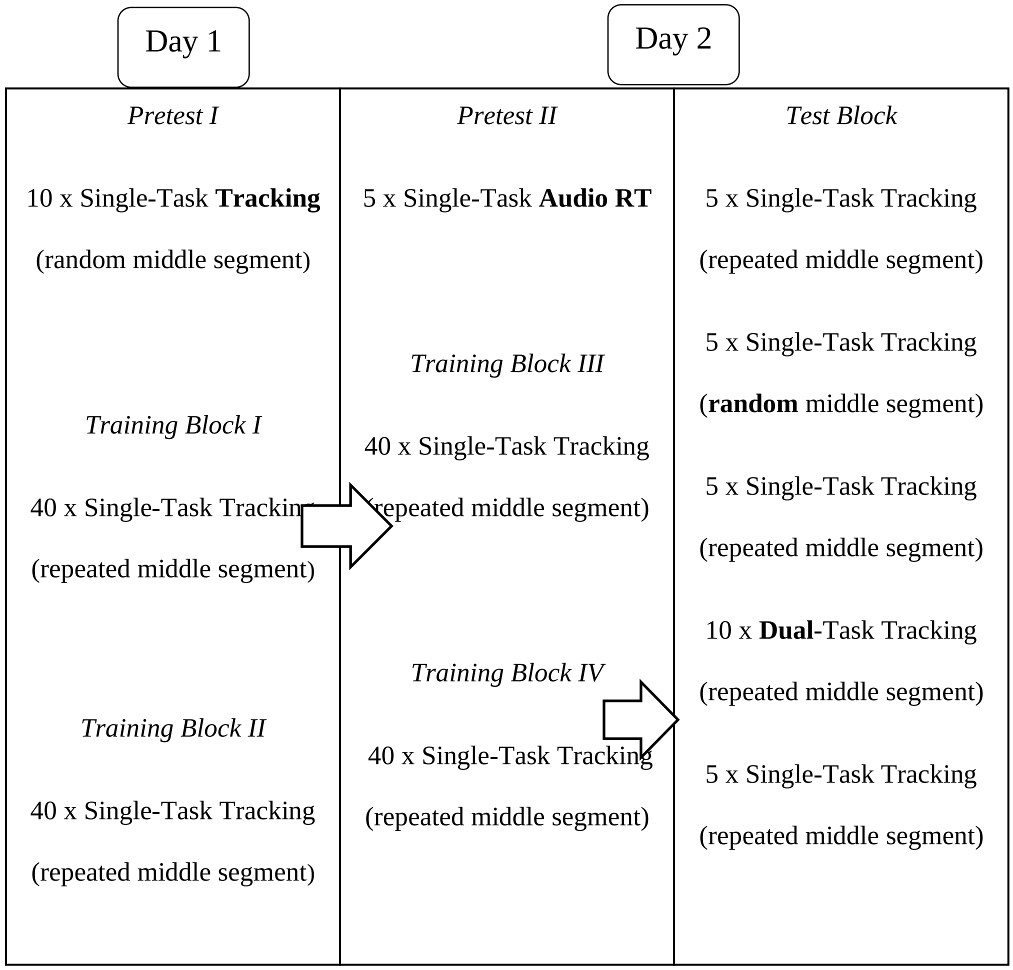

Figure 1. Experimental design for experiment 1. Both pretests were done for familiarization and stimuli were randomized preventing learning.

On the first day participants completed 10 familiarization trials followed by 10 pre-test trials which were single-task tracking of a random segment. They then completed two training blocks with a repeated middle segment consisting of 40 trials each. Just before the training blocks, participants in the *explicit group* received information that there would be a repeating middle segment in the training blocks (no such instruction was given to the *implicit group*). On the second day participants were prepared for the go/no-go reaction time task by completing 5 familiarization trials followed by 5 pre-test trials. They then completed two training blocks as on day one. At the end of the second day, participants completed a test block of 30 trials in different conditions in the following order: 5 trials as in the training block; 5 trials with a random middle segment; 5 trials as in the training block; 10 dual-task trials with the auditory task (participants were asked to pay equal attention to both tasks); 5 trials as in the training block (see Figure 1). After all blocks were completed, the *implicit group* answered a questionnaire to determine how aware they were of the repeated middle segment. The questionnaire contained seven questions designed to gradually probe participants about their knowledge of the repeated middle segment; The questions were: 1) Did you notice anything special during the experiment? 2) Was there something that helped or hindered you while performing the tracking? 3) Did you apply any rules? 4) Did you notice anything special concerning the path of the target? 5) The target followed a certain path. Did you notice any segments in this path? 6) There were three segments in the path, the first, the middle and at the last segment. One of these segments was always repeated? Did you notice? 7) Which segment was the repeated segment, the first, the middle or the last segment?

Data analyses

The main dependent variable in the tracking task was the root mean square error (RMSE; Wulf & Schmidt, 1997) calculated from the difference between the target curve and the curve made by the user-controlled cursor. We followed the recommendations by Zhu et al. (2014) to take the average performance of the outer segments to compare with the repeated middle segment as they showed that performance deteriorates over time within a trial. For the auditory go/no-go task we recorded reaction times and errors. To test learning effects we submitted average RMSEs to a 4 × 2 × 2 mixed analysis of variance (ANOVA) with within subjects factors Training Block (4 training blocks), Segment (middle segment vs. outer segments), and between subjects factors Group (implicit vs. explicit), with a significant Block * Segment interaction indicating learning of the repeating segment. Using the RMSEs from the test block we checked learning by comparing performance on catch trials (random middle segment) compared to trials with a repeating middle segment. We performed two 2 × 2 × 2 mixed analyses of variance (ANOVA), one with within-subjects factors Condition (single-task with repeating segment vs single-task with random segment in the middle), and Segment (repeated middle segment vs. outer segments), and between-subjects factor Group (implicit vs. explicit). The single-task with repeating segment in the middle condition was the average of the three times we tested this condition, see Figure 1. The other 2 × 2 × 2 ANOVA contained the same factors, except for the Condition factor, where we now compared single-task vs dual-task performance, both with a repeating middle segment. The differences in performance between the repeated segment and the outer segments within the dual-task condition were tested using a paired-samples t-test. Finally, to test the effect of the tracking on reaction times (RT's) we performed a 2 × 2 analysis of variance (ANOVA) on reaction times, with factors Task (single or dual) and Group (implicit vs. explicit). A Greenhouse-Geisser correction was used when the assumption of sphericity was violated.

Results

First we checked whether the repeated segment was learned at all by analyzing tracking performance during the training sessions. There were overall improvements in tracking indicated by a main effect of Block, $F(1.89, 66.22) = 12.43$, $p < .001$, $\eta^2_p = .26$ (see Fig. 2). Performance was better on the middle segment than on the outer segments as shown by the significant effect of Segment, $F(1.89, 66.22) = 12.43$, $p <.001$, $\eta^2_p = .26$ (middle $M = 1.42$, $SD = 0.24$; outer $M = 1.55$, $SD = 0.22$). Importantly, a Block × Segment interaction showed that, over the blocks, participants improved more on the repeating middle segment than on the random outer segments, $F(2.19, 76.64) = 9.81$, $p < .001$, $\eta^2_p = .219$ (see Figure 2). No effect of group was found, $F(1, 35) = 2.03$, $p = .163$.

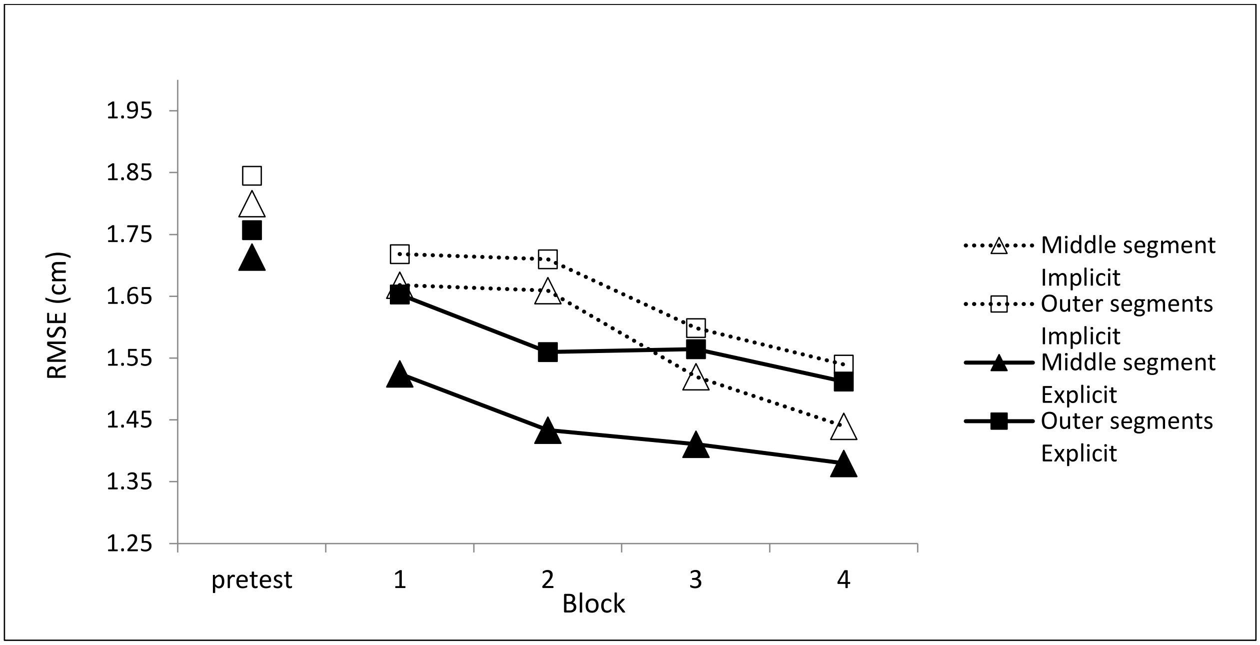

Figure 2. Mean RMSE scores throughout the training blocks. Training blocks 1-4 had repeating middle segments while the pre-test had random segments in the middle.

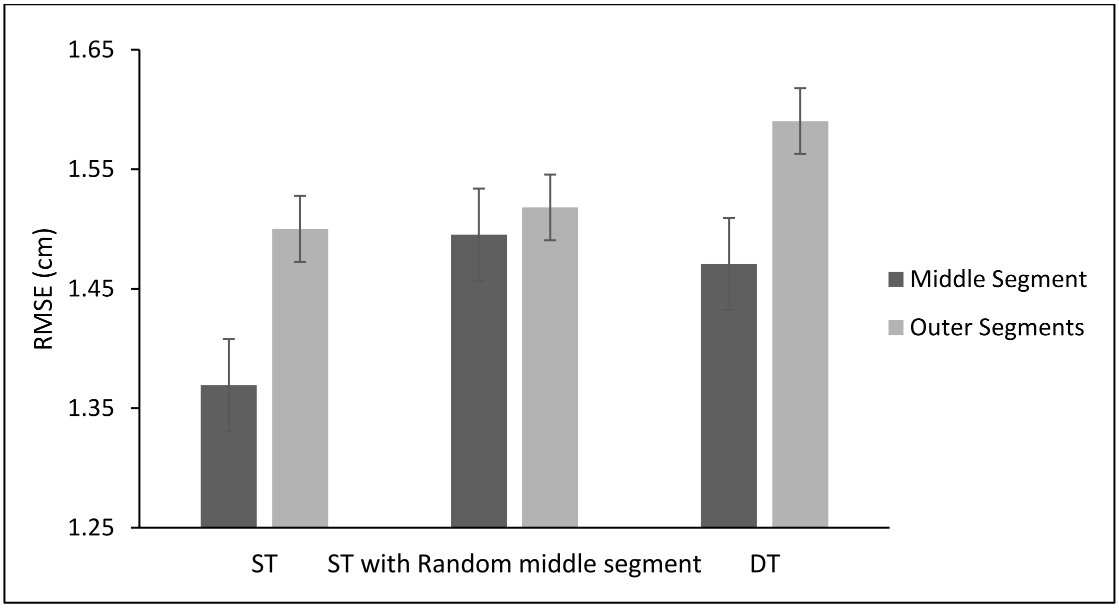

Figure 3. Results of the test block for the implicit and explicit group together, comparing the effect of putting a random segment in the middle and of dual-tasking with a repeating middle segment, ST = Single-task, DT = Dual-task.

In order to prove that the repeating middle segment was learned we swapped it for a random middle segment during the test-block. Results revealed that performance for the condition with a repeating middle segment was better than with a random middle segment, $F(1, 35) = 20.13$, $p < .001$, $\eta^2_p = .365$, with a Condition (repeating middle segment vs random middle segment) × Segment (middle vs outer segments) interaction proving that the difference is due to changes in the middle segment since difference in performance on the outer segments was 0.03 and 0.13 for the middle segment, $F(1, 35) = 20.08$, $p < .001$, $\eta^2_p = .376$, See figure 2. An interaction between Condition and Group (implicit vs explicit) indicated that the difference in performance with a repeating segment in the middle compared to a random segment in the middle was greater for the explicit group than for the implicit group ($M = 0.18$ cm, $SD = 0.04$ for the explicit group, $M = 0.09$ cm, $SD = 0.03$ for the implicit group), $F(1, 35) = 4.169$, $p = .049$, $\eta^2_p = .106$.

To test the effect of dual-tasking we compared the single task Condition with a repeated segment in the middle with the dual-tasking, see Figure 3. A main effect of Condition (Single-task vs Dual-Task) showed that performance in the dual-task condition deteriorated, $F(1, 35) = 14.13$, $p = .001$, $\eta^2_p = .228$. A main effect of Segment indicated better performance on the middle segment, $F(1, 35) = 71.919$, $p < .001$, $\eta^2_p = .673$, and a paired samples t-test revealed that during dual tasking, performance on the repeated segment ($M = 1.47$, $SD = 0.23$) was better than on the outer segments ($M = 1.59$, $SD = 0.21$; $t(36) = 6.64$, $p < .001$. No main effect of Group could be found, $F(1, 35) = .226$, $p = .637$, $\eta^2_p = .006$.

For the second task, the auditory reaction time task, RTs lower than 200 ms and higher than 1000 ms were discarded, resulting in 5 discarded trials. We found a significant main effect of Condition, $F(1, 33) = 26.78$, $p < .001$, $\eta^2_p = .448$, because RTs were significantly slower in the dual-task condition ($M = 558$ ms, $SD = 58$) than in the audio-only pre-test ($M = 510$ ms, $SD = 57$). No effect of Group, $F(1, 33) = 0.172$, $p = 0.681$, and no Condition × Group interaction was found, *F*(1, 33) = 0.363, *p* = .551. In another ANOVA no significant effect of Segment, *F*(1, 35) = 1.681, *p* = .203 could be found, indicating a repeating tracking segment did not lead to better performance on the reaction time task. We did not find a significant Group × Segment effect, *F*(1, 35) = 3.636, *p* = .065.

Participants of the implicit group could not verbalize explicit knowledge about the repeated middle segment during the first 5 probing questions. For question 6 two participants said they noticed a repeating segment but for question 7 only one of them correctly identified the middle one as repeating. Table 1 shows a summary of the answers to the questionnaire.

Answers to question 7, where participants were asked to say which segment was repeating even if they did not notice a repeating segment in question 6, were as follows: 4 said the first segment, 12 said the middle segment, 4 said the last segment.

Discussion

The purpose of this experiment was to investigate whether predictability helps dual-task performance. Predictability was gained by either implicit or explicit knowledge of the tracking task. Better performance for both groups on the predictable segment during dual-tasking shows that predictability indeed had a beneficial effect on dual-task performance. To the knowledge of the authors this study is the first to use a continuous tracking task to assess the benefit of knowledge gained in single task conditions to performance under dual task conditions. The fact that we found no difference between the explicit and implicit group is in line with SRT task performance under dual-task conditions (Curran & Keele, 1993), which is important because it shows that the implicit and explicit memory system might function similarly for discrete and more continuous tasks. It is often argued that the secondary task prevents the expression of explicit knowledge by using up all attentional resources, meaning the better dual task performance on the repeating segment is due to implicit knowledge only (Curran & Keele, 1993; Heuer & Schmidtke, 1996; Nissen & Bullemer, 1987). The design of the current study does not allow us to determine the contribution of implicit knowledge for the explicit group however.

The implicit group exhibited significantly larger improvements on the repeating middle segment than on the random outer segments and decreases in performance when the repeated segment was exchanged by a random segment, which we take as evidence for implicit learning. Furthermore, only one of the participants revealed explicit knowledge of the repeating segment in the questionnaire, noticing a repeating middle segment and subsequently correctly identifying the middle one. When forced to choose between the three segments, 12 of the 20 participants chose the middle segment. These results are unlike the awareness reported in previous studies (eg, de Oliveira et al., 2017) and may suggest that participants gained more access to explicit knowledge about the repeating middle segment during the interview than they were aware of during the experiment itself. Another explanation comes from an informal interview after the current study which revealed that participants excluded the first and the last segment being repeated because they remembered that the first segment always started in the middle of the left side of the monitor and then sometimes went up or down. Similarly, the last segment ended by either coming from the top or bottom before ending in the middle at the right side of the monitor. From this they inferred that the middle segment must have been constant. Other authors have suggested that verbal reports might not be the ideal way to assess explicit knowledge in the tracking paradigm since the knowledge is not easily verbalizable by its very nature, instead recognition or production of the tracking curve could be a more compatible way of measuring awareness of the repeating middle segment (Chambaron et al, 2006). In any case, the results of the questionnaire do indicate that during the training and test block participants were unaware of the repeating middle segment.

The explicit group learned the repeating middle segment equally well as the implicit group. This is in contrast with SRT studies which show that knowing the sequence beforehand leads to very fast initial performance (lower RTs) compared to an implicit learning condition (Curran & Keele, 1993). It should be noted that in our study explicit knowledge was gained by instructing participants that the middle segment was always the same, rather than offering knowledge of what the repeating segment looked like beforehand. As such our methods are more in line with Caljouw et al. (2016) who instructed participants to look for the sequence in an SRT task in the explicit condition and found that the younger group, similar in age as the participants in our study, performed comparable to the implicit condition while the older group was worse compared to the implicit condition. The finding that explicit instructions do not benefit motor learning when compared with implicit instructions concurs with findings in whole body movement tracking tasks (Shea et al., 2001) and a catching task on the computer (Green & Flowers, 1991). The design of the current study does not allow for a complete dissociation of implicit and explicit knowledge, therefore it cannot be determined if the positive effect found in the explicit condition in dual-tasking is due to explicit knowledge itself or caused by the implicit learning system being unimpeded by the explicit instructions.

Dual-task costs in the reaction time task were not reduced by predictability of the tracking task. When the tracking task becomes more automatic or less taxing, bottleneck theories predict that processing should become more available for the RT task, either by bypassing the bottleneck (task automatization) or stage-shortening. Resource theories would predict freeing up of resources. Since dual-task costs did not disappear our findings are more in line with the idea of stage-shortening, where the processing stages in the bottleneck model are shortened, rather than automatization (Ruthruff et al., 2006). However, it is problematic to identify a separate perception, response selection and execution phase in a continuous tracking task, although some authors have tried to do so (Netick & Klapp, 1994). Our findings concur with the results of Schmidtke and Heuer (1997), who did not find an advantage of a learned repeating sequence in an SRT task on the reaction times of a simultaneous go/no-go auditory task with random tones. Further study is needed but it could be that predictability does not influence the mechanisms that produce dual-task interference, rather it improves dual-task performance by facilitating the predictable task only. Since it could be argued that motor learning rarely takes place in single-task conditions; there usually are distractions or multiple tasks to be performed in many sports for instance, we now turn to the question what happens with implicit and explicit learning under dual-task conditions. Furthermore, since we didn’t find an effect of informing participants about the repeating middle segment for single-task training we need to assess whether this information is beneficial or detrimental in a more demanding learning environment, further clarifying the role of implicit and explicit knowledge.

Experiment 2

In the second experiment we investigated whether a repeated tracking segment could still be learned under dual-task conditions, depending on whether instructions about the repeating middle segment were given or not. For comparable results we kept the setup and experimental procedure of Experiment 1 but asked participants to perform the training blocks under dual-task condition.

Conflicting results have been found in SRT studies regarding the question of whether implicit learning is still possible in dual-task conditions. Some studies have found acquisition of knowledge is eliminated or severely hampered with a secondary task (Nissen & Bullemer, 1987; Schmidtke and Heuer, 1997). However, Frensch et al. (1998) found that mainly the expression of knowledge is prevented but that implicit learning can still be demonstrated under single-task conditions although, with the same amount of training, the effect was weaker. Blischke et al. (2010) also investigated learning of the SRT with a secondary task. In the training phase this task was combined with a cognitively demanding secondary task and they found dual-task costs completely disappeared. However, since dual task costs appeared again when a different secondary task was used it seems unlikely that the SRT task had been automatized. This was in contrast to a previous study by Blischke et al. (2001), where they found that a ballistic jumping task was completely automatized after dual-task practice. The authors suggested this finding might have been due to the explicit sequential component of both tasks in the SRT study favoring more cognitive control mechanisms (see also Saling & Philips, 2007). Since the current study uses a task with a stronger motor component rather than an easy to verbalize explicit sequence we expect automatization, shown as an absence of dual-task costs, to be more likely. Furthermore, as learning under dual-task conditions is more resource demanding than single-task training we expect that explicitly informing the participants of the repeating segment might hamper performance, although some authors have suggested that activation of the explicit memory system aids the performance of the implicit system (Berry & Dienes, 1993; Reber et al., 1980). As in the first experiment we do not expect effects of predictability to carry over to the reaction time task, dual-task training would in fact more likely serve to uncouple the two unrelated tasks in order to process them more efficiently, in accordance with the Integrated Task Processing concept of Manzey (1993).

Materials and Methods

Participants

The implicit group contained 19 participants (*M* = 24.00 years old, *SD* = 2.51) and the explicit group had 20 participants (*M* = 23.76 years old, *SD* = 2.44). All participants had normal or corrected-to-normal vision and no reported neurological disorders. All participants gave informed consent prior to the start of the experiment and received remuneration of 20 € or course credit after completing the experiment. The research was approved by the local ethics committee. Experiment setup, task and display were identical to Experiment 1.

Procedure

The procedure of Experiment 2 differed from Experiment 1 in that participants performed the training of the tracking task always together with the auditory reaction time task (see Figure 4 for the complete protocol). The pre-test included single task and dual-task trials. Participants were asked to try their best on both tasks equally throughout the experiment. Another difference with experiment 1 is that the training blocks contained 20 trials instead of the 40 trials because we found in a pilot that fatigue played a much larger role in the dual-task training than the single task training. Furthermore, the test block was expanded to contain both testing under single and dual task conditions. Lastly, a retention test was done on a third day, a week after the test block was performed. The retention test was exactly the same as the test-block and was added to see if learning was consolidated and test performance without the possibly confounding effect of fatigue resulting from putting the test-block at the end of multiple training blocks.

