MOTOR-COGNITIVE DUAL-TASK PERFORMANCE: A NEURO-COGNITIVE APPROACH INVESTIGATING AGE-RELATED DIFFERENCES BASED ON THE ‘THEORY OF VISUAL ATTENTION’

Dissertation
zur Erlangung des akademischen Grades

doctor rerum naturalium (Dr. rer. nat)

vorgelegt dem Rat der Medizinischen Fakultät
der Friedrich-Schiller-Universität Jena

von Erika C. S. Künstler
geboren am 06/04/1988 in Harare, Simbabwe

Gutachter:

1. PD Dr. Peter Bublak, Universitätsklinikum Jena
2. Prof. Dr. Stefan R. Schweinberger, Friedrich Schiller Universität, Jena
3. Prof. Dr. Torsten Schubert, Martin-Luther-Universität Halle-Wittenberg

Tag der öffentliche Verteidigung: 15/12/2020

Dissertation, Friedrich-Schiller-Universität Jena, 2020

1 Table of Contents

2 List of Abbreviations

ANOVA	Analysis of Variance
C	processing rate; a parameter estimated through the TVA-based Whole Report
CIE	Colour space model proposed by Commission Internationale de l'Elcairage
DFG SPP	Deutsche Forschungsgemeinschaft Schwerpunktprogramm
DT	Dual Task; a condition in which two tasks are carried out simultaneously
DTC	Dual Task Costs; performance decrements caused by dual tasking
ECTVA	Executive Control of the Theory of Visual Attention; proposed by Logan and Gordon (2001)
EHI	Edinburgh Handedness Inventory; a questionnaire used to determine handedness
IQ	Intelligence Quotient; an estimate of intelligence
K	size of VSTM storage capacity; a parameter estimated through the TVA-based Whole Report
M	Mean value
MWT-B	Mehrfachwahl-Wortschatz-Intelligenztest Teil B; a questionnaire used to estimate crystalised intelligence
PRP	Psychological Refractory Period; the duration for which response to the second stimulus is slowed by the processing of the first stimulus
SD	Standard Deviation
SOA	Stimulus Onset Asynchrony; the time difference between the presentation of the first stimulus and the second one
ST	Single Task; a condition in which only one task is carried out
TVA	Theory of Visual Attention; proposed by Bundesen (1990)
t0	Visual threshold; a parameter estimated through the TVA-based Whole Report
VSTM	Visual Short Term Memory

3 Zusammenfassung

Trotz seiner großen Bedeutung für den Alltag sind für das motorisch-kognitive Dual-Tasking - die Fähigkeit, eine kognitive und eine motorische Aufgabe gleichzeitig auszuführen - noch viele offene Fragen vorhanden. Zudem sind die bestehenden Erkenntnisse widersprüchlich, was zum Teil auf die Vielfalt der verwendeten Methoden zurückzuführen ist. Darüber hinaus sind die kognitiven Mechanismen, die diesen Fähigkeiten zugrunde liegen, noch nicht ausreichend verstanden. Dies gilt insbesondere für den altersbedingten Abbau der Dual-Tasking-Fähigkeiten, bei denen sich gezeigt hat, dass gerade die von visuellen Aufgaben verursachten Anforderungen besonders anspruchsvoll sind. Dies kann schwerwiegende Folgen für ältere Erwachsene haben. So ist dieser Abbau unter anderem mit einem höheren Sturzrisiko verbunden, was wiederum zu Krankenhausaufenthalten, eingeschränkter Mobilität und verminderter Lebensqualität führen kann. Ein besseres Verständnis für die vom Alterungsprozess betroffenen Dual-Task-Mechanismen könnte daher zur Entwicklung von Maßnahmen zur Verringerung des Sturzrisikos beitragen. Deshalb wurden im Rahmen dieser Arbeit zwei Studien durchgeführt. Studie 1 führte ein neuartiges Paradigma ein, um die motorisch-kognitive Dual-Task-Leistung objektiv zu messen, während Studie 2 dieses neue Paradigma nutzte, um die Auswirkungen des Alterungsprozesses auf die Dual-Tasking-Fähigkeiten zu untersuchen. Diese Studien basierten auf der „Theory of Visual Attention“ (TVA). Dieses mathematisch formalisierte Modell ermöglicht die parametrische Schätzung unterschiedlicher Aspekte der visuellen Aufmerksamkeitsleistung. Es stellt damit ein Mittel zur Verfügung, mit dem die für Dual-Task-Beschränkungen verantwortlichen Mechanismen bewertet und die Auswirkungen des Alterungsprozesses quantifiziert werden können.