Data Analyses

To test learning effects during the training blocks we submitted RMSE scores to a 4 × 2 × 2 mixed analysis of variance (ANOVA) with within subjects factors Training Block (4 training blocks), Segment (repeated middle segment vs. outer segments), and between subjects factors Group (implicit vs. explicit). To analyze test block and retention test performance on a learned middle segment against performance on a random segment for dual or single-task conditions we had the choice to either compare the repeated middle segment with a random middle segment or to compare the repeated middle segment with the random outer segments. Since the data suggested that segment position might be a confounder, better scores on the middle segment during the pre-test (see Figure 5), we chose the first option and analyzed RMSE scores with a 2 × 2 × 2 × 2 ANOVA with within-subjects factors Test (test-block vs retention test), Segment (Constant vs Random, both in the middle), Condition (Single-task vs Dual-task) and between-subjects factor Group (Implicit vs Explicit). Similarly we submitted reaction times to a 2 × 2 × 2 ANOVA with within-subjects factors Test (Test-block vs Retention test), Condition (Repeating segment in the middle vs Random segment in the middle) and between-subjects factor Group (Implicit vs Explicit). To check for the existence of dual-task costs during the test-block and retention test we performed another 2 × 2 × 2 ANOVA with within-subjects factors Test (Test-block vs Retention test), Condition (Dual-task with repeating segment in the middle vs Single-task) and between-subjects factor Group (Implicit vs Explicit).

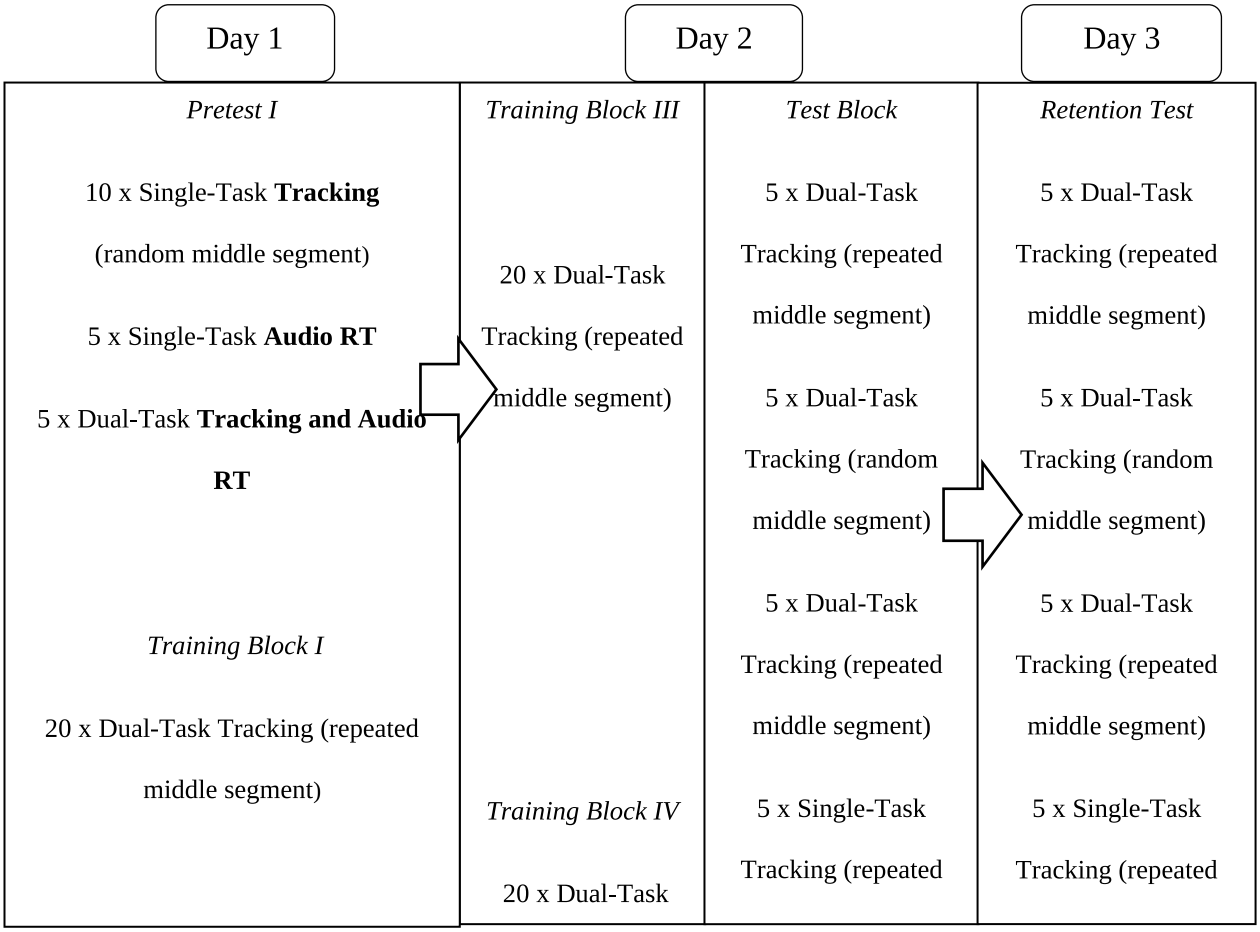

Figure 4. The experimental design of experiment 2. Tracking curves in the pre-test did not contain a repeating segment.

Results

The questionnaires revealed that one participant in the implicit group discovered the repeating middle segment, this data was removed from analyses.

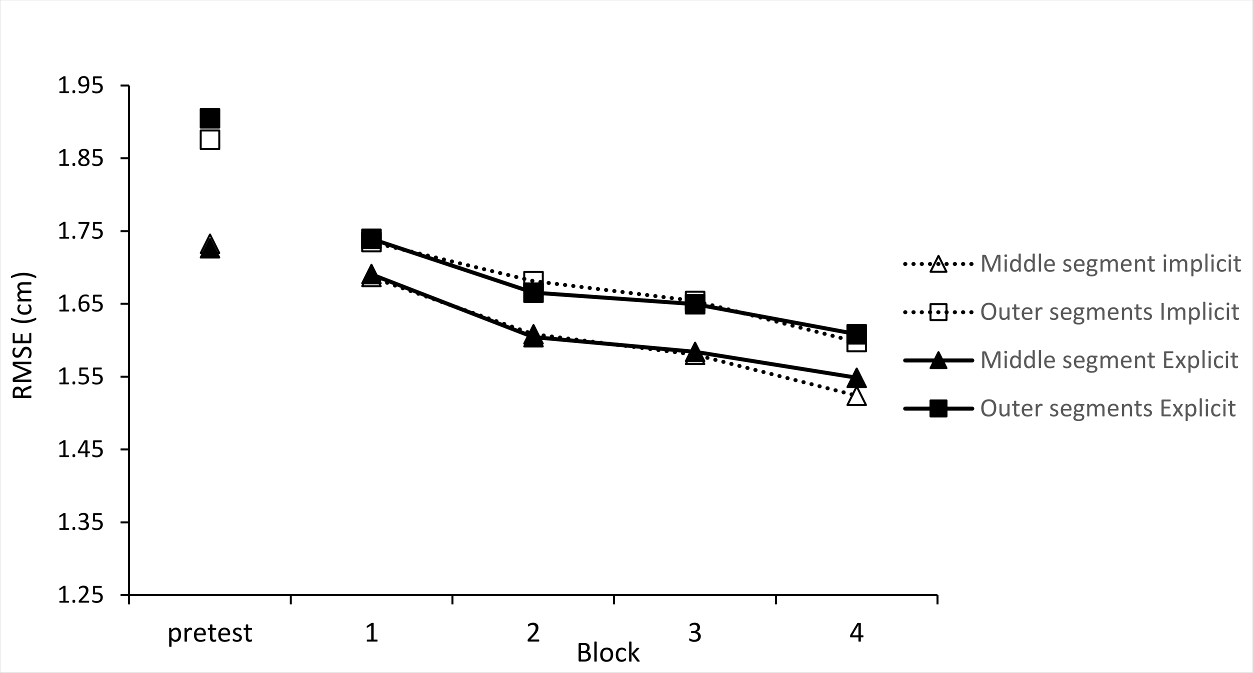

Figure 5. RMSE scores for the training blocks. The pre-test, Block 1 and Block 2 were completed on one day, Block 3 and Block 4 were completed on another day.

During the training blocks participants improved, *F*(1.569, 58.046) = 7.206, *p* = .003, η^2_p = .163, and performance on the repeated segment was better than on the random segments, *F*(1, 37) = 11.446, *p* = .002, η^2_p = .236, but crucially we could not demonstrate an interaction effect between Block and Segment, *F*(2.189, 80.975) = 0.516, *p* = .672, indicating that learning of the repeating segment was not better than learning of the random segments, see Figure 5. No difference between the implicit and explicit group could be found, *F*(1,37) = .001, *p* = .972.

In the test-block and retention test, see figure 6, we found better tracking of a constant segment, *F*(1, 36) = 10.610, *p* = .002, η^2_p = .228. No significant dual-task costs could be found although it almost reached significance, *F*(1, 36) = 3.356, *p* = .075. We did not find a significant interaction between condition (dual-task vs single-task) and segment (constant vs random), *F*(1, 36) = 1.651, *p* = .207. No difference between the implicit and explicit group could be found, *F*(1, 36) = .002, *p*

= .969. There was a significant interaction effect of Test and Group (test-block vs retention test), *F*(1, 36) = 4.209, $p < .048$, $\eta^2_p = .105$, indicating that the explicit group improved from test-block to retention-test while the implicit group did not.

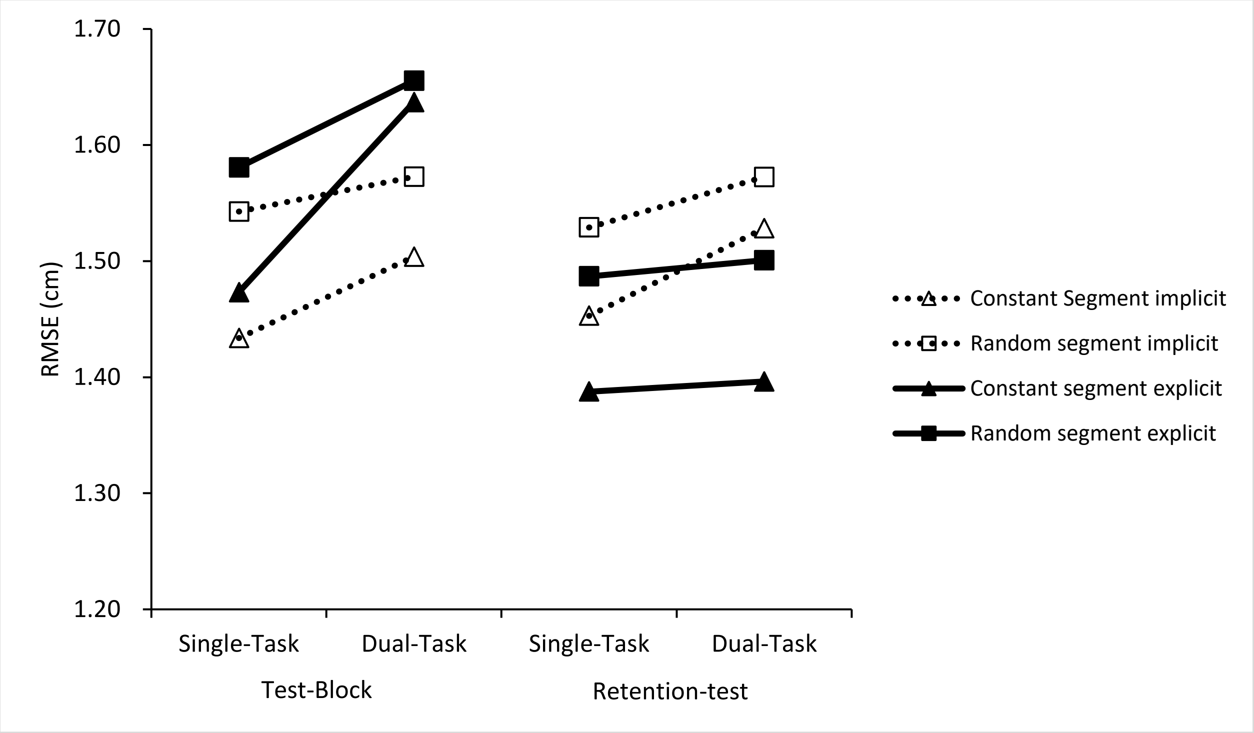

Figure 6. RMSE scores for the test-block and retention test performed one week later.

No difference in reaction times between the repeating segment (*M* = 538 ms, *SD* = 69) and random segment was found (*M* = 538 ms, *SD* = 72), *F*(1,36) = 3.279, $p = 0.083$, nor was there a difference between the implicit (*M* = 531 ms, *SD* = 69) and explicit group (*M* = 554 ms, *SD* = 73), *F*(1,37) = 1.391, $p = 0.246$. We did find better performance on the retention-test (*M* = 527 ms, *SD* = 66) compared to the test-block performed earlier (*M* = 557 ms, *SD* = 76), *F*(1, 36) = 16.310, $p < .001$, $\eta^2 = .312$. Dual-task costs were still present at the test-block and retention test when comparing dual-task performance on the repeated segment (*M* = 538 ms, *SD* = 69) with single task performance (*M* = 482 ms, *SD* = 57), *F*(1, 36) = 57.188, $p < .001$, $\eta^2_p = .614$.

Moreover, a significant interaction effect between Condition and Group, *F*(1, 36) = 5.902, *p* = .020, $\eta^2_p = .141$ indicated that the difference in reaction times between Dual-task with a repeating segment and Single-task was greater for the explicit group (*M* = 76 ms, *SE* = 8) than the implicit group (*M* = 39 ms, *SE* = 13).

Discussion

For the second experiment we did not find training effects during the training blocks, but we did see better performance on a repeated middle segment than a random middle segment during the test-block. These results concur with Frensch et al. (1998) in that a secondary task does not prevent learning, rather the expression of what is learned is suppressed. Although not significant, there seems to be some indication that explicit instructions hamper performance during dual-tasking more than no instructions, see Figure 6. This raises the question what the content of the learned information was for the explicit group. In the current experiment we cannot say whether the explicit group made use of explicit knowledge or that for them implicit knowledge was also helpful, whereas the interviews clearly prove that the implicit group did not make use of explicit knowledge. In other words, the results for the explicit group are consistent with the view that explicit knowledge is helpful for learning but the expression is suppressed during dual-tasking. But the results also concur with the view that only *implicit* learning occurs under dual-task conditions and that the explicit group in the current study acquired implicit knowledge in addition to the in dual-task situations harmful explicit knowledge.

The explicit group improved their tracking performance from the test-block to the retention test seemingly beyond that of the implicit group, whose performance remained the same. There is some evidence that the explicit memory system might inform or stimulate the implicit learning system

(Reber et al., 1980; Willingham, 1999), although the contrasting view that explicit knowledge, especially instruction on how to perform movements, is also often found to be detrimental to the formation of motor skills (Poldrack & Packard, 2003). Our results are compatible with both these views since we did not give explicit instructions on how to perform the tracking movements, rather the explicit instructions more likely had the effect of focusing attention to the repeating segment aiding implicit learning.

As in the Experiment 1 reaction times did not decrease during the predictable tracking segment, possibly a sign of effective task shielding, a concept closely related to the Integrated Task Processing concept of Manzey (1993) introduced earlier, which states that training two tasks together should enable participants to uncouple them, therefore reducing interference and improving dual-task performance. Task shielding is useful to protect a primary task from distractors but might also lead to less cognitive flexibility, so that the predictability of the tracking task in our study could not be exploited for the reaction time task (Plessow et al., 2011; Plessow et al., 2012). If the strategy during the current experiment was to decouple the tasks there is no reason to assume that predictability of one task influences performance on the other task. The influence the two tasks might have on each other, for better or worse, is exactly what participants learned to avoid. Another explanation is that predictability does not transfer between modalities, in line with the idea of multiple resources. The visual-manual system may not share resources with the auditory-pedal system and a reduction of resource usage for predictability does not help the other system.

General Discussion

The finding of both experiments suggests there is a beneficial but limited role of predictability in multitasking performance. Our task differs from the SRT task used in similar investigation but there seems to be converging evidence that in dual-task situations explicit knowledge of a sequence is not as beneficial as implicitly learned movement sequences (Frensch et al., 1998; Heuer & Schmidtke, 1996). Although the effect was not statistically significant, our results seem to agree with this: after single-task training both explicitly instructed and implicitly trained participants performed better on predictable segments of the tracking segment whereas after dual-task training, *initially* only the implicit group demonstrated learning effects in the dual-task condition. However, when tested again a week later the explicit group demonstrated similar learning effects and a larger overall improvement in performance compared to the implicit group. A possible explanation is that explicit instructions aid implicit motor learning but initially interfere with the expression of knowledge. Another explanation is that explicit instructions fatigued the participants more, the test-block was performed after two training blocks while the retention test was performed on a different day without any training blocks.

The fact that we found learning after dual-task training is in contrast with the hypothesis of Nissen and Bullemer (1987) who argued that learning may occur without awareness but always requires attention, following from their findings that no learning was found when combining the SRT task with a secondary task. Since then this view has been sharpened by results from Cohen, Ivry & Keele (1990) and Curran & Keele (1993) who found evidence that unique sequences, where each item is always uniquely followed by a certain other item, can be learned in the presence of attentional distraction, whereas sequences that lacked such an item to item connection could not. As such our findings are in agreement with the idea of a non-attentional and an attentional learning system, either with or without awareness.

A limitation of the current study is that while we tested for the absence of explicit knowledge in the implicit group we did not confirm the existence of explicit knowledge in the explicit group. Future studies should employ methods to test how explicit knowledge of the repeating segment is stored, reproducing or identifying the repeating segment might be more suitable methods of assessing explicit knowledge than describing the curve. Furthermore, a comparison with an implicit group would be necessary because these methods cannot completely distinguish between implicit and explicit knowledge (Chambaron et al., 2006).

In conclusion, predictability through knowledge aids dual-task performance, which can be explained by different learning mechanisms. In dual-task training explicit instructions seem to initially worsen performance, possibly because of fatigue, but ultimately they lead to better consolidation of motor learning. The other main finding is that predictability of one task does not increase performance in the other task. Future research will focus on further elucidating the role of predictability in dual-task performance by investigating the effect of making each task predictable, for instance making the auditory reaction time task be a constant sequence, or by making both tasks predictable as a unit facilitating task integration and countering task-shielding.

Acknowledgments

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Article 2. Ways to improve multitasking:

Effects of predictability after single- and dual-task training

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Abstract

In this study we investigated the effect of predictability on dual-task performance in two experiments. In the first experiment 33 participants separately practiced a continuous tracking task and an auditory reaction time task. Both tasks had a repeating element that made them predictable; in the tracking task this was a repeating segment, and in the auditory task this was an auditory sequence. In addition, one group obtained explicit knowledge about the repeating sequence in the tracking task while the other group trained implicitly. After training, single- and dual-task performance was tested at a post test and retention test. Results showed that predictability only improved performance in the predictable tasks themselves and dual-task costs disappeared for the tracking task. To see whether the task-specific effect of predictability was the results of task prioritization, or because task representations did not have much chance to interact with each other, we conducted a second experiment. Using the same tasks as in Experiment 1, 39 participants now trained both tasks simultaneously. Results largely mirrored those of the first experiment, demonstrating that freed-up resources due to predictability in one task could not be re-invested to improve in the other task. We conclude that predictability has a positive but task-specific effect on dual-task performance.

Introduction

Switching between tasks in complex work environments, dividing attention between cellphones and TVs or simultaneously handling complex car cockpits and driving - multitasking is omnipresent in modern society. In lab settings, performing multiple tasks simultaneously reliably leads to dual-task costs which are most often explained by structural or strategic bottlenecks (Meyer & Kieras, 1997; Pashler, 1994), capacity limitations (Damos & Wickens, 1980; Kahneman, 1973; Navon & Gopher, 1979; Wickens, 2008) or cross-talk (Navon & Miller, 1987; Swinnen & Wenderoth, 2004). However, some studies have seen reduced or even eliminated dual-task costs, either after large amounts of training (Ruthruff et al., 2006), or by using ideomotor-compatible tasks (Halvorson et al., 2013; Halvorson & Hazeltine, 2015). Künzell et al. (2018) argued that both large amounts of practice and ideomotor compatibility, make tasks more predictable which can facilitate automatic processing and reduce interference between tasks. Previous studies indeed found a beneficial effect of making one of two tasks predictable, although performance improvements were only visible in the predictable task. For instance, adding predictability to a tracking task improved tracking accuracy when simultaneously performed with an auditory reaction time task, but reaction times did not improve (Broeker et al. submitted; Ewolds, Broeker, Oliveira, Raab, & Künzell, 2017). To further elucidate the role of predictability in multitasking, Experiment 1 of our study aimed to elaborate on these previous findings. We investigated whether the simultaneous performance of two predictable tasks, as opposed to just one predictable task as in previous studies, would enhance dual-task performance in both tasks after single-task training on both tasks. Following the findings of Experiment 1, which indicated only task-specific effects of predictability, we decided to conduct Experiment 2, in which participants did dual-task training.

In motor control, the expected sensory consequences are predicted by forward models (Wolpert et al., 1995). When going down a familiar set of stairs (as a proficient walker) or a well-known ski run (as an expert skier), there is a match between expected consequences and actual sensory feedback. If there is no mismatch, movement is controlled with minimal awareness and attention. However, if a mismatch occurs, be it due to an error in the forward model or the unpredictability of the situation, attentional processes will intervene (Frith et al., 2000; Neumann, 1984). Attentional processes require resources, which are limited (Wickens, 2008), therefore increased predictability should reduce resource requirements. Predictability of a task during dual-tasking may be desirable not just because that task itself becomes less resource dependent, but also because performance of the other task might benefit from the freed-up resources.

Whereas the above arguments are theoretically convincing, empirical evidence is less clear. For instance, Ewolds et al. (2017) found the beneficial effects of predictability to be contained in the predictable task; the resources freed up by increased predictability were not invested into the other task. A possible explanation for this is that resource allocation strategy may depend on specific task characteristics (Tombu & Jolicœur, 2003) rather than just available resources. It is possible that the predictable tracking task in Ewolds et al. (2017) prevented resources to be carried over to the reaction time task, because a tracking task requires continuous execution. In this tracking task a moving target had to be followed with a joystick as closely as possible. Since it is impossible to take a break in a tracking task without a visible increase in error it demands resources continuously, shifting priority to that task. Second, Navon and Gopher (1979) argued that when there is only one limited pool of general resources, humans employ utility considerations to decide on economic allocation of limited resources, so not reinvesting into another task might satisfy this. Third, making a task predictable may have a side effect of making that task more salient in the course of an experiment. Therefore, the resources freed up in the tracking task might all have been reinvested into the tracking task itself, and not, as the equal-priority instructions were meant to achieve, distributed equally over both tasks. This raises the question of what would happen if both tasks are made predictable.

Prior knowledge can make a situation predictable. For instance, in tennis knowledge of the usual motion of a tennis ball in combination with visual information will tell a practiced player in advance where the ball will arrive (Körding & Wolpert, 2006). To address the question of how this form of predictability might influence multitasking performance, we investigated the effect of predictable and unpredictable movement sequences, as has often been done in tracking studies (Künzell et al., 2016; Pew, 1974; Wulf & Schmidt, 1997) and in serial reaction time (SRT) tasks (Curran & Keele, 1993). In tracking tasks participants typically follow a target that in a certain segment of the screen (i.e. first third, second third or last third) always has the same movement pattern across trials, whereas the other segments contain random movement patterns every trial. Similarly, in SRT tasks participants are instructed to press buttons in response to cues on a screen which, for the majority of the time, follow a repeating order. Typically, participants perform better on repeating segments and orders after some practice compared to random segments or orders. This happens without subjects being aware of the repetition, therefore these tasks provide an excellent paradigm to study implicit learning.

Implicit learning and explicit learning may both lead to a mostly implicit knowledge base over time, as many studies in motor learning have shown (Kal et al., 2018), but in the beginning of practice different knowledge bases can be identified. Via questionnaires the absence of explicit knowledge can be established which may indicate a largely implicit knowledge base (Schmidtke & Heuer, 1997). The absence of implicit knowledge is difficult to measure, so the degree to which explicitly instructed participants also build an implicit knowledge base cannot be determined, although it is often assumed that learning shown in the presence of a dual task is an indication of implicit learning (Curran & Keele, 1993; but see Shanks et al., 2005). Explicitly instructed participants benefit directly from explicit knowledge about regularities in an SRT task while implicitly learning participants are slower but achieve better performance on retention tests. Both implicit and explicit knowledge about regularities are a basis of anticipatory control of perception and action. Data from previous experiments confirmed the idea that both types of knowledge aid dual-task performance since both unaware and aware participants benefited from repeating sequences (Ewolds et al., 2017). In contrast, many studies employing more complex movements (with tracking probably lying somewhere between the SRT task and most sports in terms of complexity) report that for experts in particular explicit knowledge hampers performance, presumably because it interferes with well-learned ‘automatized’ processes (Beilock et al., 2002; Koedijker et al., 2011; Masters, 1992; Poolton et al., 2006). It has been argued that the attentional demands during dual-task learning favor implicit learning and may even prohibit explicit learning, leading to better performance of implicitly instructed participants (Berry, 1993; Maxwell et al., 2003). The current study examines both implicitly and explicitly instructed participants to test whether implicitly instructed participants have an advantage in dual-task situations.

In the first experiment we tested the effect of predictability on dual-tasking with both a predictable tracking task and a predictable auditory reaction time task. The tracking task comprised of two outer random segments and a repeating segment in the middle; the auditory task across the full trials involved either a repetitive tone sequence or random tones. Both tasks were practiced and learned as single tasks and only later tested as a dual task. If both tasks draw on a single resource and if predictability influences prioritization of both tasks equally, both tasks should benefit from predictability in the other task. Alternatively, if both tasks draw on separate resources predictability in one task might only enhance processing for this particular task, but not for the other task.

Experiment 1

Materials and Methods

Participants

Seven participants dropped out during the testing, leaving 33 university students (18 female). The *implicit learning group* had 17 participants (*M* = 25.0 years, *SD* = 2.2) and the *explicit learning group* had 16 participants (*M* = 25.1 years, *SD* = 2.8). A previous study found an effect size of $\eta_p^2 = .365$ when comparing performance on repeating segments with random segments (Ewolds et al., 2017). Based on this a G*Power (Version 3.1.9.2) analysis revealed a test power of .95 and a required sample size of 14 participants (effect size f = 0.76, $\alpha = .05$, $1-\beta = .95$). All participants reported normal or corrected-to-normal vision and no neurological disorders. Participants gave informed consent prior to the start of the experiment and received payment of 20 € after completing the experiment. The research was approved by the local ethics committee.

Experimental setup

Participants sat at a table with their preferred hand controlling a joystick (Speedlink Dark Tornado). At a distance of 40 cm from the joystick the task was displayed on a 24” computer screen (144 Hz, 1920 × 1080 pixel resolution). The tracking program ran on a Windows 7 computer and data was recorded at 120 Hz. The stimuli of the auditory go/no-go task were delivered via Philips SHP2500 stereo headphones and we recorded responses with a foot pedal (f-pro USB-foot switch, 9 × 5 cm). To ensure that tracking performance was not influenced by moving the joystick through the resting zone, which causes an irregularity in resistance, we made sure that the motion required to position the cursor from the upper to the lower edge of the screen fell within the upper half of the range of motion of the joystick on the y-axis.

Tasks and display

The tracking task was based on the study by Künzell et al. (2016). The tracking path consisted of three segments. The formula used to create the segments was taken from Wulf & Schmidt (1997):

$$f(x) = b_0 + \sum_{i=1}^{6} a_i \sin(i \cdot x) + b_i \cos(i \cdot x)$$

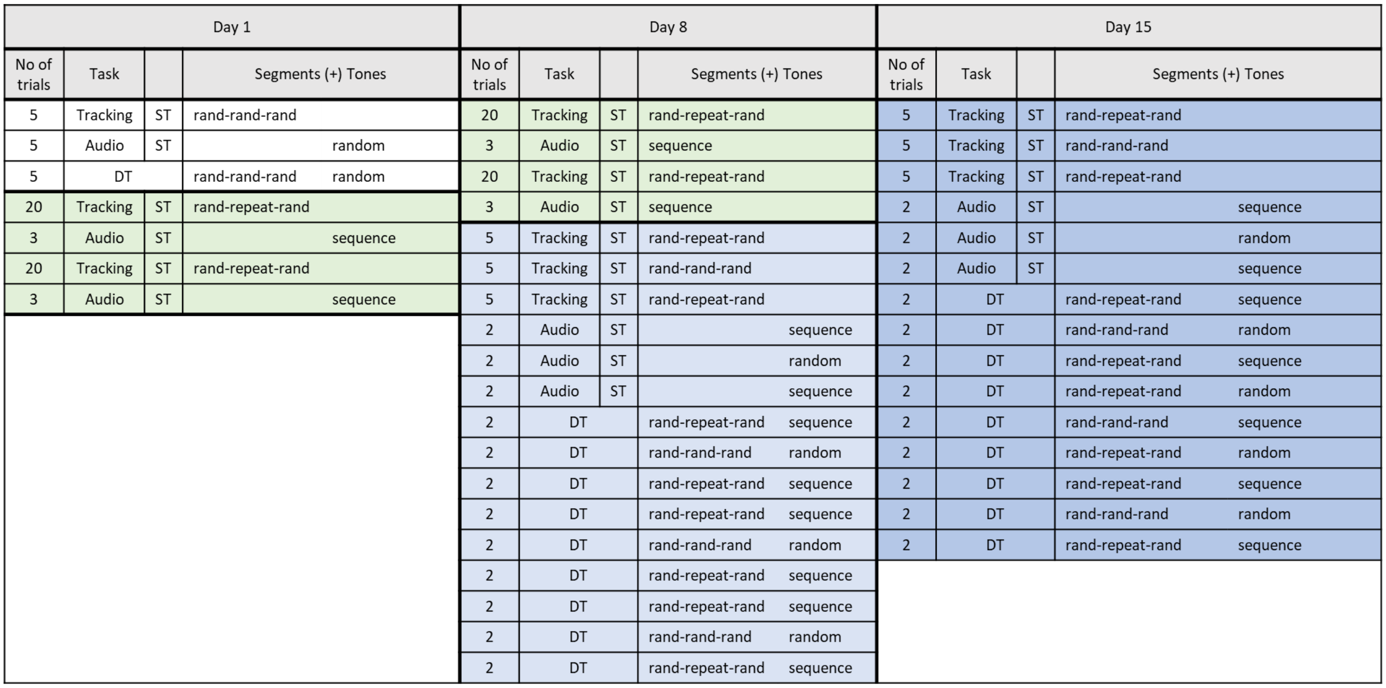
with a_i *and* b_i being a randomly generated number ranging from -4 to 4 and x in the range $[0, 2\pi]$. For this experiment 41 segments of similar length and number of extrema were selected to prevent learning effects due to differences in difficulty (Chambaron et al., 2006). From the 41 segments available, the path for each participant consisted of a (unique) middle repeating segment and two outer segments selected randomly without placing back from the remaining 40. We chose the outer segments in such a way that each segment occurred an equal amount of time across participants. This meant that each participant would learn a different middle segment while the overall difficulty level was kept equal. For the tracking task, participants tracked a red target square along the invisible curve by controlling a cursor displayed as a white cross (both target and cursor fit within 19 × 22 pixels). Velocity of the target was constant along the curves, ensuring a uniform difficulty level across the trial. Trials lasted between 40 and 44 seconds since Künzell et al. (2016) were best able to find motor learning at those target velocities.

The second task was an auditory go/no-go reaction time task, similar to the second task used in dual-task studies investigating implicit sequence learning in SRTs (e.g. Heuer &

Schmidtke, 1996). For the reaction time task participants pressed a pedal for the target tone (Tone A: 1700 Hz, 75 ms) and ignored distractor tones (Tone B: 217 Hz, C; 600 Hz, D: 1086 Hz, 75 ms). On each trial the number of target tones was 9 or 10 and the number of distractor tones was 26 or 27, depending on the length of the track. The duration between tones on random and sequenced trials varied between 700-1200 ms and no tones were placed earlier than 500 ms after the start of the trial or 500 ms before the end of the trial. In the predictable reaction time task tones were always placed in the same order, yielding a very simple repeating sequence of tones (BCADBCADBCAD etc.), whereas in the random tone task the tones were positioned in a random order. Frequency distributions of the four tones were the same for the random and predictable reaction time task.

Procedure

After giving informed consent each participant sat at the table and adjusted their seat and pedal. The experimenter explained that the cursor and the target moved automatically from left to right along a sinusoidal curve, and that the goal was to keep the cursor as accurately as possible on the target by moving the joystick forward and backward (movement was coupled to the target along the x-axis). For the auditory reaction time tasks participants were asked to respond as quickly as possible to the target tone (played beforehand) by pressing a pedal with their preferred foot. Participants were told to not respond in anticipation but wait until they heard the target tone. Every five trials feedback about performance on both tasks was given on the screen. Participants were instructed to try their best on both tasks equally.



Day 1				Day 8				Day 15			
No of trials	Task		Segments (+) Tones	No of trials	Task		Segments (+) Tones	No of trials	Task		Segments (+) Tones
5	Tracking	ST	rand-rand-rand	20	Tracking	ST	rand-repeat-rand	5	Tracking	ST	rand-repeat-rand
5	Audio	ST	random	3	Audio	ST	sequence	5	Tracking	ST	rand-rand-rand
5	DT		rand-rand-rand random	20	Tracking	ST	rand-repeat-rand	5	Tracking	ST	rand-repeat-rand
20	Tracking	ST	rand-repeat-rand	3	Audio	ST	sequence	2	Audio	ST	sequence
3	Audio	ST	sequence	5	Tracking	ST	rand-repeat-rand	2	Audio	ST	random
20	Tracking	ST	rand-repeat-rand	5	Tracking	ST	rand-rand-rand	2	Audio	ST	sequence
3	Audio	ST	sequence	5	Tracking	ST	rand-repeat-rand	2	DT		rand-repeat-rand sequence
				2	Audio	ST	sequence	2	DT		rand-rand-rand random
				2	Audio	ST	random	2	DT		rand-repeat-rand sequence
				2	Audio	ST	sequence	2	DT		rand-repeat-rand random
				2	DT		rand-repeat-rand sequence	2	DT		rand-rand-rand sequence
				2	DT		rand-rand-rand random	2	DT		rand-repeat-rand random
				2	DT		rand-repeat-rand sequence	2	DT		rand-repeat-rand sequence
				2	DT		rand-repeat-rand sequence	2	DT		rand-rand-rand random
				2	DT		rand-rand-rand random	2	DT		rand-repeat-rand sequence
				2	DT		rand-repeat-rand sequence				
				2	DT		rand-repeat-rand sequence				
				2	DT		rand-rand-rand random				
				2	DT		rand-repeat-rand sequence				

Figure 1. Experimental design for Experiment 1. The pretest was done for familiarization and stimuli were randomized preventing learning. A predictable tracking task contained a repeating middle segment (i.e. rand-rep-rand), an unpredictable tracking tasks contained three random segments (i.e. rand-rand-rand). The predictable audio task was a tone sequence (i.e. sequence), with every fourth tone being the target tone. The unpredictable audio task used the same tones but in a random order (i.e. random). ST = single task, DT = dual-task.

On the first day participants completed five familiarization trials in tracking, the reaction time task and the dual-task, all with random tracking sequences and random tone placement (using the same tones as in later phases). They then completed two tracking task training blocks with a repeating middle segment consisting of 20 trials each. Just before the training blocks, participants in the *explicit learning group* received information that there would be a repeating middle segment in the training blocks (no such instruction was given to the *implicit learning group*). After the tracking training block participants performed three trials of the auditory task, which was enough to induce explicit knowledge of the tone sequence as shown in a pilot. One week later (day 8) they completed two additional training blocks as on day one. At the end of day

8 participants completed a test block of 39 trials in different conditions as displayed in Figure 1. Participants were informed which tasks they had to do but neither group was informed about the occurrence of a repeating middle segments during the test trials. The test block was repeated on a third day in a retention block.

After all blocks were completed, the *implicit learning group* answered a questionnaire to determine how aware they were of the repeating middle segment. The questionnaire contained seven questions designed to gradually probe participants about their knowledge of the repeating middle segment. The questions were: 1) Did you notice anything special during the experiment? 2) Was there something that helped or hindered you while performing the tracking? 3) Did you apply any rules? 4) Did you notice anything special concerning the path of the target? 5) The target followed a certain path. Did you notice any segments in this path? 6) There were three segments in the path, the first, the middle and at the last segment. One of these segments was always repeating? Did you notice? 7) Which segment was the repeating segment, the first, the middle or the last segment?

Data analyses

Tracking performance was measured by calculating the root mean square error between the target and user-controlled cursor (RMSE; Wulf & Schmidt, 1997). One RMSE corresponds to about 0.56 cm difference between cursor and target on the screen. We followed recommendations by Zhu et al. (2014) to take the average performance of the two outer segments and compare it against the repeating middle segment. For the auditory go/no-go task we recorded reaction times and errors. Since data revealed that participants made very few errors in the reaction time task, less than 1 error per trials in all conditions, we took RTs as the variable of analysis for the reaction time task.

A prerequisite for the testing of predictability effects is the establishment of learning effects specific to the repeating segment and the predictable tone sequence. To test for the acquisition of such knowledge we submitted training block RMSEs to a 4 × 2 × 2 mixed analysis of variance (ANOVA) with within-subjects factors Block (4 training blocks) and Segment (middle segment vs. random segments), and between-subjects factor Group (implicit vs. explicit). Similarly, learning in the auditory reaction time task was tested with a repeated measures ANOVA with the within-subjects factor Block (4 training blocks). Note that for the reaction time task we cannot establish in this phase how much of the learning is due to general training effects or sequence specific knowledge, since no comparison with a random reaction time task was made.

To test the effect of predictability on RMSEs in the Test block and Retention Block, we ran a 2 × 3 × 2 × 2 mixed ANOVA with the factors Segment (predictable vs. random), Tones (predictable vs. random vs. none - with 'none' being single task tracking), Test (Test vs. Retention test) and between-subjects factor Group (implicit vs. explicit).

To test the effect of predictability on reaction times in the Test Block and Retention Block, we ran a 3 × 2 × 2 × 2 mixed ANOVA with factors Segment (none vs. predictable vs. random), with 'none' being single task performance, Tones (predictable vs. random), and Block (Test Block vs. Retention Block) and between-subjects factor Group (implicit vs. explicit). Whereas in the Training Blocks the effect of predictability in the tracking task was calculated by comparing performance on the middle segment against performance on the outer segment, in the Test block and Retention Test we always compared middle segments, which contained all possible conditions; predictable or random tracking with no tones, predictable tones or random tones. Significance level was set at $p < 0.05$. Greenhouse-Geisser correction was applied if the sphericity assumption was violated.

Results

Acquisition of predictability-based knowledge

We first established that there were learning effects specific for the repeating segment during the training phase. For the tracking task there was a main effect of Block, $F(1.81, 56.04) = 9.63$, $p < .001$, $\eta_p^2 = .237$ (Block 1: $M = 1.64 \pm 0.24$ cm; Block 4: $M = 1.50 \pm 0.32$ cm), showing that participants improved tracking performance across blocks in general, and a main effect of Segment, $F(1, 31) = 26.42$, $p < .001$, $\eta_p^2 = .460$ (Repeating segment: $M = 1.51 \pm 0.27$ cm; Random segment: $M = 1.60 \pm 0.26$ cm), showing that participants performed better on repeating compared to random segments. There was no effect of Group, $F(1, 31) < 1$, $p = .596$, and none of the interactions were significant, Block × Segment, $F(3, 93) = 1.58$, $p = .200$, Group × Block, $F(3, 93) < 1$, $p = .707$, Block × Segment × Group, $F(3, 93) = 1.85$, $p = .144$.

For the reaction time task there was also a main effect of Block, $F(1.74, 53.89) = 7.64$, $p < .001$, $\eta_p^2 = .198$, (Block 1: $M = 445 \pm 73$ ms, Block 4: $M = 399 \pm 84$ ms), so participants improved reaction times from the first to last training block. There was no effect of Group, $F(1, 31) < 1$, $p = .436$, and no Group × Block interaction, $F(3, 93) < 1$, $p = .816$.

Test Block and Retention Block

Regarding the tracking task, there was a significant main effect of Segment, $F(1, 30) = 13.32$, $p = .001$, $\eta_p^2 = .307$ (repeating segment $M = 1.46 \pm 0.32$ cm; random segments $M = 1.55 \pm 0.34$ cm) on RMSEs, so participants' tracking performance was better on repeating segments compared to random segments, see Figure 2. There was no effect of Tones, $F(2, 60) < 1$, $p = .568$, or Group, *F*(1, 30) < 1, *p* = .878, nor of Test, *F*(1, 30) < 1, *p* = .432. The failure to find an effect of tones meant that there was no effect on tracking performance whether a random tones or sequenced tones were played. Moreover it means that we found no significant dual-task costs (No tones *M* = 1.48, sequenced tones *M* = 1.51, random tones *M* = 1.51.We found a significant Test × Segment × Group interaction, *F*(1, 30) = 4.67, *p* = .039, η_p^2 = .135, which indicated that whereas the implicit learning group improved from Test to Retention on the repeating segment (from *M* = 1.52 cm to *M* = 1.40 cm), the explicit learning group did not (from *M* = 1.44 cm to *M* = 1.47 cm). However, since the power to detect such an effect was fairly low (<.29), this effect is likely not reliable. No other interactions were significant.

For the reaction time task there was a main effect of Tones, *F*(1, 30) = 178.73, *p* < .001, η_p^2 = .856 (sequenced tones *M* = 426 ± 79 ms; random tones *M* = 567 ± 55 ms) on RTs, showing that RTs to sequenced tones were lower than to random tones (Figure 3). We found significant dual-task costs, *F*(1.66, 30) = 15.268, *p* < .001, η_p^2 = .337, because RTs in the single-task condition (no segment) were shorter (*M* = 474 ± 67 ms), than in dual-task conditions. Participants responded to tones similarly fast while tracking both a repeating segment (*M* = 509 ± 67 ms) and a random segment (*M* = 505 ± 68 ms). Furthermore, there was a main effect of Test, *F*(1, 30) = 5.80, *p* = .022, η_p^2 = .16, because participants improved significantly from Test to Retention test (from 503 ms to 490 ms), and this effect was mainly due to the implicit learning group improving rather than the explicit learning group, as evidenced by a significant Test x Group interaction, *F*(1, 30) = 7.60, *p* = .010, η_p^2 = .202. While the implicit learning group lowered RTs from 518 ms to 489 ms, the explicit learning group slightly increased RTs from 488 ms to 490 ms. Lastly, we found a significant Tones × Segment interaction, *F*(2, 60) = 4.17, *p* = .020, η_p^2 = .122, which indicated that responding to random tones suffered more from dual-task conditions (ST = 540 ms and DT = 581 ms) than did responding to sequenced tones (ST = 409 ms and DT = 433 ms). No other interactions were significant.

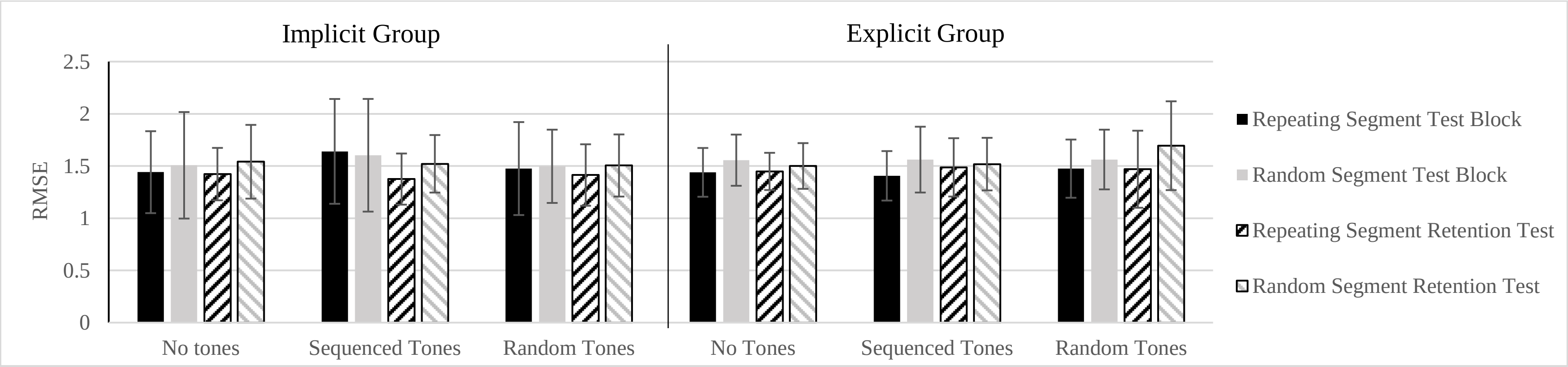


Figure 2. Tracking results from the Test Block and Retention Test in Root Mean Square Error (RMSE). Bars within a cluster show the tracking performance for repeating and random segments per group while the different cluster represent the conditions of the auditory task. We found significantly better tracking on repeating segments, but no differences between groups or tracking with sequenced or random tones. Error bars represent the standard deviation of the mean.

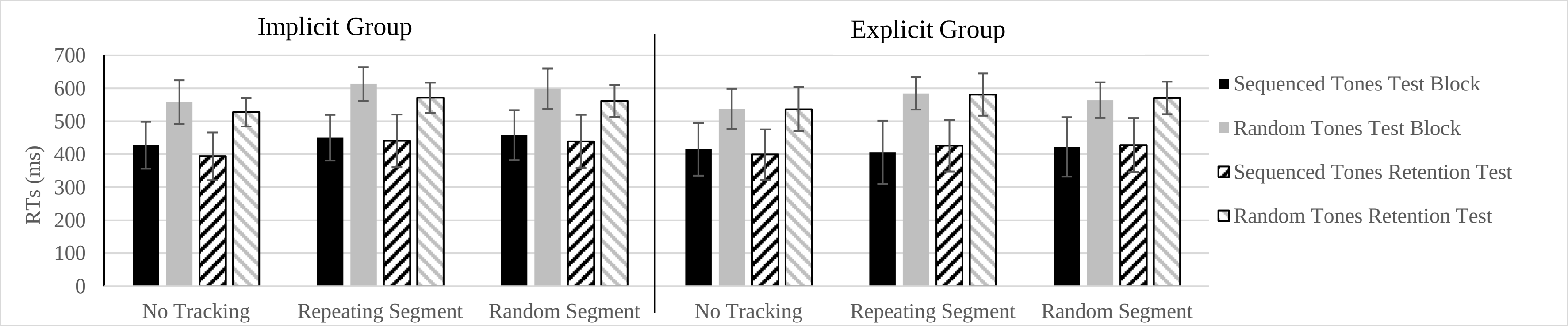


Figure 3. Reaction time results from the Test Block and Retention Test. Bars within each cluster show the RTs for sequenced and random tones per Group. Cluster

on the x-axis represent the different conditions of the tracking task. Reactions to sequenced tones were significantly faster, but there was no difference in reaction times while tracking repeating or random segment. Error bars represent the standard deviation of the mean.

Explicit knowledge interviews

None of the participants in the implicit learning group could verbalize explicit knowledge about the repeating middle segment during the first 5 probing questions. For question 6 (“There were three segments in the path, the first, the middle and at the last segment. One of these segments was always repeating? Did you notice?”) two participants said they noticed a repeating segment, however for question 7 (“Which segment was the repeating segment, the first, the middle or the last segment?”) only one of them correctly identified the middle one as repeating. Two participants said the first segment, seven said the middle segment, and eight said the last segment would repeat. All participants noticed the repeating pattern of the tones after the first trial. This may have caused a shift in prioritization to the tone task. If predictability influences prioritization, as argued above, this should have equalized prioritization effects through this factor if we assume that prioritization can also be influenced by predictability caused by implicit learning.

Discussion

The goal of the first experiment was to investigate the effect of predictability on dual tasks after single-task training. Predictability benefitted both tasks under dual-task conditions but this did not extend to the other task, mirroring the results of previous studies that the effect of predictability seems to be contained within the predictable task itself (Ewolds et al., 2017). Even though data suggested that resources were freed up in both tasks, participants did not exploit this to improve performance on the other task, as indicated by the absent effect of tones on RMSE. In line with Tombu and Jolicoeur (2003), who argued that task characteristics are decisive for resource allocation, it seems like “motor predictability” benefited visuomotor performance and auditory predictability benefited audiomotor performance only.

Furthermore, we found no dual-task costs in the tracking task, regardless of whether participants were tracking a random or predictable segment, and regardless of whether they tracked while responding to random or predictable tone sequences. For the auditory reaction time task, significant dual-task interference remained. A possible explanation for this is that the tracking task was trained for much longer.

Differences between implicitly and explicitly instructed participants were minor. During the test block the explicit learning group showed slightly better tracking performance on the predictable segment, but during the retention block the implicit learning group caught up and ended up better than the explicit learning group. The lower initial performance of the implicit learning group is not due to them entering the test phase with a lower amount of knowledge because at the end of the training phase both groups performed similarly (explicit learning group RMSE = 1.45 cm ± 0.23, implicit learning group RMSE = 1.46 cm ± 0.29). Nor can it be explained by a shift in priority by the implicit learning group from the tracking task to the reaction time task, the results of which followed a similar pattern as the tracking task, with initially worse performance but equally fast RTs on the retention test. Overall, this seems to suggest that the implicit learning group initially responded more poorly to dual-tasking than the explicit learning group, but then achieved similar RTs to those from the explicit learning group and even superior tracking performance.

The fact that we found no segment-specific learning effects during the training phase casts some doubt on whether segment effects in the test block reflected learning at all. In tracking studies learning effects have sometimes been ascribed to peculiarities of the repeating segment itself, which cannot have been the case in the current study as each participant received a unique repeating segment to practice. Nevertheless, segment effects might also be due to positioning, with performance usually being best at the start and deteriorating with time on task (Zhu et al., 2014). However, by placing the repeating segment in the middle and taking the average of the first segment and last segment as the performance metric for random tracking we should control for the time on task effect. A further possible measure to ensure that segment effects are due to learning only is by placing the repeating segment at the start, middle and end for different participants, which we did in Experiment 2.

In summary, we failed to show a redistribution of freed-up resources to both tasks during dual-tasking after both tasks are made predictable. We ruled out that this is due to prioritization effects due to only one task being predictable. A remaining reason for priority effects playing a role in these findings is that the tracking task was trained for a lot longer than the reaction time task. A possible way to let predictability effects spill over to the unpredictable task might therefore be through dual-task training, with both tasks being predictable, which we tested in Experiment 2. This would allow an equal amount of practice for both tasks, but a more important argument of why dual-task training might achieve spill-over effects is that we force participants to perform both tasks simultaneously from the beginning, which may result in the adoption of a more parallel task processing strategy where predictability in both tasks is exploited (Fischer & Plessow, 2015).

Experiment 2

In the first experiment we found a task-specific effect of predictability on dual-task performance after practicing two predictable tasks separately. In the second experiment we investigate whether interference can be reduced through dual-task practice. This equalizes the amount of time spent on both tasks, ruling out the possibility that findings in Experiment 1 were due to the tracking task being practiced more. We kept the setup and experimental procedure of Experiment 1, see Figure 1, but asked a new sample of participants to perform the training blocks under dual-task conditions, with the same predictable tracking and tone sequence that participants had learned (separately) in Experiment 1. The other difference compared to Experiment 1 is that the repeating segment of the tracking task now was placed either at the start, in the middle or at the end, equally distributed among participants within the implicit and explicit group, ensuring that learning effects are not due to peculiarities of tracking a segment in the middle position.

Materials and Methods

Participants

We tested 39 participants (29 female), the implicit learning group contained 19 participants (*M* = 24.0 ± 2.5 years) and the explicit learning group had 20 participants (*M* = 23.8 ±2.4 years). The implicit group had only 19 participants because 1 participant discovered the repeating segment and was removed from analyses. None of the participants of Experiment 2 participated in Experiment 1. All participants had normal or corrected-to-normal vision and no reported neurological disorders. All participants gave informed consent prior to the start of the experiment and received remuneration of 20 € or course credit after completing the experiment. The research was approved by the local ethics committee. Experiment setup, task and display were identical to Experiment 1, except that we varied the position of the repeating segment in the tracking task between participants, for 12 participants the repeating segment was placed at the start, for 13 in the middle and for 10 at the end. The reason for this decision was that data from Experiment 1 showed that there might be an effect of segment position on performance, with generally better performance on the middle segment.

Procedure

The procedure of Experiment 2 differed from Experiment 1 in that participants performed the training of the tracking task always together with the auditory reaction time task. Participants were asked to give equal priority to both tasks.

Data analyses

Data analyses were similar to Experiment 1, with the exception that establishment of segment specific learning effects and learning of the always predictable reaction time task was done by applying one single ANOVA to the RMSEs and RTs, with within-subjects factors Block (4 training blocks), Segment (repeating segment vs. random segments), and between-subjects factors Group (implicit vs. explicit) and Segment position (start vs middle vs end).

Results

Acquisition of predictability-based knowledge

In the tracking task there was a main effect of Block as participants improved their tracking from Block 1 to 4, $F(1.27, 36.75) = 13.98$, $p < .001$, $\eta_p^2 = .325$ (Block 1: $M = 1.97 \pm 0.45$ cm; Block: 4 $M = 1.60 \pm 0.43$ cm), and a main effect of Segment, $F(1, 29) = 9.86$, $p = .004$, $\eta_p^2 = .253$, (repeating segment: $M = 1.75 \pm 0.42$; random segment: $M = 1.81 \pm 0.39$ cm), as performance on the repeating segment was better than on the random segments. There was no main effect of Group (implicit vs. explicit), $F(1, 29) < 1$, $p = .589$. There was no significant Block × Segment interaction, $F(2.12, 61.40) = 1.21$, $p = .308$, so tracking of the repeating segment did not improve more than tracking of the random segments. Also, the positioning of the repeating segment did not have a significant effect on tracking performance, $F(2, 29) < 1$, $p = .530$. In summary these effects show that knowledge specific to the repeating segment was acquired.

In the reaction time task there was also a main effect of Block $F(1.57, 36.75) = 13.23$, $p <$ .001, $\eta^2_p = .313$, (Block 1: $M = 431 \pm 95$ ms; Block 4: $M = 365 \pm 97$ ms), but no effect of Segment, $F(1, 29) = 1.67$, $p = .207$, or Group, $F(1,29) < 1$, $p = .468$.

Test Block and Retention Block

Analyses of the tracking task showed there was a main effect of Segment, $F(1, 31) = 6.46$, $p =$ .016, $\eta_p^2 = .172$, (predictable segment: $M = 1.53 \pm 0.39$ cm; random segment: $M = 1.59 \pm 0.41$ cm), showing that tracking of predictable segments in the test block and retention test was significantly better than of random segments (Figure 4). There were no effects of Tones, $F(2, 62) = 2.25$, $p = .114$, or Group, $F(1, 31) = 1.81$, $p = .188$, so tracking performance did not differ between random, sequenced and no tone conditions, so there were no dual-task costs, and performance did not differ between the implicit and explicit learning group. Likewise, there were no significant effects of Test, $F(1, 31) = 3.34$, $p = .077$, $\eta_p^2 = .097$, or Test × Group interaction, $F(1, 31) = 3.20$, $p = .084$, $\eta_p^2 = .093$. Finally, although we had no hypothesis for it, we found a significant Segment × Test effect, $F(1, 31) = 5.11$, $p = .031$, $\eta_p^2 = .141$, indicating that performance improved more on random (test block: $M = 1.67 \pm 0.29$ cm; retention test: $M = 1.51 \pm 0.14$ cm) compared to repeated segments (test block: $M = 1.56 \pm 0.31$ cm; retention test: $M = 1.49 \pm 0.28$) between the test block and the retention block.

Looking at the reaction time task performance, there was a main effect of Tones, $F(1, 27) = 147.24$, $p < .001$, $\eta_p^2 = .845$ (predictable tones: $M = 411 \pm 72$ ms; random tones: $M = 563 \pm 56$ ms), as responding to predictable tones was faster than responding to random tones (Figure 5). No main effect of Group was found, $F(1, 27) < 1$, $p = .675$. We found a significant Segment effect, $F(2, 54) = 10.01$, $p < .001$, $\eta_p^2 = .270$, because RTs in the single task condition were shorter ($M = 463 \pm 67$ ms), than in dual-task conditions ($M = 499 \pm 62$ ms). No differences in performance between a repeating vs random segment were found. Furthermore, we found a significant Segment × Test × Group interaction, $F(2, 54) = 5.49$, $p = .007$, $\eta_p^2 = .169$, which meant that the implicit learning group improved from test block to retention block on the repeated segments (from $M = 517$ ms to $M = 487$ ms), the explicit learning group got worse on repeated segments ($M = 481$ ms to $M = 518$ ms). No other interactions were found.

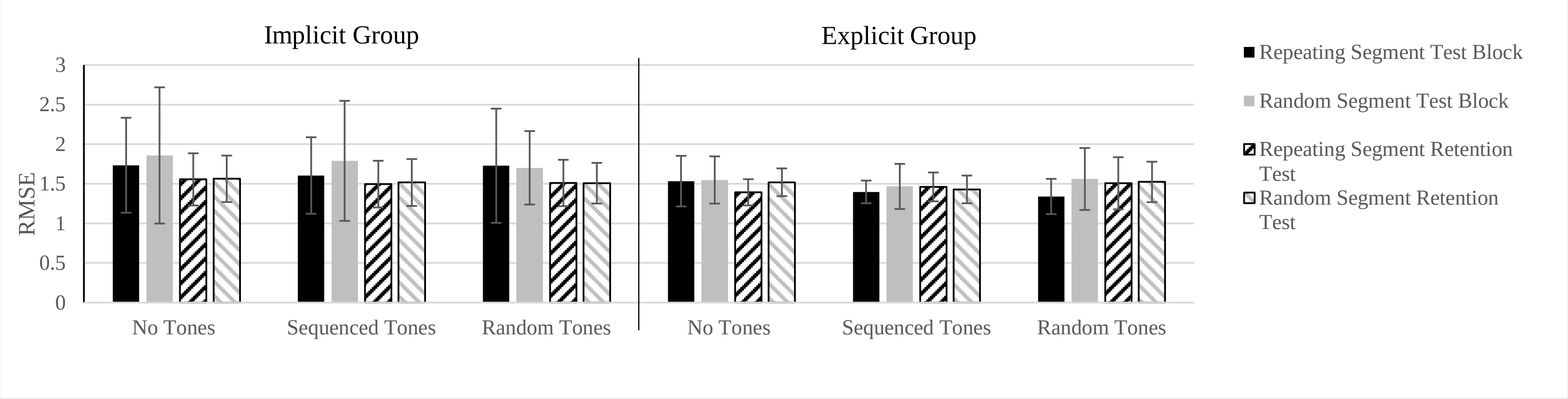


Figure 4. Tracking results from the Test Block and Retention Test in Root Mean Square Error (RMSE). Bars within a cluster show the tracking performance for repeating and random segments per group while the different cluster represent the conditions of the auditory task. We found no significant difference in tracking with sequenced or random tones. Error bars represent the standard deviation of the mean.

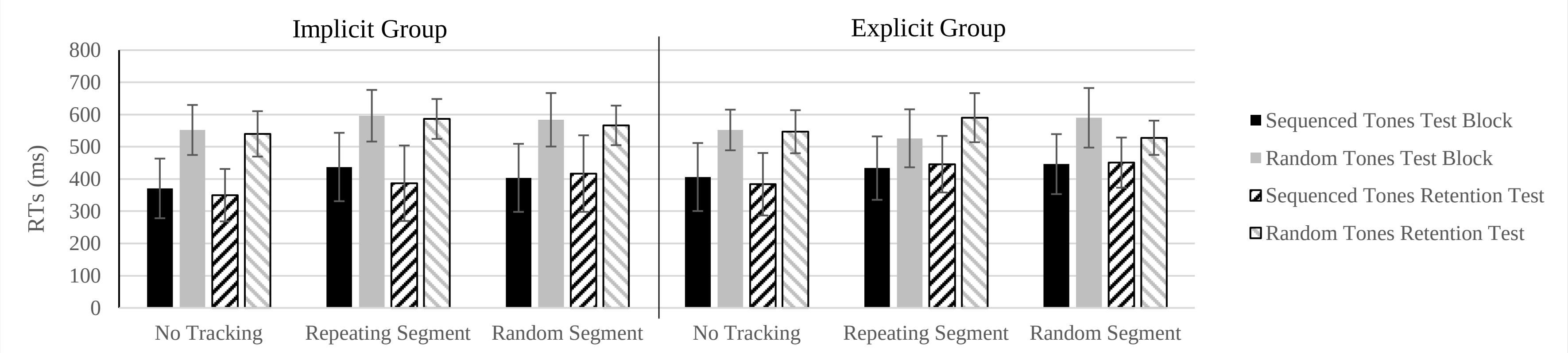


Figure 5. Reaction time results from the Test Block and Retention Test. Bars within each cluster show the RTs for sequenced and random tones per Group. Cluster on the x-axis represent the different conditions of the tracking task. There were no significant differences between reaction times while tracking a repeating or random segment. Error bars represent the standard deviation of the mean.

Discussion

In Experiment 2 we found a task-specific effect of predictability on dual-task performance, similar to Experiment 1. Even after extensive dual-task practice, predictability in each task only improved performance on that task, ruling out the possibility that time on task was the reason for the task-specific predictability effects seen in Experiment 1. Importantly, the results of Experiment 2 also make it less likely that the task-specific predictability effects in Experiment 1 were due to a more serial processing mode as a consequence of having trained the tasks separately.

There was a consistent performance advantage of the predictable segment in Experiment 2, although, as in Experiment 1, we found no segment-specific training effects during the training blocks. It is likely that this is because the bulk of the segment-specific learning took place within the first training block. Alternative reasons for better performance of the repeating segment are segment-specific peculiarities and segment positioning but both were varied across participants and were shown to have no effect. We therefore conclude that learning did take place. Data of SRT task studies on whether a sequence can be learned while performing another task is conflicting but seems to point to difficulty being a key factor. Simpler, or first-order sequences (where each element in the sequence has a unique successor), may be learned under dual-task conditions whereas learning of second-order sequences is more susceptible to dual-task interference (Cohen et al., 1990; Curran & Keele, 1993; Keele et al., 2003b; Nissen & Bullemer, 1987). In this connection our data support the idea that implicit learning of a tracking path is more similar to learning first-order sequences in SRT tasks, and that learning is not prevented by performing an additional task.

General Discussion

The goal of the current study was to investigate the effect of performing two predictable tasks simultaneously. We hypothesized that two predictable tasks reduce the need for resources for each task, and that both tasks would benefit from the overall reduction in capacity requirements and thereby reduce interference. Instead, we found that the effects of predictability only expressed themselves within each task, both after single- and dual-task practice. The main conclusion of the current study is that even after extensive dual-task practice the beneficial effects of predictability remain contained within each task.

Predictability and prioritization

In Experiment 1 we ruled out that task-specific predictability effects were due to differences in prioritization caused by predictability. In Experiment 2 we showed that differences in prioritization due to time on task were not the cause of the task-specific predictability effect, and that the increased time that tasks were practiced in the presence of each other also did not lead to a more even redistribution of resources. We hypothesized that a more even redistribution of resources might have occurred since a parallel mode of processing, which increases between-task interaction, might also 'open up' the task processing streams to benefit from resources freed-up in the other task. Usually, a more parallel processing mode can be demonstrated by the presence of backward crosstalk effects (Hommel, 1998; Janczyk et al., 2014; Navon & Miller, 1987), but this is difficult to establish with continuous tasks. On the other hand, the continuous nature of the tracking task makes it unlikely that the tracking task was ever 'paused' to process the auditory task. While not investigated in the current study, pauses in tracking were absent in Broeker et al. (2020b)(under review), which used a similar paradigm as the current study, but see

Netick and Klapp (1994) for a demonstration of hesitations in tracking during dual-task performance. These hesitations in tracking at the moment a tone is played would be an indication that there is some interference at the motor level, which might not show up in a summarized statistic of tracking performance over a whole trial, i.e. RMSE.

Even though prioritization effects were not due to time on task, the continuous nature of the tracking task may still have caused it to be prioritized. The distance between cursor and target serves as continuous feedback which is difficult to ignore. Such continuous feedback and the demand for continuous action is missing for the auditory task. Usually, instruction emphasizing equal importance of both tasks is used to prevent prioritization effects but the effectiveness of such instructions may be questioned. An equitable distribution of resources is difficult to achieve when there is no direct control over these resources. Indeed, in a study using similar tasks by Broeker et al. (2020b, under review), a third of participants admitted to prioritizing the tracking task even though equal prioritization was instructed. Along with task features, a meta-analysis by Wickens et al. (2015) showed that in task-switching, task difficulty, salience and interest are all factors that can affect which tasks are prioritized. These factors may be at least partially individually determined, emphasizing the usefulness of an individual differences perspective and taking into account the effect of prioritization on resource allocation in dual-task performance (Broeker et al., 2018).

A further possible explanation for the effects of predictability might be due to the nature of the auditory task. The go/no-go task might call on significant inhibitory processes, which could lead to participants favoring a task-shielding strategy that might reduce interference but also prevents the spilling over of resources to the other task (Fischer & Plessow, 2015; Jong et al., 1995). The current experiments were not set up to detect different levels of involvement of inhibitory processes or task shielding, we can therefore not rule out that these processes played a role in the beneficial effects of predictability being contained within each task. Future studies could employ a task that is not reliant on inhibitory processes and measure the degree of task shielding to broaden the understanding of how predictability influences dual-task performance.

Susceptibility to dual-task costs

Data from both experiments show that the tracking task was not susceptible to dual-task performance decrements. Capacity theories predict the absence of dual-task costs when there is sufficient capacity available for both tasks and state that capacity can be increased by eliciting more effort from participants, which can be achieved by the dual-task situation itself (Kahneman, 1973; Tombu & Jolicœur, 2003). There are of course limits to this and with difficult tasks a capacity limit is quickly reached, leading to the interference effects found in most studies. It is hard to assess how difficult the tracking task was, and how consistent the level of difficulty was across participants. Nevertheless, it may be argued that tracking is a highly ideomotor compatible task, and these types of tasks have sometimes been shown not to be strongly influenced by dual-task interference (Greenwald, 2003), but see Lien et al. (2003) for a rebuttal.

Another reason for the absence of dual-task costs in tracking might have been that the tasks became intertwined so that participants were more used to ‘reacting with their foot while tracking a target’, than performing the tasks on their own, effectively representing or conceptualizing it as one task (Künzell et al., 2018), and possibly requiring costly response inhibition when only the tracking task was presented (Huestegge & Koch, 2014). The finding that speaks against integration of the two tasks, however, is that we found dual-task costs in the reaction time task. Task integration might be achieved by covarying both tasks, which should improve performance on both tasks (de Oliveira et al., 2017; Schmidtke & Heuer, 1997).

The finding that only the tracking task was free of dual-task interference is in line with the idea that a certain amount of capacity was saved for better performance on this task, with performance decrements only visible in the auditory task, in line with general capacity theories (Tombu & Jolicœur, 2003). As stated before, this prioritization of the tracking task is likely to be due to its continuous nature and not overridable through instructions, predictability effects, or time on the task. On the other hand, the multiple resource theory by Wickens (2008), more readily explains the task-specific effects of predictability by proposing that predictability only increases the available resources in the modalities of the specific task. These tasks draw from separate pools of resources that are not shared between tasks, so freeing up resources within these pools will only benefit the task itself, as they cannot be transferred to the resource pool of the other task. In summary, the difference in dual-task cost effects can be explained by prioritization or resource-saving effects acting on a general resource, whereas the effects of predictability staying within their respective tasks suggests that these tasks draw from separate pools of resources that are not shared between tasks. It should be noted that the general resource theory and the multiple resource theory are not incompatible with each other, indeed Wickens (2008) does not deny the existence of a general resource (or effort), and Kahneman (1973) noted that occurrences of structural interference could not always be accounted for by an undifferentiated resource pool. Indeed, an overview of the dual-tasking literature by Wahn and König (2017) shows that for studies combining object based tasks with spatial orientation tasks the evidence points towards a partial sharing of resources.

Limitations

This study has some limitations. Firstly, it is difficult to assess to what extent an additional task takes up resources. Participants may be instructed to pay equal attention to two tasks but it is unclear what kind of problem-solving strategy is used. Do participants adopt a type of task-switching strategy where they alternatively focus on the tracking and tone task, and to what extent can participants divert their attention proportionally? These different strategies in solving dual-task problems are likely to be individually determined (Broeker et al., 2018). Furthermore, adding another task does not only take up attention, it also seems to alter the overall task structure itself, and it is not clear to what extent a dual-task consists of the two original single tasks or if task conceptualizations overlap (Künzell et al., 2018; Röttger et al., 2019). A promising avenue of research is therefore to find out how individuals differ in how they solve dual-task problems and how task conceptualizations might be influenced to optimize performance.

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Article 3. No impact of instructions and feedback on task integration in motor learning

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Abstract

This study examined the effect of instructions and feedback on the integration of two tasks. Task-integration of covarying tasks is thought to help dual-task performance. With complete task integration of covarying dual tasks, a dual-task becomes more like a single task and dual-task costs should be reduced as it is no longer conceptualized as a dual task. In the current study we tried to manipulate the extent to which tasks are integrated. We covaried a tracking task with an auditory go/no-go task and tried to manipulate the extent of task-integration by using two different sets of instructions and feedback. A group receiving task-integration promoting instructions and feedback (N = 18) and a group receiving task-separation instructions and feedback (N = 20) trained a continuous tracking task. The tracking task covaried with the auditory go/no-go reaction time task because high-pitch sounds always occurred 250 ms before turns, which has been demonstrated to foster task integration before. The tracking task further contained a repeating segment to investigate implicit learning. Results showed that neither instructions, feedback, nor participants' conceptualization of performing a single task vs. a dual task significantly affected task-integration. However, the covariation manipulation improved performance in both the tracking and the go/no-go task, exceeding performance in non-covarying and single tasks. We conclude that task-integration between covarying motor tasks is a robust phenomenon that is not influenced by instructions or feedback.

Keywords: Task-integration, multitasking, implicit learning

Introduction

Task-integration is a major factor in the study of dual-task performance, where studies claim that it can improve dual-task performance, depending on the task characteristics. When integrating tasks, people are thought to functionally combine the features from the main task and the secondary task, rather than processing the features of the two tasks separately. Some authors suggest that task-integration is a natural principle of human processing since people have great difficulty processing two tasks separately, and so they would strive for task integration even if being instructed to perform two tasks (Röttger et al., 2017; Schmidtke & Heuer, 1997). The task integration hypothesis proposes that when two tasks contain a sequence, participants do not process these sequences separately, but rather perceive the two sequences, and thus tasks, as one combined sequence comprised of sequence elements of both tasks (Schmidtke & Heuer, 1997).

Task integration can however be either detrimental or beneficial to performance. A combined sequence is usually more complex than the sequences within either task, and as such task integration can cause costs and prevent participants from learning the single sequences within each task (Schmidtke & Heuer, 1997). On the other hand, task integration has been shown to be beneficial, especially for motor learning. One circumstance that has been shown to foster integration and optimal performance is covariation of task features in the serial reaction time task (SRTT, see Nissen and Bullemer (1987)) and an auditory task, demonstrated by Schmidtke and Heuer (1997). In their study participants pressed buttons in response to visual and auditory stimuli. When stimuli of the visual and auditory task alternate and both tasks contain an equal number of elements in a predictable sequence, the combined sequence is a lot less complex than when the number of elements is unequal. This type of covariation of tasks (combining visual and auditory stimuli) led to better dual task performance than when tasks did not co-vary (Schmidtke

& Heuer, 1997). Covariation in this case provided predictability to the task, where each element of the combined sequence can be predicted by the previous element, even though it belonged to the other task. In contrast to tasks without covariation, task integration of covaried tasks should enhance dual-task performance with covaried tasks.

While most studies on task integration employ some kind of covariation between tasks to study task integration (de Oliveira et al., 2017; Röttger et al., 2017; Schmidtke & Heuer, 1997), some authors view task integration differently. Ruthruff et al. (2006) tried to demonstrate task-integration by comparing single-task and dual-task training effects of non-covarying tasks. They examined dual-task performance with an auditory-vocal and visual-manual task after training only task 1, only task 2, or dual-task training. The authors argued that evidence for task-integration would be obtained if dual-task practice led to greater improvements than single-task practice. Conversely, if single-task practice was more effective, task automatization would be the cause for dual-task cost reduction. Ruthruff and colleagues found no indication of task-integration. The mechanism behind the beneficial effect of task-integration in this study would not have been covariation, as described in the studies before. Instead the authors argued that dual-task training caused better task scheduling leading to less interference caused by a response selection bottleneck (Pashler, 1994). Task-integration of non-covarying tasks may also take place, and indeed play an important role in the performance of many everyday motor tasks. In the present study, however, since a beneficial effect of task-integration has thus far mostly been demonstrated in covarying tasks, we chose to use this method to test whether task-integration can be manipulated via instructions.

Whether people really do integrate tasks into a single task, and to what extent, may partly depend on how the tasks are presented (besides covariation). Both, instructions and type of feedback (Halvorson et al., 2013; Srna et al., 2018) may contribute to task-integration and better performance, eventually even leading to the conceptualization of two tasks as a single task. Conceptualization, so the perception of dual-tasking and its impact on subsequent performance has been investigated by Srna et al. (2018). In their study participants were asked to solve two puzzles that through instructions and context were either presented as being a single task (task-integrating instructions) or two different tasks (task-separating instructions). The task features did not covary. Participants receiving the task-separating instructions rated the tasks more strongly as multitasking, and performed better, than participants in the task-integrating group. However, given that the task features did not covary, the attempt to integrate tasks was harder than keeping them separate and so task-integrating instructions might have had a negative effect in this study. Nevertheless, since their instructions were effective in changing the way participants perceived the tasks, we adapted their instruction to fit with the covariation manipulation we used in the current study. We also used a similar questionnaire as in Srna et al. (2018) to obtain a measure of how participants conceptualized the tasks.

In a study closely related to ours, de Oliveira, Raab, Hegele and Schorer (2017) investigated whether task-integration also benefits motor learning, so they combined a tone counting task with a repeated segment in a manual tracking task. They covaried the two tasks by placing tones shortly before occurrences of turns in the tracking path so that tones made turns predictive. Note that with this manipulation, the tone task predicted the tracking task but not vice versa, thus tasks did not become interdependent as in the SRTT of Schmidtke and Heuer (1997); where tones and visual stimuli were both predictive of each other. De Oliveira and colleagues (2017) found no benefits of covariations for implicit learning when comparing the “integration group” to a group performing only single tasks or non-convaried tasks. However, other research examining implicit learning and task integration in continuous tasks is sparse. In the present study we adapted the paradigm by de Oliveira et al. (2017) but we exchanged the counting task for a motor response task and we used a within-group design to test whether implicit learning under task-integration conditions would transfer to single and random dual-task conditions. In addition, we focused on the question of whether the extent of task integration could be manipulated by instructing the tasks differently, as in Srna et al. (2018). In one group, task-separating instructions emphasized the existence of two tasks and explained that the two tasks were distinct, with the idea that this would give a stronger perception of performing two tasks at the same time and reduce between task interactions (Fischer & Plessow, 2015). The task-integration group performed the same tasks, but instructions framed them as a single task. The instructions (see Methods) were formulated to be as contrasting as possible on the dual-task vs single-task dimension, i.e. a strong focus on the existence of two tasks for the task separation-group while all wording referring to the existence of two tasks was avoided for the task-integration group. In addition to the two instructions, we manipulated feedback. While the task integration group received two scores, one for each task, the task separation group received a single score for both tasks together. To also contrast the environment as much as possible, without altering the actual task demands for both groups, we also took care of different familiarization phases. While the task-integration group practiced the tasks together from the very beginning, the task separation group had to practice the tasks separately.

In sum, we hypothesized that covarying two tasks would foster task integration, which would improve dual-task performance reflected by superior tracking performance and lower reaction times. In addition, we hypothesize that this effect will be stronger for the group receiving task-integrating instructions and one feedback score compared to the group receiving task-separating instructions and two separate feedback scores. Furthermore, we expected implicit learning to be preserved. The results of our study would add to the understanding of how people conceptualize tasks with the same task features which only differ in instructions and feedback.

Methods

Participants

Forty students participated in the experiment for course credit (22 Female; *M* = 20.3 years, *SD* = 2.2). Sample size was based on de Oliveira et al. (2017), who found an effect size of 0.24 with a sample size of 30 in a between-subjects design. Participants had normal or corrected-to-normal vision and no experience in tracking. Participants were assigned to a task-integration group (n = 20) or a task-separation group (n = 20). Two participants of the task- integration group were later removed from data analysis because of problems with data recording[3]. Before the start of the experiment, participants gave informed consent. Ethics approval was obtained from the local ethics committee and conformed with the principles of to the Declaration of Helsinki.

Apparatus and Material

The experimental setup was adapted from de Oliveira et al. (2017), in which implicit learning was demonstrated. Participants were seated in front of a 24’’ computer screen (144 Hz, 1920 × 1080 resolution). The cursor in the tracking task was controlled by a T.16000M FCS joystick. Positional data was recorded at 120 Hz on a Windows 7 Computer. Stimuli of the auditory task

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[3] The problems with data recording concerned the auditory task. These two subjects showed no reaction time recordings for large sections of the experiment. This is likely caused by participants not lifting their foot up enough after pressing the pedal, which prevents subsequent reactions from being registered. This problem was spotted during the practice trials and corrected, but it re-surfaced later in the experiment. We are sure that this problem did not exist for the remaining participants because very few RT errors were made.

were presented through Sony stereo headphones and participants responded by pressing the pedal on an f-pro USB-foot switch (9 cm × 5 cm).

Task and Display

The tracking task entailed pursuing a red target square of 19 × 22 pixels with a joystick-controlled white cross of equal dimensions from the left side of the screen to the right side of the screen. Only vertical movement of the cursor was user-controlled, horizontal tracking of the target happened automatically. The path of the target followed a wave created from three segments of equal length where no segment could repeat within a single trial. The formula to create the segments was taken from Wulf and Schmidt (1997):

$$f(x) = b_0 + \sum_{i=1}^{4} a_i \sin(i \cdot x) + b_i \cos(i \cdot x)$$

with a_i and b_i being a randomly generated number ranging from -4 to 4 and x in the range of $[0, 2\pi]$, see Figure 1. For this experiment 32 segments similar in length and number of extrema were selected. Twenty segments were selected to give each participant which was repeated every trial during the training phase. As in Künzell et al. (2016) each participant per group received their own repeating segment, ensuring that practice effects were not due to difficulty differences between segments or between segments of the two groups (Chambaron et al., 2006; Wulf & Schmidt, 1997). The two random segments on each trial were chosen so that each occurred an equal number of times. Three groups were created that differed in positioning of the repeated segment. The repeating segment was positioned at the start, in the middle, or at the end of the training trials, since segment positioning might be a possible confounder of tracking performance. Trial duration was between 24 and 37 seconds.

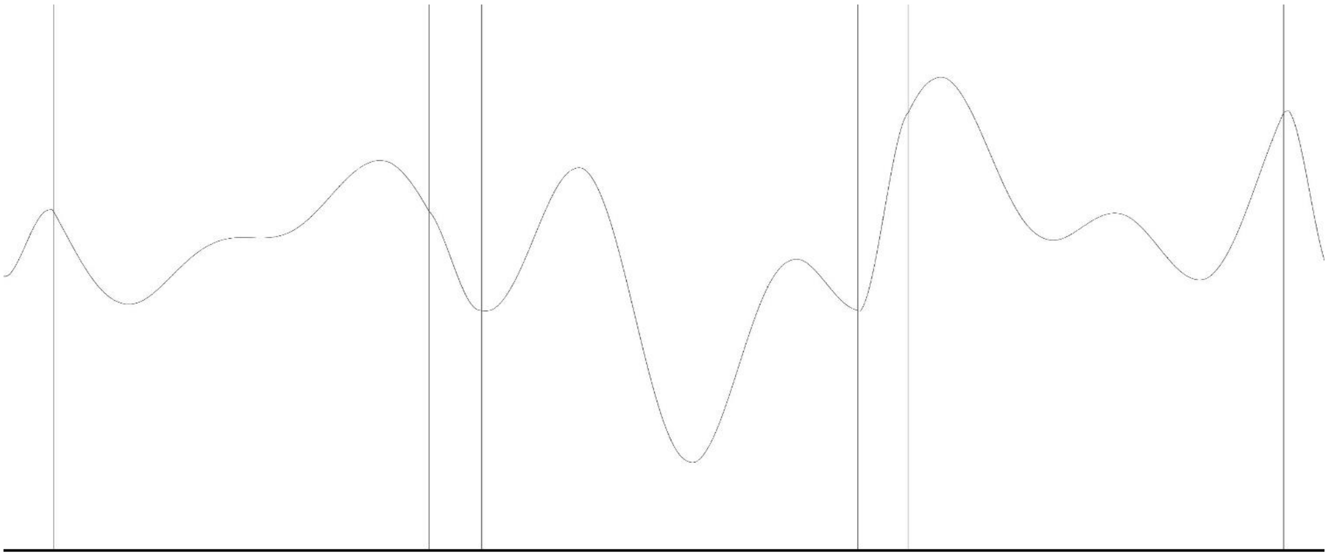

Figure 1. An example of a fictional path used in the tracking task for illustration purposes. The target square moved from left to right along the path depicted. Target tones were placed immediately before reversal points, signaling an upcoming turn, in addition distractor tones were placed randomly. During the experiment participants could not see the path or the vertical lines depicted. The small areas between the three sections indicate zones that were used to connect the three segments, data was not collected there.

The auditory task was a go/no go reaction time task and required pressing a pedal upon hearing high-pitched tones (1086 Hz) while ignoring low-pitched tones (217 Hz), adopted from Schmidtke and Heuer (1997). In total, there were 10 target and 10 distractor tones per trial, and target tones were positioned 250 ms before a reversal point in the curves in the training phase.

Procedure

Participants read the instructions on the screen before the experiment. Instructions for the task-separation group emphasized the existence of two tasks to induce the perception of performing a dual task: ‘Task 1: You sit in front of a computer screen. The start screen will display a red square on the left side of the screen. You will also see a white cursor which you can control with the joystick. To align the cursor with the target square, move the joystick forwards. When they are aligned you can press the button on the front of the joystick and the experiment will begin. After the start the red square will move up and down. It is your task to use the cursor to follow the target square as to the right side of the screen. Track the target square as accurately as possible. To do this you only move the joystick vertically. The horizontal movement is automatic. After every trial the starting screen appears again. By clicking the joystick, you can start the next trial. After every five trials you will see the amount of points you scored in the tracking task and in the tone task. The higher the score the better your performance was. The points will be used by the researcher.'

In contrast, task-integrating instructions presented the tasks as being one, they explained the connection between the tones and tracking task, and avoided all mentions of multitasking to induce the perception of performing a single task. Instruction for the task-integration group were: 'You will perform one task while sitting in front of a computer screen with a pedal below the desk. The start screen will display a red square on the left side of the screen. You will also see a white cursor which you can control with the joystick. To align the cursor with the target square, move the joystick forwards. When they are aligned you can press the button on the front of the joystick and the experiment will begin. After the start the red square will move up and down. It is your task to use the cursor to follow the target square to the right side of the screen. Track the target square as accurately as possible. To do this you only move the joystick vertically. The horizontal movement is automatic. At the same time place your preferred foot on the pedal below the table. You will hear two different tones through the headphones. The higher tone will indicate there will be reversal of direction of the target square on the screen; Confirm with a pedal press as quickly as possible that you hear the higher tone, ignore the lower tones. Every five trials you will see a score that reflects how accurately you have done this task. The higher the score the better the performance. The points will be used by the researcher.'

During the familiarization phase, the task-separation group first practiced the tracking task and auditory task separately, then as a dual task. Practice for the task-integration group only involved dual-task trials. Throughout the experiment participants received feedback after every five trials. For the task-integration group this feedback was a single score on the screen constructed from scores of both tasks. Performance on each task was converted so that lower root mean square error (RMSE) and lower RTs both result in a higher score, in addition the RT score was multiplied by a factor so that it contributed about equally to the integrated score as the RMSE score. The task separation group received a score for each task separately but calculated the same way. To start each trial participants moved the cursor to the target square and pressed a button on the joystick. Instructions were repeated every two blocks to reinforce the manipulation.

The experiment took place over three days. On the first day participants were familiarized with the tasks and did two training blocks. For both groups training blocks consisted of twenty trials with the repeating segment and with the tones predicting reversals in the tracking path. On the second day, one week later, they did two further training blocks and the test block. In the test block, all participants performed five single task (ST) trials in each task and then five dual-task (DT) trials as in the training blocks. At the end, participants performed five dual-task trials without the covariation between the tracking task and tone task. Instead, tones were presented randomly. On the third day, the test block was repeated as a retention test.

After the retention test explicit knowledge of the repeating segment was checked for with the same questionnaire used in Ewolds et al. (2017). The questions were: (1) Did you notice anything special during the experiment? (2) Was there something that helped or hindered you while performing the tracking? (3) Did you apply any rules? (4) Did you notice anything special concerning the path of the target? (5) The target followed a certain path. Did you notice any segments in this path? (6) There were three segments in the path, the first, the middle and at the last segment. One of these segments was always repeated. Did you notice? (7) Which segment was the repeated segment, the first, the middle, or the last segment?

Additionally, for the task-separation group, we tried to find out whether they noticed the connection between the tracking task and the tone task by asking the following additional questions (8) Did you notice anything about the combination of the tracking task and tone task? (9) Did you discover a pattern between the tracking and tone task? (10) If so, what was the pattern? Finally, as in Srna, Schrift, and Zauberman, (2018), we asked participants of both groups to rate on a scale of 1 to 7 how strongly they felt that they had been doing a single task or two tasks, with a 1 indicating strong feelings of single-tasking and a 7 indicating strong feelings of dual-tasking.

Data analyses

Tracking performance was measured by the root mean square error (RMSE), calculated from the difference in position between the target square and the user-controlled cursor. Performance on the repeated segments was compared to average performance of the two random segments. Reaction times (RTs) and errors were recorded for the tone task.

To test for learning effects during the *training phases* RMSE, RTs and errors were submitted to a 4 × 2 × 3 × 2 mixed analysis of variance with within-subjects factor Training Block (four training blocks), Segment (Repeating vs Random), segment Position (placement of the repeating segment), since this might influence learning (Zhu et al., 2014), and between-subjects factor Group (Task-integration vs Task separation).

To test for effects on RMSEs in the *test block and retention* test we performed a 3 × 2 × 2 × 2 mixed analysis of variance with within-subjects factors Condition (Single task, DT with covariation, DT without covariation), Segment (Repeating vs Random), Test (Test block vs Retention block) and between-subjects factor Group (Task-Integration vs Task-Separation) and Position (placement of the repeating segment). For the RTs we did a 3 × 2 × 2 mixed analysis of variance with within-subjects factor Condition (Single task, DT with covariation, DT without covariation), Test (Test block vs Retention block) and between-subjects factors Group (Task-Integration vs Task-Separation). Finally, to test whether reaction times were quicker during repeated tracking segments we performed a 2 × 2 ANOVA with Segment (Repeating vs Random) and Condition (DT covariation vs DT without covariation). A Greenhouse-Geisser correction was used when the assumption of sphericity was violated. To test differences in perceptions of dual-tasking vs single-tasking for the two groups a Mann-Whitney test was performed.

Results

We expected participants to improve both RMSEs and RTs as a result of covarying the tasks. Although these effects were not clear during the training phase, they were apparent in the Test Block and Retention Test. We could not find evidence that giving task-integrating or task-separating instructions influenced the degree to which tasks were integrated subjectively, nor did it affect dual-task performance (see results below).

Training blocks

Improvements in tracking, $F(2.28, 72.95) = 97.99$, $p < .001$, $\eta_p^2 = .754$, and RTs, $F(3, 96) = 42.81$, $p < .001$, $\eta_p^2 = .572$, were observed during the training blocks, see Figure 2 and Figure 3. Errors also reduced with training, $F(1.72, 54.96) = 8.22$, $p = .001$, $\eta_p^2 = .204$, although they were already rare with just 0.27 errors per trial in Block 1. No implicit learning of the constant segment could be demonstrated by using RMSEs as we did not find a Block × Segment interaction, *F*(3, 96) = .463, $p = .709$, $\eta_p^2 = .014$. The position of the repeating segment did not have an effect on RMSE, *F*(2, 32) = 0.33, $p = .721$, $\eta_p^2 = .045$. Reaction times did improve more during repeating segments than on random segments, *F*(3,96) = 4.80, $p = .004$, $\eta^2 = .130$.

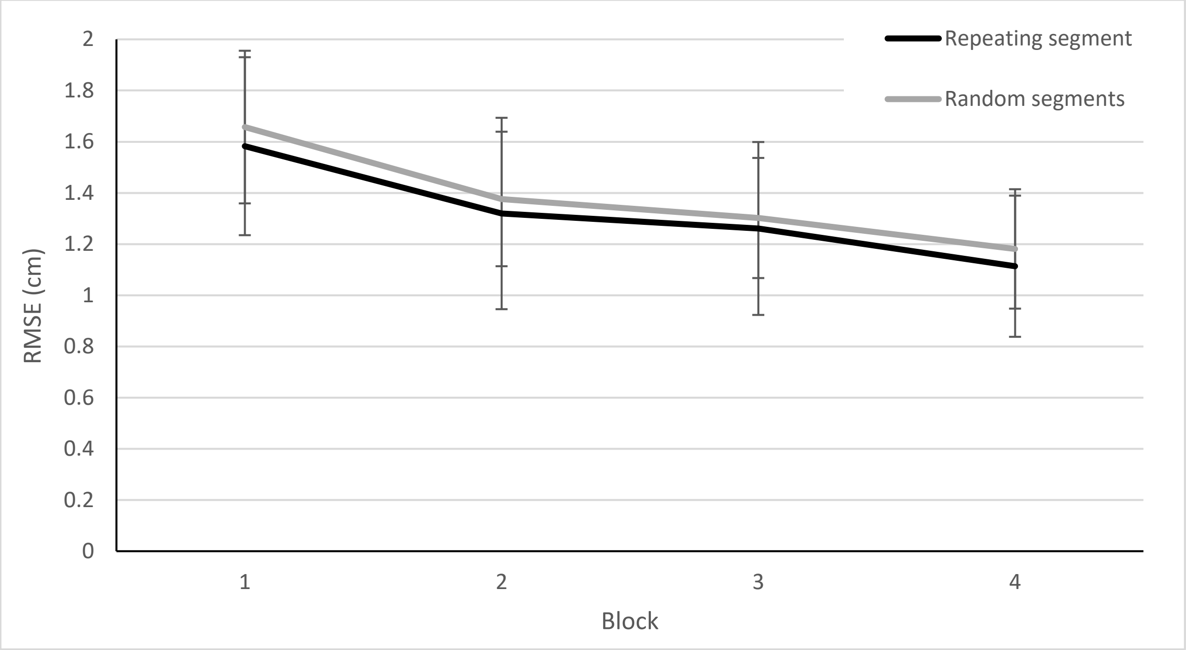

Figure 2. Root mean square error (RMSE) improved from the first to the last training block**.** Errors bars represent the standard deviation of the mean.

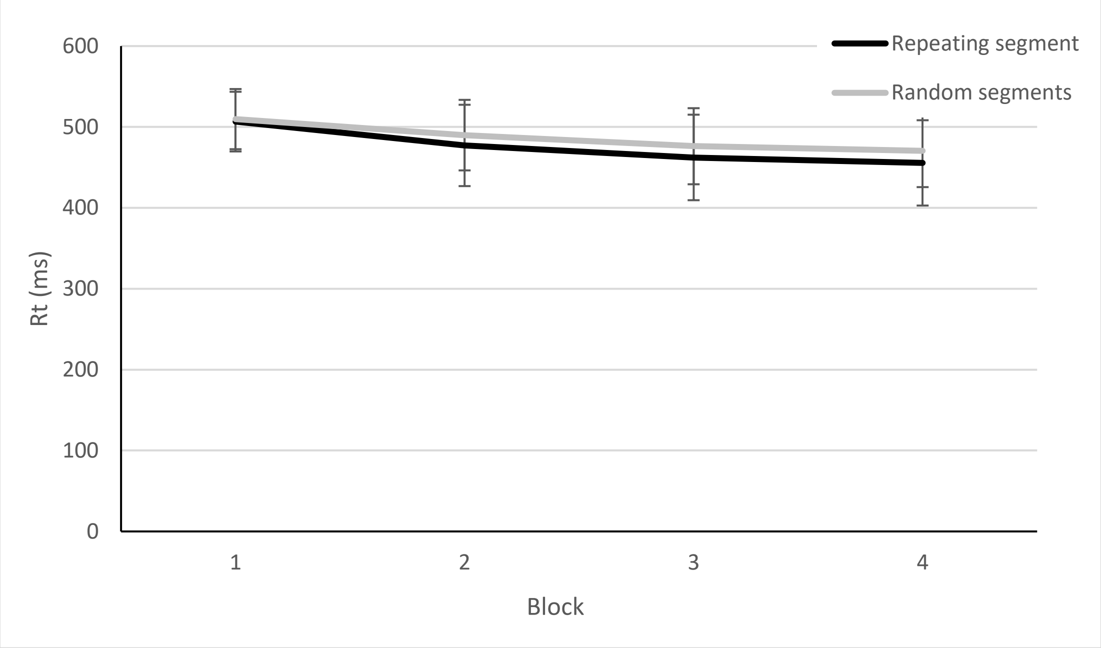

Figure 3. Reaction times (RTs) during the training blocks. Errors bars represent the standard deviation of the mean.

Test Block and Retention Test

The results of the ANOVA on RMSEs revealed a significant effect of Condition, $F(2, 64) = 120.71$, $p < .001$, $\eta_p^2 = .790$, with the best performance in the DT covariation condition, then the single task condition and worst performance on the DT without covariation condition, all $p < .001$, see Figure 4.

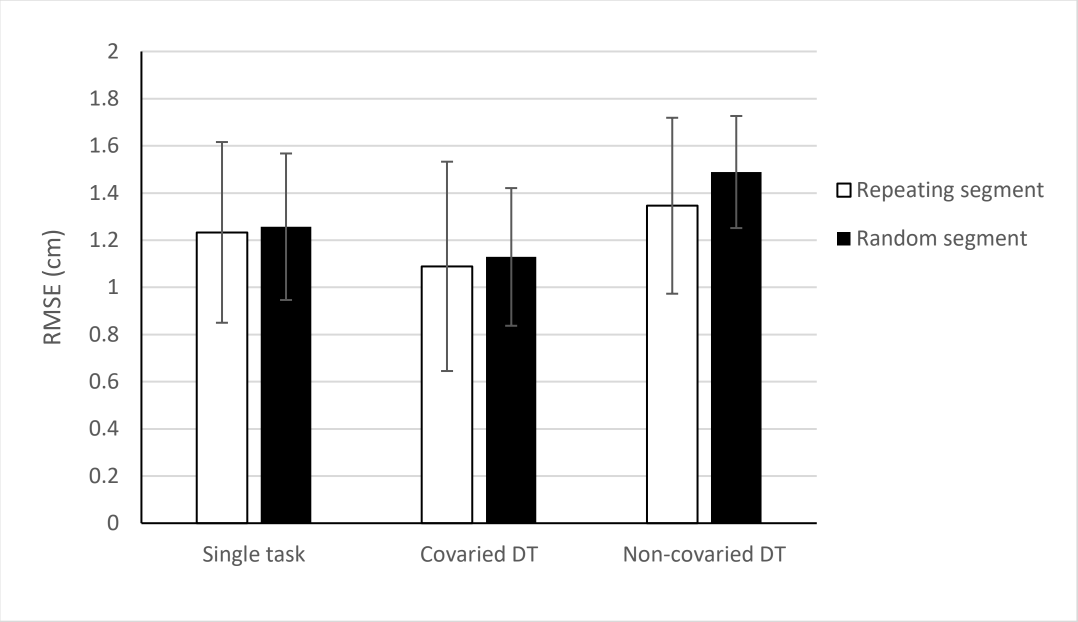

Figure 4. Tracking performance (RMSE) of the test block comparing single-task, covaried dual-task (DT) and non-covaried DT. Regardless of segment, performance on the covaried DT surpassed performance on the non-covaried and single-task trials. Performance on the repeated segment was significantly better in the non-covaried DT condition only. Error bars represent the standard deviation of the mean.

Tracking performance on repeating segments was better than on random segments, as indicated by a main effect of Segment, $F(1, 32) = 9.45$, $p = .004$, $\eta_p^2 = .228$. A significant Segment × Condition interaction, $F(1.60, 51.06) = 20.81$, $p < .001$, $\eta_p^2 = .394$, indicated that the difference in performance between the repeating and random segments was mainly found in the DT without covariation condition. Neither a difference between the test block and retention test was found, $F(1, 32) = 1.71$, $p = .201$, $\eta_p^2 = .051$, nor could we find a significant effect of Group, $F(1, 32) = .36$, $p = .553$, $\eta_p^2 = .11$ or Segment-Position, $F(2, 32) = .33$, $p = .721$, $\eta_p^2 = .020$.

For reaction times we found a significant effect of Condition, $F(2, 64) = 41.31$, $p < .001$, $\eta_p^2 = .564$. Post-hoc comparisons using the Bonferroni procedure revealed that best reaction time performance was found in the covaried DT, then the single task condition and worst performance in the non-covaried DT condition, all $p < .001$, see Figure 5.

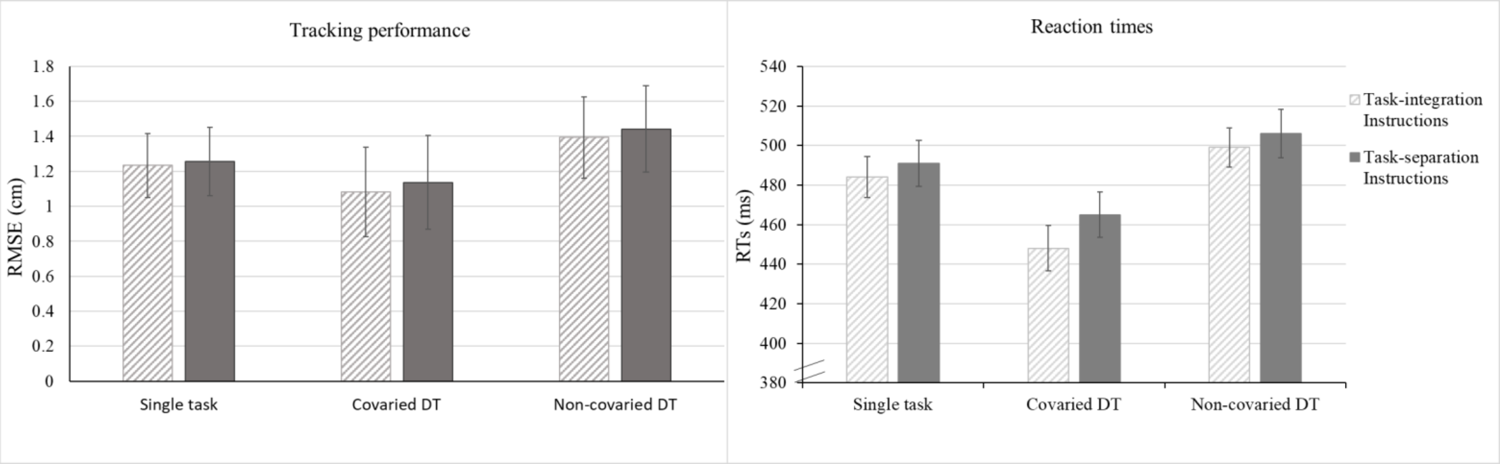

Figure 5. Tracking (RMSE) and reaction time (RT) performance during the test block. Best performance was found in the covaried DT condition. No effect of instruction was found. Error bars represent the standard deviation of the mean.

A significant effect of Test, $F(1, 32) = 10.74$, $p = .003$, $\eta_p^2 = .251$ indicated that reaction times improved from the test block ($M = 481$ ms, $SE = 59$ *ms*) to the retention test ($M = 471$ ms, $SE = 55$ *ms*). We found no effect of Group, $F(1, 32) = .30$, $p = .588$, $\eta_p^2 = .009$, so the task-integration and task-separation group did not differ significantly. A significant effect of Position, $F(2, 32) = 4.72$, $p = .016$, $\eta_p^2 = .228$, indicated that position of the repeating segment matters. Post-hoc paired comparisons with Bonferroni correction revealed that when the repeating segment was at the end, RTs were 46 ms faster than when it was in the middle, $p = .014$. Testing RT during repeating and random tracking we could not find a main effect of Segment, $F(1, 32) = 1.73$, $p = .197$, $\eta_p^2 = .051$, but there was a significant Segment × Condition effect, $F(1, 32) = 13.20$, $p = .001$, $\eta_p^2 = .292$, which indicated that in the covariation dual task, reactions were 16 ms faster during repeated tracking compared to random tracking, while in the non-covariation condition no difference between repeated and random tracking paths could be found.

Interviews

Analyses of the interviews showed that 8 participants had explicit knowledge of the repeating segment. Overall, when forced to make a choice, 63% of the participants correctly named the position of the repeating segment. Of the 20 participants in the task-separation group 14 nevertheless noticed this covariation. Perception of dual-tasking vs single-tasking did not differ between the groups, as frequency distributions to question 11, *'How strongly do you feel that you were doing one task or two tasks?'*, did not significantly differ between the task-integration (*mean rating = 3.7*) and the task-separation group (*mean rating = 3.6*), *U* = 188, *p* = .758, see Figure 6.

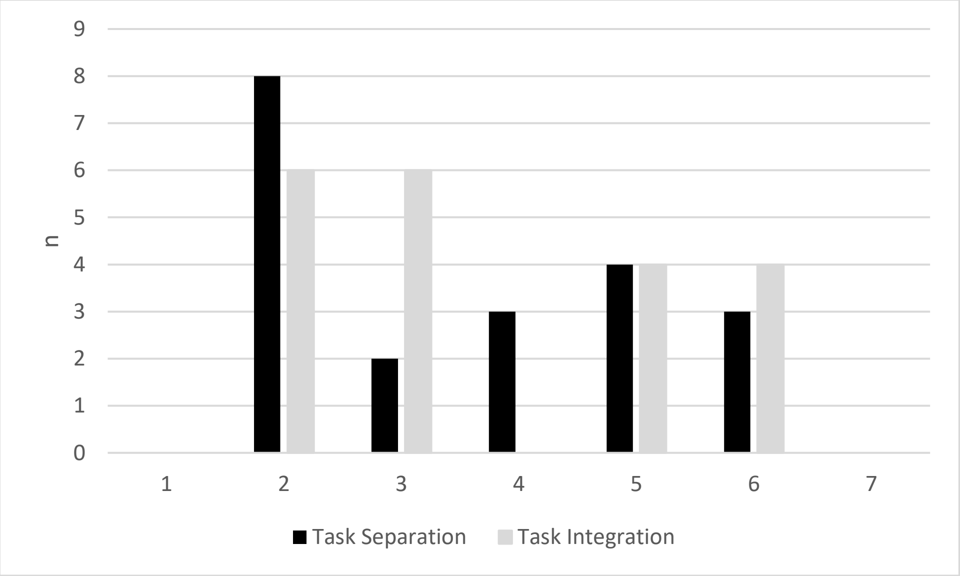

Figure 6. Frequency distributions per group (task integration vs task separation) of the ratings participants gave to the question 'How strongly do you feel that you were doing one task or two

tasks?’ With '1' indicating very strong feelings of single-tasking and '7' very strong feelings of dual-tasking.

Discussion

The goal of the current study was to investigate whether task integration likely resulting from covariation of the tasks improved multitasking, and whether it enables implicit learning in dual-tasking. Our results showed that covariation improves performance on both the tracking and the reaction time task. Performance in covaried dual-tasks was better than in non-covaried or single tasks. Since the tones announced the changes in the tracking curve, lower tracking errors might not be surprising, however, reaction times were also faster in the covaried dual-task condition, even though the tracking path did not predict the occurrence of sounds. Yet one might argue that whenever the target square approaches the edges of the screen the occurrence of a turning point and thus a target tone becomes more likely, so the boundaries of the monitor entailed some predictability in this regard. Better performance in tracking and reaction times indicate that participants likely integrated the two tasks, which is why we adhere to the position that task integration can be beneficial to dual-task performance and not necessarily costly. We were unable to demonstrate that this effect was stronger for the group receiving task-integrating instructions and feedback, so we suggest that the task-features were the main driver for task integration, rather than instructions or feedback.

Reaction times were more sensitive than RMSEs to the predictability in the tracking task during training (see Figure 1 and 2), demonstrating that the benefits of predictability within one task can transfer over to the other task when the tasks can be integrated. The current experiment confirms the conclusion by Röttger et al. (2017) that implicit sequence learning during dual-tasking can be preserved when tasks covary, showing this is also true for more complex motor tasks. The extent to which sequence knowledge was used seemed to differ for the different conditions, with the largest advantage of implicit knowledge shown in the most difficult condition, the dual-task without covariation, indicating that implicit information can be used flexibly, and is not necessarily tied to the conditions under which it was acquired. However, the opposite was found for reaction times, where participants benefited from the repeating segment only in the covarying dual-task, which was the easiest condition. Possibly this discrepancy is caused by a shift in priority to the tracking task in the most difficult condition (Broeker et al., 2018).

As in de Oliveira et al. (2017) we found better performance in the task-integration condition than in the single task condition. Better dual-task performance than single-task performance is otherwise rare, but has been found in highly automatized behaviors such as saccades during pointing movements (Huestegge & Koch, 2014) and expert performance in sports (Beilock et al., 2002). It is unlikely that the effects in our study are due to task automatization, since in that case performance on the non-covaried dual task would not differ much from the covaried dual-task, which it did. Instead when one task informs the other tasks, it becomes more predictable allowing for advanced motor planning.

Our study does not provide an explanation about how dual-task costs are reduced, but it contributes to the literature by showing that covariation is beneficial to first and secondary task performance. Whether a covariation manipulation removes dual-task effects or alters the tasks in different ways is difficult to determine, but it does at least show that the benefit from the predictability provided by the secondary task offsets any dual-task performance deficits caused by having to respond to a secondary task. One finding that speaks for the absence of dual-task performance deficits, and the realization of a fully integrated task, is that performance on the covaried task surpassed that of single task tracking. The structural similarity might have caused the two tasks to be processed as a single unit. Since dual-task costs are often explained in terms of tasks competing for limited resources or a bottleneck in processing, reducing a dual-task to an integrated single task would remove the theoretical limitation to dual-task performance. So far, however, the dual-task literature indicates that task-integration is only helpful when structural similarities exist. Learning is impaired when tasks do not covary, likely because there is no relation between successive elements (Schmidtke & Heuer, 1997). In the case of two unrelated tasks, the preservation of task boundaries is helpful, as shown by the effectiveness of instructions emphasizing *task-separation* in preserving implicit learning (Halvorson et al., 2013; Röttger et al., 2017).

We tested task-integration by instructions and type of feedback, and whether this would improve performance measures. The degree of task integration was not influenced by instructions or by feedback scores, in line with the finding that participants' perception of performing single vs dual tasks did not significantly differ between groups. This was surprising since the instructions were formulated to contrast each other as much as possible, and because similar instructions have been found to be effective before (Halvorson et al., 2013; Srna et al., 2018). Since the majority of the participants in the task-separation group discovered the covariation between the tasks, it is likely that task perception was influenced by the task features. Simply the fact that two different effectors and stimuli streams are used might make some people classify this situation as a dual-task, while others may be convinced through the covariation that it is more like a single-task. It is difficult to theoretically establish what constitutes a single task or a dual-task (Freedberg et al., 2014; Künzell et al., 2018; Rogers & Monsell, 1995), it may be even more difficult to induce a subjective experience of single-tasking or dual-tasking with covarying tasks.

Limits of our study and future research

The degree to which tasks are actually integrated is difficult to measure, performance measures alone are helpful but likely insufficient since dual-task training without covariation will also reduce dual-task costs. Interviews as in our study provide a performance-independent measure, but suffer from subjectivity and they do not consider that the way participants perceive tasks during performance might not be explicitly clear to participants themselves at the interview. A promising avenue for research would be to focus on the neural mechanisms behind dual-tasking. Studies have shown that different brain areas are active during dual-tasking and single-tasking (Garner & Dux, 2015; Watanabe & Funahashi, 2014). Garner and Dux (2015) found that training of non-covarying dual-tasks promotes a separated perception of the tasks in the brain, accompanied with performance improvements. Hypothetically long-term training of covarying tasks could lead to more integrated perceptions of tasks. This might answer the question whether task integration causes the formation of a single task (Künzell et al., 2018) or whether it allows for hyper efficient task scheduling (Salvucci & Taatgen, 2008).

While it seems tempting to assume that task integration is only possible or beneficial when certain features of tasks are covaried, it is not straightforward to determine where this covariation must come from. In the current study the covariation was quite obvious for most participants. Motor learning often involves integrating several sub components to work as a whole, but how exactly these components are integrated is not always obvious. Finding out how tasks may be combined to integrate them effectively and beneficially is a promising area of research (Franz et al., 2001; Klapp & Jagacinski, 2011; Swinnen & Wenderoth, 2004) and one with immense practical applications in our current world.

Conclusion

Data from the current study show that the perception of dual-tasking versus single-tasking with covarying tasks may be difficult to influence, but this perception may not matter for task performance. Nevertheless, because the type of covariation used was quite arbitrary, and will probably not be encountered with many real-world tasks, there is a possibility that manipulation of perceptions of less subtle covarying tasks may improve task performance. In a world where multitasking is unavoidable, providing a covariation between tasks and presenting them in a way in which that covariation can be fully exploited could significantly increase productivity.

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Conflict of interest: The authors declare that they have no conflict of interest.

Open practices: The experiment was not preregistered. Data and materials are available upon request.

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Article 4. What is a task? An ideomotor perspective

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Abstract

Although multitasking has been the subject of a large number of papers and experiments, the term task is still not well defined. In this opinion paper, we adopt the ideomotor perspective to define the term task and distinguish it from the terms goal and “action”. In our opinion, actions are movements executed by an actor to achieve a concrete goal. Concrete goals are represented as anticipated sensory consequences that are associated with an action in an ideomotor manner. Concrete goals are nested in a hierarchy of more and more abstract goals, which form the context of the corresponding action. Finally tasks are depersonalized goals, i.e., goals that should be achieved by someone. However tasks can be assigned to a specific person or group of persons, either by a third party or by the person or the group of persons themselves. By accepting this assignment the depersonalized task becomes a personal goal. In our opinion, research on multitasking needs to confine its scope to the analysis of concrete tasks, which result in concrete goals as anticipated sensory consequences of the corresponding action. We further argue that the distinction between dual- and single-tasking is dependent on the subjective conception of the task assignment, the goal representation and previous experience. Finally, we conclude that it is not the tasks, but the performing of the tasks, i.e. the actions that cause costs in multi-tasking experiments.

What is a task? – An ideomotor perspective

‘Task’ is an important concept in psychology and action science. However, despite a growing body of literature addressing opportunities and limits of human dual- or multi-tasking, the term task is still poorly defined. More than 20 years ago, Rogers and Monsell (1995, p. 208) acknowledged “that it is difficult to define with precision, even in the restricted context of discrete reaction tasks, what constitutes a ‘task’”. More recently, Schneider and Logan (2014) stated that this plea for a definition has largely been ignored since then. In the following, we argue that a definition of the term task is required to constrain the scope of multitasking research, to clarify how many tasks a person performs, and to broaden our understanding of interference between tasks.

In everyday language, tasks are usually understood as demands that are generally achievable by an action or a set of actions, e.g. bake a cake, be a good student, or switch on the light. However, the required actions may not be specified by the assignment of the task. Tasks may differ in their levels of abstractness and may consist of several less abstract subtasks, which can be completed sequentially or simultaneously (e.g. learning for the exam, attaining lessons, participating in an experiment, press a button).

Conversely, in cognitive science papers, “the term task can be basically understood as ‘what subjects have to do in an experiment’.” (Philipp & Koch, 2010, p. 383) or, in more formal terms, is defined as a “representation of the instructions required to achieve accurate performance of an activity” (Schneider & Logan, 2014, p. 29). Kiesel et al. state that “tasks entail performing some specified mental operation or action in response to stimulus input” (2010, p. 850). Yet, these statements are descriptions rather than definitions of a task, and do not help to differentiate distinct tasks.

The vague definition of the term task leads to serious ambiguities in the understanding of multitasking behavior and its cognitive underpinnings. To give an example, it remains unclear if bimanual coordination tasks like playing piano should be regarded as a single task (Monno et al., 2002; Wolff & Cohen, 1980), or if playing with the right hand and the left hand must be seen as two independent tasks and thus as a case of dual-task behavior (Franz et al., 2001; Swinnen & Wenderoth, 2004). According to the former assumption, professional pianists would simply accomplish a single task and there would be no reason to predict interference between actions of the left and the right hand at all. However, if the latter assumption holds, pianists would perform a dual-task but bypass interference or crosstalk. As a consequence, such dual-task skills would question theories postulating a bottleneck and arguing that tasks can only be processed sequentially (Pashler, 1994). Freedberg et al. (2014) argue that the distinction between single and dual task is not determined by objective criteria but rather “depends on how the participants conceive of their task” (2014, p. 1698). This view is supported by experiments of Dreisbach and coworkers (Dreisbach et al., 2007; Dreisbach & Haider, 2008, 2009), who observed that the way participants are instructed changes their perception about the task being a single or dual task. Recently, McIsaac et al. (2015) suggested a taxonomy of dual tasks. They propose that “dual tasking is the concurrent performance of two tasks that can be performed independently, measured separately and have distinct goals” (McIsaac et al., 2015, p. 2). However, in their concept it remains unclear which performance exactly is considered as a task and what “distinctiveness” means with respect to goals.

The goal of this paper is to bring more clarity to the blurred concept of a task. In agreement with McIsaac et al. (2015), we propose that a task relates to an action to be executed and a goal to be achieved. In our opinion, it is helpful to adopt an ideomotor perspective that takes the mutual relationship between actions and goals into account. The ideomotor perspective surely narrows the scope of our task definition, however it serves to explicate tacit assumptions. Moreover it will help scientists from other theoretical fields to sharpen their understanding of the term task by accepting or rejecting parts of our assumptions.

The ideomotor perspective

Every action, from complex action sequences studied in sports and exercise sciences to simple button pressing used in cognitive psychology, elicits perceptual consequences. According to the ideomotor principle (Herbart, 1825; see Hommel et al., 2001 for a more recent formulation; James, 1890) behavior is selected, initiated, and controlled by an anticipation of the sensory consequences that will follow from the respective action. The bidirectional associations between actions and their sensory consequences are acquired in two phases. In the first phase, associative links between cognitive representations of actions and effects are established. The associations are learned by producing movements, either randomly or reflexively, and observing the sensory consequences. Importantly, Elsner and Hommel (2004) revealed that this learning relies on predictability (i.e., contingency) and temporal proximity (i.e. contiguity).

In the second step, these associations are used to intentionally re-produce previously learned effects (Elsner & Hommel, 2001; Jordan & Rumelhart, 1992). Thus, the representation of the intended effects directly trigger the corresponding action pattern (for reviews, see Hommel, 2013; Shin et al., 2010) and this close link of mental representations of goals, associated motor patterns and actually perceived effects provides the basis of action control.

Unfortunately, the term goal is ill defined as well. The definition of ‘goal’ has to take different levels of abstractness into account (Hommel et al., 2016; Monsell, 2003). Abstract goals (like “be a good student”) can be achieved in multiple ways by a series of different actions, and the actual achievement of abstract goals may eventuate a considerable amount of time after the actions. Concrete goals (like “pressing a button as quickly as possible”) are achieved by ideomotor actions, whereas abstract goals will not be associated with sensory consequences and therefore will not lead to actions. Rather, “at best, they can be helpful when looking for a concrete, sensory action goal” (Hommel et al., 2016, p. 65). For example, the abstract task of being a good student will provide the basis for the compliance with a task, like pressing a button as quickly as possible (see Figure 1).

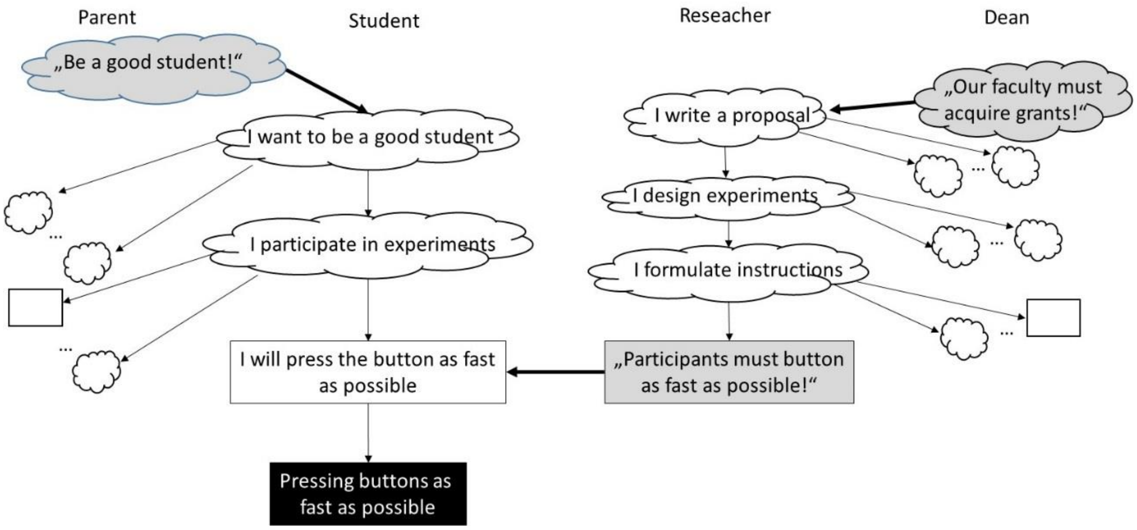

Figure 2: Hierarchy of tasks, goals, and actions. Tasks are marked with a grey background, goals with a white background and the action with a black background. In this example, the dean formulates the task to acquire grants. He or she assigns this task to the researcher. By accepting this assignment the task becomes the researcher’s personal goal. Abstract goals and tasks are in clouds, concrete goals and tasks in rectangles. The empty clouds and rectangles indicate that abstract goals could have several (concrete or abstract) subgoals. Bold arrows indicate the assignment of a task to a specific person. The abstract goals form the context of the concrete goal, in this case to comply with the researcher’s task assignment.

Our narrow definition of concrete goals overcomes the problem that different nested abstract goals like being a good student, smarming over the professor, and earning course credit can be achieved by just a single action – pressing a button. Although in this example three nested abstract goals are achieved (and therefore three nested abstract tasks are performed) through the same single action, this behavior would not be considered as multitasking.

Having defined actions and goals, we now turn to the definition of a task. Goals and tasks share central features, in that they represent future states that usually differ from the current state. Both, goals and tasks, can relate to relative abstract or concrete states. We suggest, that the difference between the two is that a goal is personal, meaning that it is bound to a specific person striving for this goal. On the contrary, a task is not bound to a specific person, because it describes “what has to be done” by any participant. However, the link between a task and a goal is that a task can be assigned by a third party (a single person, a group of persons or an institution to a person or a group of persons (Of course, it is possible to assign a task to oneself, too). It is then the duty of every single person to decide whether he or she accepts the task assignment. If he or she does, the depersonalized task becomes a personal goal of that specific person.

The abstractness of a goal and the associated sensory consequences may depend on the level of expertise and the amount of practice of action, however. This has direct implications for the conceptualization of a task. We tackle two questions, which need to be addressed when analyzing dual-tasking or multitasking behavior. a) What separates a task-driven motor behavior from behavior that would not be regarded as task-driven? b) When can behavior be considered as driven by a single task, and when do we speak of dual- or multi-tasking? In the following sections, we no longer focus on the difference between goal and task, but presuppose that a person, who was assigned a specific task, accepts this assignment as his or her personal goal.

A task or not a task?

As mentioned above, the abstractness and the representation of a goal may be dependent on the experience an individual has with the corresponding action. Learning research has shown that practice does not only improve performance on that activity, but that it can also lead to a qualitatively different mode of processing. This change in processing mode is commonly referred to as automatization.

Automatization is mostly regarded as a process that evolves continuously over time, without any discontinuities from a least automatic processing mode to a most automatic processing mode. Models and theories of automatization have been developed for different domains of activities. For motor activities, Fitts and Posner (1967) developed a three stage model of motor learning. In the cognitive phase, the learner has to identify the goals of the actions and develop strategies to reach these goals. In the associative phase, cognitive processes are not only focused on the control of the actuators, but movements are associated with situational constraints. In the automatic phase, the actor can achieve the action’s goals without conscious attentional processes being involved. Although Fitts and Posner define different stages, they conceptualize continuous transitions from stage to stage, rather than a clear-cut entry into a certain stage. For bimanual coordination tasks, Puttemans et al. (2005) showed significant changes in brain activation in the course of learning from the cognitive stage to an advanced level of automatization.

Similarly, Shiffrin and Schneider (1977) demonstrated a transition from conscious to automatic processing in the course of learning for perceptual tasks. For instance, they argued that children learning to read are required to process features, letters, words and their meaning but that parts of this learning process can be automatized, and so they concluded that conscious, or controlled, processing is limited but can be used for complex learning.

In the present article we aim at discussing whether, from an ideomotor perspective, the transition from a non-automatic to an automatic activity equals the transition from a task to a non-task. Ideomotor theory conceptualizes motor cognition as a combination of automatic and non-automatic subcomponents (Thomaschke et al., 2012a, 2012b). Non-automatic motor components are typically associated with action planning. That is, for example, deciding which hand to use, which object to grasp, which object to avoid. Action planning operates on largely categorical representations, is relatively slow, and is mostly accompanied by conscious awareness (Glover, 2004; Thomaschke, 2012). These non-automatic components are concerned with the selection of action options in an ideomotor fashion (i.e. based on their goals). For automatic action components, there are two different concepts of how automatization can be explained, the directions-of-processing approach and the levels-of-control approach (Neumann, 1984). According to the directions-of-processing approach, automatic processing meets three main criteria: it operates without capacity, it is not demanding attention, and – most important in the context of this article – it is driven by bottom up processes and not by intention (but see Neumann, 1984; W. Schneider & Shiffrin, 1977). The levels-of-control approach claims that action parameters are specified by three sources, skills, input information, and attentional processes. In the case of underspecification, skills and input information are lacking or not specific enough, so attentional processes are necessary to specify the action parameters. In the case of overspecification, input provides the information in several variants, e.g. multiple apples in a tree, each of which specifies the action of grasping (Neumann, 1989). Attentional processes are needed to specify the choice of the concrete goal. How these choice problems relate to multitasking is discussed in Broeker et al. (2018) in this issue. If skills and input information specify action parameters there is no need for attentional processes (Neumann, 1984, 1989). Action is then controlled by an automatic "subroutine", where the anticipated effects do not necessarily rise to awareness. Blakemore et al. (2002) presented an overview of empirical evidence in favor of the latter approach. They found that awareness of movement only happens when the discrepancy between intended and actual sensory consequences becomes large.

With respect to a task definition, the question of whether automatic activities are goal directed, i.e. controlled by anticipated sensory consequences, becomes important. The two concepts of automatization would offer different answers to this question. Within the direction-of-processing approach, automatic activities are not under intentional control. As a consequence they are not directed towards an intended goal, not controlled by sensory consequences and cannot be considered as driven by a task. Following the levels-of-control approach, automatic activities are goal-directed and thus must be seen as driven by a task. Blakemore et al. (2002) developed their approach to automatization from the theory of internal models, which is highly compatible with the ideomotor approach. Both approaches stress the importance of a goal as anticipated sensory consequences for controlling action, although ideomotor theory does not contain a forward signal. As such ideomotor theory is more focused on perception as controlling factor in action, whereas internal models emphasize motor control (Gentsch et al., 2016). Consequently, with the ideomotor perspective, we regard highly learned automatic activities as goal directed actions and thus as driven by a task.

One task or multiple tasks?

The human cognitive system is adept at integrating related information. The consideration of task integration is important when analyzing multitasking behavior because task integration could turn a seeming dual task into a single task. In implicit learning, in particular task integration, refers to the concept of an old evolutionary system that binds information that covaries in the world, which has often been demonstrated in serial-reaction time studies with a covarying secondary task (Keele et al., 2003b; Schmidtke & Heuer, 1997). The integration of related information, or features, broadly equaling the understanding of task-integration, can be explained through approaching its influencing top-down and bottom-up factors. While the top-down factors impose features on the task based on individual processing habits or preferences, bottom-up factors explain how participants extract relevant co-occurring features from a task.

If action is controlled by its sensory consequences then it is likely that the integration of related information also occurs on the level of these sensory consequences or effects. Introducing distal effects into the experimental setting allows for dissociating the action (e.g. “press button”) from the action’s goal (e.g. “switch on the light”). As Hommel (1993) nicely demonstrated, the introduction of a goal has serious consequences for action control and – in his experiment – inverts the Simon effect. In a striking experiment, Mechsner et al. (2001) had participants rotate two levers under a table. The lever’s rotation was transmitted to a rotation of flags visible above the table. For one lever, this transmission was done in a crooked ratio, e.g. 4:3. The participant’s goal was to produce an antiphase rotation of the two flags, which required a 4:3 ratio of lever rotations. This is strong evidence for information integration on the level of goals. Others also showed that even actions between two co-actors are coded in terms of one’s own effects (e.g. Pfister et al., 2013) or joint effects (e.g. Konvalinka et al., 2010). Hence, two tasks, which can be coded in terms of their (joint) sensory consequences, can potentially be integrated into a single task (for an overview, see Mechsner, 2004).

A further factor to be considered is combination specific learning. On the one hand, Hazeltine et al. (2002) demonstrated no impact of combination-specific learning when they presented to their participants stimuli for a visual-manual and an auditory-vocal task. Unlike most dual-task experiments, they did not use the same set of stimuli for training and test sessions, but introduced some stimulus combinations in the test session only. Beyond the expectation that dual-task costs would be reduced because of the learning of stimulus pairs, they found equally elaborate performance for unpracticed stimulus combinations compared to practiced combinations and concluded that combination specific learning and integration had not occurred. On the other hand a chord task experiment by Hazeltine et al. (2007) showed that a large portion of performance improvement could be explained by the learning of specific piano chords. In their task, participants pressed either 3 out of 5 piano-like keys with one hand for an individual chord, or 6 out of 10 piano-like keys (2 x 5) with both hands for a combined response. Results show that although both novel and practiced individually performed chords were similar in quality, slower performance for unpracticed chords occurred for combined responses, suggesting combination-specific learning for simultaneous task execution. The authors suggested that these contrasting results emerged from different use of modalities. Whereas the chord task required the same modalities, distinct modalities in the earlier study might have reduced the likelihood of forming associations between the two tasks. Also Hazeltine and collaborators (2007) hypothesized that the chord task, which in contrast to the earlier study forced participants to produce simultaneous responses, fostered an integrated representation and increased the likelihood of conceptualizing the experiment as one task. The significance of the diverging results is important for the aspect of “separating information” as highlighted above. If simultaneous, same-modality tasks lead to the integration of two tasks, then participants may either be unable to perform each task as a single-task after learning them as a dual-task or perform the secondary task comparatively deficient together with a different primary task (Wohldmann et al., 2010).

Another top-down factor is the type of practice. Several experiments found dual-task performance to be better compared to single-task performance when the dual-task had been trained as such. Performance on a time production task for example was better when simultaneously performed with an alphabet-counting task because participants felt the secondary task aided the primary task e.g. in an arbitrary rhythm (Healy et al., 2005). Researchers concluded that participants learned procedures that eased simultaneous performance and that primary and secondary task were treated as, and merged into, a fully integrated set of requirements of a single functional task (Waszak et al., 2003). As elaborated earlier, performance changes could be also attributed to automatization of one or both tasks. However Ruthruff et al. (2006) argued that automatization is distinct from task-integration. According to a task-integration hypothesis, dual-task practice would be more effective than single task practice and reduce or eliminate dual-task costs. An automatization hypothesis would predict successful dual-tasking independent of whether single or dual-task conditions have been practiced.

Additionally, instructions may lead to task integration. In a task switching experiment (Dreisbach et al., 2007), participants had to react to eight different stimuli (words) with the respective key press. Participants received different instructions, yet defining the same actions. One group had to perform eight tasks with each task corresponding to an S-R mapping. Another group received instructions that integrated four S-R mappings to one distinct task with respect to the word color, resulting in two different integrated tasks. Although in this experiment task integration was highly disadvantageous and led to significantly higher reaction times, participants were unable to separate the integrated tasks. In another experiment Dreisbach and Haider (2008) also analyzed switch costs and were able to prove that it was also possible to integrate all eight SR-mapping into one single task with the appropriate instructions.

In addition to top-down factors, there is some evidence about the influence of bottom-up factors on task-integration. One basic idea is that mechanisms of covariation or statistical learning allow the extraction of structure (Chun & Jiang, 1999; Turk-Browne et al., 2005) and that task integration will occur when covariations in one or more dimensions, such as time or space in the stimulus environment, exist (Heuer & Schmidtke, 1996; Reber, 1989; Schmidtke & Heuer, 1997).

To illustrate the idea of covariation learning of specific stimulus-response contingencies, consider a typical serial reaction time (SRT) task (Nissen & Bullemer, 1987). Participants typically exhibit faster reaction times (RTs) in blocks of trials that follow a specific sequence and prolonged RTs in blocks with random sequence. This difference is taken as an indicator of covariation learning. Taking this further, Schmidtke and Heuer (1997) combined this SRT with an auditory go/no go task that required a pedal press upon hearing high-pitched tones. Tones were either random, in 5-element or in a 6-element sequence. When tone sequences of six elements were combined with visual sequences of six elements participants were able to reduce reaction times and the mean number of attempts to learn the sequence. Schmidtke and Heuer (1997) argued that the additional tone-counting task could be integrated into the sequence of alternating repeated visual cues. In another paper, Heuer and Schmidtke (1996) already claimed that primary-task stimuli and secondary-task stimuli are not processed separately but as an "integrated sequence of alternating visual and auditory stimuli" (p. 132). It has further been argued that the integration of two simultaneously presented tasks is likely to occur when there is consistency in the task requirements (Wohldmann et al., 2010), when it is perceived as resource-saving or at least as reducing the number of action goals (Donk & Sanders, 1989; Lehle & Hübner, 2009) or when there is a large similarity between stimulus and response modalities and they are not perceived as distinct (Hazeltine et al., 2007). Theories of associative learning thus concluded that either the degree of similarity between individual stimuli properties or combined properties of stimuli define the strength of associations, and thus participants' representations of the tasks and the propensity to integrate them (Freedberg et al., 2014; Philipp & Koch, 2010).

Conclusion

We define a task as an abstract, depersonalized description of a future state. A task can be assigned to a person, and if that person accepts this assignment, it becomes their personal goal. According to the ideomotor perspective, concrete goals are coded as anticipated sensory consequences of the corresponding action, while abstract goals form the context that constrain the number of possible concrete goals. We confine our considerations regarding the definition a task to concrete goals. This restriction helps to clarify the scope of scientific investigations concerned with dual- or multitasking. Results obtained from concrete dual-task experiments, like button pressing and tone counting, may not transfer to abstract dual-tasks like being a good student and preparing for a lecture. With these specifications, we argue that actions that were automatized through extensive learning must be regarded as tasks, because they are initiated and controlled by intentional processes, albeit not necessarily associated with conscious awareness. Therefore, activities like walking or the control of posture must be treated as tasks. This is in line with the current opinion, where researchers use walking or postural control as one task in dual-task experiments (McIsaac & Benjapalakorn, 2015; Woollacott & Shumway-Cook, 2002; Yogev-Seligmann et al., 2008).

The conception of a task as one single integrated task or as two independent single tasks is highly dependent on top down processes and can be influenced by instructions or experience. There is experimental support that this integration occurs on the level of the sensory consequences of the respective actions (e.g. Mechsner et al., 2001). In addition, bottom-up processes serve to detect covariations in perception or action. Exploitation of these covariations also leads to task-integration (e.g. Schmidtke & Heuer, 1997). Consequently, it is not possible to define a distinction between dual- and single tasks independent of experience of the participants, presentation of the instructions or features of the situation. This subjective characteristic demands the analysis of participants’ behavior on an individual level. Caution is needed to avoid circular explanations of dual-task behavior: Dual-task costs should not serve to prove the processing of two single tasks and at the same time be used as dependent variable to measure dual-task costs.

Finally, we considered the difference between action and task. In our opinion, the main difference is the depersonalization of a task. A task can be undertaken by another person or can be delegated to another person. Moreover, a task can be assigned to a team or an institution. Additionally, a task is not necessarily associated with observable behavior. In contrast, an action is intrinsically tied to a specific actor, the person that is performing the task by achieving his or her goal, and always includes a motor behavior that can be observed. Therefore, there is no problem assigning multiple tasks to a participant - in an experiment or in real life. The problematic part is to achieve multiple goals and to execute multiple actions. Consequently, it is more appropriate to speak of “multi-action” instead of “multi-tasking”.

Compliance with Ethical Standards

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3. General Discussion

The main aim of these experiments was to investigate the effect of predictability on dual-task performance. Because of the way we operationalized predictability, namely prior knowledge acquired either explicitly or implicitly by practicing a repeating segment, we are also able to contribute to the ongoing debate regarding the relative benefits of explicit and implicit learning in motor learning science. The third issue we wanted to investigate was the relative effectiveness of single-task vs dual-task training, especially in relation to explicit and implicit learning. Before answering the research questions a summary of the results of the experiments may be helpful:

In Experiment 1 (ST training) we found that predictability in the CT-task indeed improvement performance, both in the ST-condition and the DT-condition, but no improvement in the RT-task was seen. We found little difference between the explicit and implicit group, except that the explicit group had a larger training effect over all four training blocks, which disappeared in the test block. This difference in the training phase was mainly seen in Block 1.

In Experiment 2 (DT-training) predictability only affected the CT-task, as in Experiment 1. Learning for the explicit and implicit group was only apparent on a retention test. Initially, in the test block, only the implicit group showed a learning effect, but on a retention test the explicit group also showed better learning of the repeated segment, beyond that of the implicit group, and better DT-performance overall.

Experiments 3 and 4 largely repeated experiments 1 and 2, but with predictability in both tasks. In Experiment 3 we tested if predictability in the RT-task improved CT-task performance, which it did not. In Experiment 4 we tested whether reducing possible prioritization effects and increasing interactions between task representations, through dual-task training, might achieve a bilateral effect of predictability. Again, results indicated predictability effects stayed within the task. No differences between explicit and implicit learning were found. No dual-task costs in the tracking task were found.

In Experiment 5 between-task predictability was investigated, which improved DT-performance in both tasks, even beyond ST-performance of either task.

Overall, the results indicate a beneficial effect of predictability in multitasking, but its role is limited, as only performance on the predictable task itself is improved. This is a robust finding, it's true for both the CT-task as well as the RT-task, after single-task training and dual-task training. What this means for the effect of predictability and multitasking theories is discussed in section 3.1. When tasks were "connected" by introducing between-task predictability, performance on both tasks improved. The effect of this task-integration seems extremely promising, Rebut more research is required, which is discussed ins section 3.5.

Regarding the explicit and implicit knowledge distinction the results are mixed and don't clearly point in one direction. There does not seem to be a strong reliable advantage of explicit or implicit learning. Some of the data indicate that explicit instructions may be beneficial in the long run, with increased performance compared to implicit instructions seen after a retention test, but as this was not replicated in the other 3 experiments this is not a reliable effect. Nevertheless, we could not find strong evidence that explicit knowledge hampers motor learning or motor performance under dual-task conditions either, which is found to be the case for several motor learning studies (Green & Flowers, 2003; Shadmehr et al., 1998). A more extensive discussion on explicit and implicit learning can be found below.

The literature indicates that in many laboratory tasks, like the SRT-task, implicit learning under dual-task conditions is reduced compared learning under single-task condition (Keele et al., 2003). Secondly, explicit learning might be largely blocked and therefore explicitly instructed participants largely learn implicitly under dual-task conditions. A short discussion of our results and the larger literature on single- vs dual-task training can be found in section 3.3.

3.1 Predictability and theory

In line with the expectations formulated in the introduction, regarding the pervasiveness of prediction in how we function and our tendency to seek more predictability (Eagleman et al., 2009; Friston, 2010; Hawkins et al., 2017), we found that predictability positively impacted dual-task performance. However, the unilaterality of this effect; meaning that predictability only affected the predictable tasks itself, also indicates that the beneficial effect of predictability may be limited. More evidence of this comes from a very similar research project, in which predictability in the CT-task was provided with visual information of the tracking path ahead (Broeker et al., 2021). In fact, only when we combined predictability provided by both knowledge and visual information, did we find evidence of predictability improving performance on both tasks (Broeker et al., 2020a).

Three possible reasons for the unilateral effect of predictability are discussed in the articles: a multiple resource account of dual-task performance, task-shielding and prioritization or other decision-making effects by the participants. The first possibility is that the tasks use different resource pools, and that saved up resources in one task cannot be transferred to a different resource pool, used by another task. This requires the assumption that the resource pool used for the CT-task and the RT-task do not overlap, which is not unreasonable. The CT-task was visual-manual, and the RT-task was auditory-pedal (operated by the foot). As such the data from these experiments could be taken as evidence for the existence of multiple resource pools. There is however one problem with this argument, which is that we still found dual-task costs in all four relevant experiments (in Experiment 3 and 4 dual-task costs were present in the RT-task, but not in the CT-task). So, explaining dual-task performance here fully with a multiple resource account is not correct, the data point towards the possibility that a certain central limitation also plays a role and/or crosstalk between for instance the hands and feet. Both the original author describing the general resource account (Kahneman, 1973), as well as the author of the multiple resource account (Wickens, 2008), do not deny multiple mechanisms are likely responsible for dual-tasking behavior. A fruitful enterprise might be finding out what the underlying properties of tasks are that determine how well they can be executed simultaneously, using principles from all multitasking theories (Salvucci & Taatgen, 2008).

Another mechanism that might be responsible for the unilateral effect of predictability is task-shielding. Task shielding is defined as a cognitive mechanism that protects processing of a prioritized task against interrupting influences of a distracting task (Dreisbach & Haider, 2008; Fischer et al., 2018). Potentially, even though it ensures minimal interference, task shielding might also prevent resources being shared between the tasks. The adoption of task shielding might therefore be non-adaptive for predictable tasks, instead in this situation a more relaxed task shielding could help a redistribution of resources (Fischer & Plessow, 2015). We argued that single-task training poorly prepares participants for the dual-task situation, and they reflexively adopt a processing mode with strong task shielding to deal with the unexpected interference in the dual-task block. Therefore dual-task training might have prepared participants better, while also allowing task representations to interact more with each other. Dual-task training is necessary for task integration, of the type described by Ruthruff et al. (2006), and might also allow for resources to be redistributed more evenly between the tasks. We found no evidence for this. Either task shielding is not the cause for the unilateral effect of predictability, or dual-task training is not effective in reducing task shielding. The argument can also be made that participants choose to shield tasks more because of dual-task training, in order to reduce interference.

The third possibility is that participants preferred not to redistribute resources to a different task, and that rendering a task predictable also has the effect of participants prioritizing that task (Broeker et al., 2018). Although in all experiments the participants were instructed to place equal priority on both tasks, this may be a difficult instruction to execute precisely. The continuous nature of the CT-task draws attention constantly, as it's at least partly based on online control. Therefore, the demand of equal prioritization may not be a realistic expectation, it cannot be achieved through instructions alone but also depends on task characteristics and individual differences.

If predicting and predictions are so fundamental to human behavior this has some far-reaching consequence how we fundamentally conceptualize human information processing. The standards information processing model is serial in nature, where perceptions lead to cognition (response selection) and then an overt motor response, in that order. The model you build of the world and the actions you take are a consequence of the stimuli you perceive. A predictive model is different in that a model perceives how you see the world and how you act in it, seeking predictability that ties your model with your perceptions (Hutchinson & Barrett, 2019). Errors in these predictions then update the model optimizing it for the future. The situation we investigated in the current thesis is where predictions are correct and presumably action happens without a response selection stage or direct parameter specification Neumann (1990). Neurophysiological studies have also called into question the serial nature of the classical perception-cognition-motor response model. Data from these studies indicate many potential actions are prepared in parallel continuously, and cognitive processes don’t need to precede action (Cisek & Kalaska, 2010). This phenomenon was already described in the 19th century by Münsterberg: "When we apperceive the stimulus, we have as a rule already started responding to it. Our motor apparatus does not wait for our conscious awareness, but does restlessly its duty, and our consciousness watches it and has no right to give it orders" (Münsterberg, 1889, p. 173: Neumann's translation) in Neumann (1990, p. 211).

Next, I would like to comment on the concept of automaticity. I state that automaticity might be the cause of the lack of dual-task costs in the CT-task in experiment 3 and 4. The problem with automaticity is that it is often the explanation for why dual-task costs disappear, while at the same time automaticity is indicated by the disappearance of dual-task costs. This casual invocation of the concept of automaticity is often seen in dual-task studies, and I am guilty of it as well. There are more sophisticated, non-circular definitions of automatization, however, and automatization may still be a useful concept. For instance see Saling and Phillips (2007), who define automaticity as an efficient, elegant and economical way of processing. Crucially, increased automaticity involves the shift in activation from more cortical pathways to subcortical pathways, which aligns with the hypothesis that automaticity in one task allows for the non-automatic processing of another task, enabling efficient dual tasking. An alternative explanation for lack of dual-task costs in the CT-task might be that it is a highly ideo-motor compatible task. The actions required to achieve optimal tracking are congruent, as an upward moving visual stimulus requires and upward movement of the hands, ideomotor tasks are know to suffer less from dual-task interference (Greenwald, 2003).

Multiple variants of ideomotor theory have been put forward. What ideomotor theory and all its variants, e.g. Mechsner (2004), have in common, is that a psychological phenomenon (e.g.

action effects) directly controls lower level motor behavior. This solves the problem of the seemingly infinite complexity involved in movement in terms of coordination of specific muscle fibers to achieve movement. Whether ideomotor theory genuinely solves this problem of complexity or simply ignores it, as our minds seem to do during the performance of these movements, is debatable. The theory is mainly the result of introspection by William James, who noted that motor processes are opaque to us, we can control them in a general sense by holding an idea of a motor movement, or its effects, in our minds. But the underlying physiological and neurological processes are impenetrable by consciousness, in the same way as digestive or body temperature regulation processes are. This is probably a good thing since the number of different combinations to achieve a certain movement towards a particular goal is nearly endless, termed the degrees of freedom problem by Bernstein (1967). Therefore, human motor control functions more like, to borrow a very illustrative example from Mechsner (2004), driving a modern car. A driver can control the steering wheel and the direction that the car will go, but the mechanisms that cause the movement of the wheels are outside of the driver’s control. In this illustration driver, steering wheel and the wheels connected to the steering wheel are analogous to the actor, the higher order (in Mechsner’s words: psychological) motor control and the lower-level processes needed for the actual execution of motor commands. These lower-level processes are governed by higher order control and opaque to the actor. When these higher order control processes can be combined to form a single “gestalt” (Klapp & Jagacinski, 2011), performance in dual-tasking is likely to be improved dramatically, which is discussed in section 3.4.

3.2 Explicit vs implicit learning

Overall, the data do not point clearly towards the advantage of one knowledge base over the other. This is in line with a meta-analysis by Kal et al. (2018), who found sparse evidence that implicitly instructed participants demonstrated higher performance levels in sports-related motor tasks. Their argument was that implicit learning should lead to more automaticity, and therefore increased performance under pressure compared to explicit learning. Arguably the motor tasks included in this meta-analysis are more complex than our tracking tasks but apart from that our experiments fit in well, as Kal and colleagues also used dual-task studies to test for the degree to which tasks were automatized. Nevertheless, is has also been shown that with expert athletes, reducing the extent to which explicit knowledge can be used increases task performance, caused by the so-called re-investment hypothesis (Beilock et al., 2002; Bellomo et al., 2018). If experts are so perturbed by explicit knowledge, why are novices not equally or even more perturbed? A possible explanation is that early on in training explicitly instructed novices learn to apply explicit knowledge effectively, but as knowledge become more implicit with further training this application of explicit knowledge become unnecessary and is phased out, resulting also in the forgetting of how to apply explicit knowledge.

The effect that explicit knowledge has on learning, how useful it is for learning in the first place, how much of the knowledge acquired is still explicit in nature, and how much is interferes with dual-task training and performance, might be dependent on how strong the motor component of a task is, as tasks with a stronger motor component tend to not find much benefit from explicit knowledge (Gabrieli, et al., 1993; Kal et al., 2018; Shadmehr et al., 1998), or even that explicit knowledge interferes (Green & Flowers, 2003). An exception to this is found in a study by Caljouw et al. (2016) in which it was found that younger adults are able to improve motor performance under dual-tasking conditions with the help of explicit instructions, but older people cannot. In the more discrete and arguably motorically simpler SRT-task explicit knowledge tends to lead to initial large benefits, although implicitly instructed participants do tend to catch up (Abrahamse, 2010; Keele et al., 2003). In sum, it seems that the benefit from explicit knowledge is dependent on how easily task relevant information can be stored symbolically, which is easy for the SRT-task (e.g., 4231214), but more difficult for the CT-task, and other motor focused tasks. Over time both implicitly and explicitly instructed people develop a largely implicit knowledge base, as stated by traditional theories of motor learning (Fitts & Posner, 1967; Kal et al., 2018).

An important question regarding learning in the tasks used in this study is what is actually learned, where does the performance improvement come from? There is an abundance of literature on what is learned during non-continuous tasks. It’s generally understood that associations between consecutive responses, stimuli and response effects can all be learned, with fast initial perceptual learning (associations between stimulus features), after which slower motor learning (associations between responses) becomes more dominant (Abrahamse et al., 2010; Abrahamse et al., 2013; Dennis et al., 2006; Willingham, 1999). Another potential mechanism for learning is the formation of chunks. A chunk is a unit formed by concatenating smaller element. Whereas at the beginning of learning information are regarded element by element, because of limits in attention, later on in learning these elements can combine to form chunks, which are treated as single elements (Abrahamse et al., 2013; Sakai et al., 2003). Chunking can play a role in memory tasks, such as remembering a phone number, and in motor production tasks, which have the additional costs of planning and optimally executing a sequence of physical movements (Ramkumar et al., 2016). In motor learning individual parts of a serial movement, like drinking a cup of tea, will become faster and more efficient. Movements also become smoother, in part because of more harmonious transitions between the individual movement elements, sometimes to the extent that the transition between two elements is no longer obvious: a new chunk has formed. Importantly, concatenation, the connecting of one chunk to another in a sequence, demonstrated by a slower reaction time to the first element of a new chunk, is not affected by an attention demanding secondary task (Abrahamse et al., 2013; Bor & Seth, 2012). Thus, it seems that the control processes involved concatenation do not draw on resources that would imperil dual-task performance, and may have played a significant role in the current dual-task experiments.

3.3 Single-task vs dual-task training

We could not discover a difference in dual-task performance after single-task training or dual-task training, not in the CT-task nor in the RT-task. The data on learning are in line with later studies in the SRT-task, showing that learning is possible but reduced in dual-task training compared to single-task training (Keele et al., 2003). Since this was true for both explicit and implicit learning under dual-task conditions, both types of instructions can be presumed to lead to largely implicit knowledge.

Dual-task interventions are often employed to improve gait and balance in elderly and populations with neurological disorders, and they are usually more effective than single-task interventions (Ghai et al., 2017). The rationale behind the dual-task interventions is that these populations try to control gait and balance consciously, by prefrontal networks, which leads to problems when these activities are combined with other tasks, which in the real world they usually are. Dual-task training is presumed to make these activities more automatic again by preventing cognitive reinvestment into functions that are better left to run automatically. These changes can be seen in the brain, with a shift from more cortical activity to more subcortical activity (Seidler et al., 2010). This may raise the question of why these interventions are so effective, since gait and balance are already usually combined with another task in real life, are we not always training a dual task? The answer is that elderly may not engage in dual tasking voluntary enough to achieve significant results, a certain difficulty of the dual task needs to be set before meaningful changes in performance can be achieved (Anguera et al., 2013; Gazzaley & Rosen, 2016).

3.4 Task integration

The results of Experiment 5 show that between-task predictability, presumably integrating the two tasks, massively improves dual-task performance of both tasks. However, the manipulation of correlating the tasks may raise the question whether we can still speak of two separate tasks. In article 4 we argue that whether something is a dual task or not is dependent of whether the two ‘tasks’ have a singular goal or action tied to them. And this section I would like to elaborate further on what task integration entails and how it might be achieved.

Some authors argue that task integration is the default mode of processing, and that whenever there is task integration of non-correlating tasks[4], task performance suffers (Halvorson et al., 2013; Halvorson & Hazeltine, 2019; Röttger et al., 2019; Röttger et al., 2021). Nevertheless, when tasks do correlate the performance benefits are undeniable (Broeker et al., 2021; de Oliveira et al., 2017). Then the question remains what the correlation might consist of. As our own studies and several SRT studies have shown is that between-task predictability, may cause beneficial task integration. In bimanual coordination studies, if we conceptualize the performance of each hand as a task, the relation can also focus on the conceptual similarity of the perceptual consequences produced by both hands (Franz et al., 2001; Mechsner et al., 2001). Altering the cognitive or perceptual organization of responses to reflect a single perceptual

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[4] Or tasks without between-task predictability, or a different form of perceptual relatedness.

‘gestalt’, or one coordinated pattern involving both hands, seems to be necessary for task integration in bimanual coordination tasks.

In the current study the covariation was obvious for most participants. Everyday motor learning also consists of integrating several subcomponents to work as a whole, but how exactly these components are combined is not always easy to see and therefore instruct. It may be that less obvious forms of covariation may be exploited, such as the start of a certain sub movement should occur when another sub movement reaches almost maximum velocity. The exploration and exploitation of these not so obvious and arbitrary covariations may well be an important component of motor learning in general and seems a promising goal for future studies.

3.5 Methodological Issues

Implicit learning in the CT-task is not uncontroversial, learning is not always found and sometimes ascribed to idiosyncrasies of the repeating segment rather than true learning (Chambaron et al., 2006; Lang et al., 2011; Lang et al., 2013). Segment specific learning in may be more difficult to demonstrate in the CT-task because learning occurs not only on repeating segments, but on the random segments as well, e.g. adapting to cursor speed, getting used to a relatively predictable number of curves and the steepness of curves (Neilson et al., 1993). This may cause a decrease in learning effect size of the repeating segment compared to other methods, such as the SRT-task.

A strength of the current thesis, however, is that the CT-task we used was improved upon compared to older paradigms and validated beforehand (Künzell et al., 2016). We used randomized repeating segments for each participants, took into account the time on task effect (Zhu et al., 2014), and randomized the placement of the repeating segment, so that increased performance on the repeating segments in the current study can only be plausibly ascribed to learning effects. A promising improvement that could be made nevertheless is the switch from the standard RMSE measure to more sensitive correlation based measures (Yang et al., 2017).

A methodological issue regarding explicit vs implicit knowledge experiments in general, is that while the systems and processes involved in explicit and implicit learning are separable, as evidenced by implicit learning remaining intact in amnesics and brain activity measurements (Cohen & Squire, 1980; Loonis et al., 2017), these systems might operate in parallel. Indeed, data show that during explicit learning significant implicit knowledge is acquired as well, with prolonged practice causing an ever increasing reliance on implicit knowledge and possibly even the forgetting of explicit knowledge (Beilock et al., 2002; Willingham & Goedert-Eschmann, 1999). A challenge to implicit and explicit learning studies is that virtually all processes investigated in psychology and movement science rely on both implicit and explicit knowledge. This is a problem because no known test is purely sensitive to either explicit knowledge or implicit knowledge, called the process purity problem (Curran, 2001). This affects our experiments in two ways. Firstly, we cannot be certain about the size of the implicit component in the knowledge of the explicit learning group. Secondly, assessing the prevalence of explicit knowledge in the implicit group with verbal questionnaires might not be ideal, as some explicit knowledge (especially in more motor focused tasks) might not be suitable to be expressed verbally (Johnson & Haggard, 2005). An improvement that can be made is to use an adaptation of the process dissociation procedure (Jacoby, 1991), a method originally used in language learning. This process means that participants first produce the trained segment, which measures both explicit and implicit knowledge. Then they produce a sequence with the instructions that they should specifically avoid the regular pattern of the trained segment, which should mostly result in explicit knowledge. While possibly an improvement, and interesting to test, some problems can be detected as well, for instance the instruction to “specifically avoid the regular pattern” is difficult to follow in a motor task compared to specifically not call out a specific word. Nevertheless the adoption of this method for future studies might be promising (Curran, 2001; Destrebecqz & Cleeremans, 2001).

We chose to use the more motor focused CT-task in our study to relate it more to activities such as driving and walking. This also has a downside however, since the RMSE measure summarizes performance over a longer period of time, whereas for instance PRP-designs zooms in on the locus of interference (Koch et al., 2018; Pashler & Johnston, 1989). Although we did not analyze this in our current studies, more fine-grained analyses are possible. For instance Netick and Klapp (1994) found hesitations in tracking, where tracking stopped, as a consequence of a distracting second task. They found that hesitations were less common after training, one of the reasons for this may be the encoding of motor responses in larger chunks. Larger chunks mean that more of the motor response is programmed per time unit, which should involve longer programming times and *more* opportunity for interference. However, larger chunks also mean longer intervals in which no interference can occur because during execution of a chunk there are no programming conflicts. Data suggest that programming time for chunks does not increase as quickly as the time length of the chunks themselves so that longer chunks reduce interference and hesitations in tracking (Klapp & Jagacinski, 2011; Netick & Klapp, 1994). Future studies could employ these methods to get a more detailed description of how interference occurs and how chunking might prevent this.

3.6 Future Studies

The most promising line of research in the quest to reduce dual-task performance decrements is investigations into task integration. If tasks can be combined in such a way that they can be conceptualized as a single task with a unified goal, large performance effects can be expected. Investigating how this task integration is presumably achieved in sports activities, such as running and controlling the ball, might open the door to improving many other dual-task situations.

The idea that predictability enhances automatic processing and causes a reduction in attentional requirements can be approached from the other side as well. Indeed, several authors have found evidence that unpredictable or uncertainty provoking stimuli and situations draw the attention of people, presumably because of the urge to explore uncertain situations in order to subsequently reduce this uncertainty (Berlyne, 1960; Feldman & Friston, 2010; Frings et al., 2019). Future investigations could investigate how these instructions might be protected against, for instance by testing the effect of, and building on, the concept of task shielding, which is a concept that is still defined too generally.

This is a problem with many of the concepts used to explain dual tasking. Dual-task research could greatly benefit from more directly measurable operationalizations of concepts such as (multiple) resources, bottlenecks, task-shielding, and task representations, for instance with brain imaging studies. Some work has been done already in this area, for instance Dux et al. (2006) demonstrated the location of a central processing bottleneck in a PRP design with FMRI (functional magnetic resonance imaging) and the separation of task representations of non-correlating tasks in the frontoparietal-subcortical system after dual-task training (Garner & Dux, 2015). Nevertheless, these practices are not common yet, and studies for instance demonstrating what happens in the brain when correlating tasks are integrated would elucidate how beneficial task integration might function.

A final suggestion for future research is a more detailed analysis of how predictability helps performance. For instance, what is the relative contribution of predictability to perceptual and motor process. Eye tracking could be employed to check if participants predict where the target is going to be, instead of tracking the target, or if the effect of predictability is mainly through priming of the motor system.

4. Conclusion

You almost never single task, in fact you almost never dual task, you are constantly bombarded with stimuli to engage with, and juggle multiple goals in your mind at any given moment, making dual tasking or even triple tasking the norm for many people (Gazzaley & Rosen, 2016). With the five experiments in thesis, we investigated the role of predictability in alleviating the performance costs that normally occur with such multitasking. By systematically introducing predictability in one task, the other task, or both tasks, we obtained reliable data that consistently showed that predictability improves dual-task performance, albeit only for the predictable task itself. The theoretical implications of this are not clear, multiple resource pools, task-shielding and prioritization effects due to the continuous nature of the tracking task are all possible explanations.

By also investigating the effects of explicit and implicit knowledge, single-task and dual-task training, and their interaction, the data from this thesis also tackles common issues in motor learning and attention research and could as such be a valuable contribution to researchers in these areas and physical educators interested in the practical application of motor learning training programs alike.

The largest effect of predictability on dual-task performance was found by creating between-task predictability. How realistic this mechanism is for improving most occurrences of everyday dual-task performance remains to be seen; there might be limitations because of its reliance on the relatedness of two tasks. Nevertheless, finding out the exact principles that suffice for the formation of an integrated “supertask”, with improved dual-task performance, seems a promising line of research.

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