In Studie 1 wurde eine auf der TVA basierende Ganzberichtsaufgabe mit einer repetitiven und kontinuierlichen motorischen Aufgabe kombiniert. Damit sollte zum einen geprüft werden, welche Aufmerksamkeitsparameter den Leistungsabfall beim Dual-Tasking reflektieren. Zum anderen sollte die Frage beantwortet werden, ob beide Aufgaben tatsächlich parallel oder eher seriell verarbeitet werden. Dieses Paradimga wurde mit 24 gesunde Erwachsene mittleren Alters getestet. Jede Aufgabe wurde separat als Single-Task-Bedingung sowie auch gleichzeitig als Dual-Task-Bedingung durchgeführt. Der Dual-Task-bedingter Abbau zeigte sich durch eine Verringerung der visuellen Verarbeitungsgeschwindigkeit und der Speicherkapazität des visuellen Kurzzeitgedächtnisses (VSTM). Die gleichzeitige motorische Aufgabe reduzierte also die visuelle Aufmerksamkeit und führte zu einer quantitativ weniger effizienten Verarbeitung der visuellen Informationen in der Dual-Task-Bedingung. Ergänzend wurden die Parameterschätzungen einer Bootstrapping-Prozedur unterzogen und die Güte der Modellanpassung berechnet. Darüber hinaus

zeigten sich keine Unterschiede in der Varianz der Parameterschätzungen oder in der Modellanpassung zwischen der Single-Task und der Dual-Task-Bedingung. Dies zeigte, dass es keinen Wechsel der Aufmerksamkeit zwischen den beiden Aufgaben gab. Die Aufmerksamkeitsressourcen wurden also auf beide Aufgaben gleichzeitig verteilt, was darauf hindeutet, dass die Aufgaben parallel ausgeführt wurden.

Dieses Paradigma wurde dann in Studie 2 verwendet, um den Einfluss des Alters auf die Dual-Tasking-Fähigkeit zu untersuchen. Es wurde erwartet, dass ältere Erwachsene im Vergleich zu jüngeren Erwachsenen einen stärkeren Leistungsabfall in der Dual-Task-Bedingung zeigen. Zudem wurde die Hypothese geprüft, ob sich ein ähnlicher Leistungsabfall auch bei jüngeren Probanden zeigt, wenn man die motorische Aufgabe für sie schwieriger macht. In Studie 2 haben daher 30 ältere Erwachsene und 30 jüngere Erwachsene das in Studie 1 dargestellte Paradigma abgeschlossen. Weitere 30 jüngere Erwachsene führten eine komplexere Version des Paradigmas durch, bei der die Aufgabenlast der motorischen Aufgabe durch eine Variation der Komplexität des Tappings erhöht wurde. Die Ergebnisse zeigten, dass ältere Erwachsene, sowie jüngere Erwachsene, welche die komplexere motorische Aufgabe durchführten, einer selektiven Verringerung der VSTM-Speicherkapazität im Dual-Tasking unterliegen. Jüngere Erwachsene, welche die einfache motorische Aufgabe durchführten, zeigten keinen solchen Effekt.

Zusammengefasst stützen die Studien das Modell einer parallelen Verteilung begrenzter Aufmerksamkeitskapazität auf eine visuelle und eine motorische Aufgabe. Sie zeigen, dass eine motorische Aufgabe dabei zentrale Aufmerksamkeitskapazität in Anspruch nimmt. Bei älteren Probanden ist dies bereits bei einer relativ einfachen motorischen Aufgabe der Fall, während jüngere Probanden erst bei einer komplexeren motorischen Anforderung dieser Einschränkung unterliegen. In beiden Fällen erweist sich der visuelle Kurzzeitspeicher als entscheidender Mechanismus für das Ausmaß, in dem eine motorische und eine visuelle Aufgabe unabhängig voneinander, oder aber nur miteinander interferierend ausgeübt werden können. Diese zentrale Kapazität wird durch ein höheres Alter wie durch die motorische Anforderung bei jüngeren Erwachsenen qualitativ ähnlich negativ beeinflusst. Diese Ergebnisse geben Aufschluss über mögliche Wege, die motorisch-kognitive Dual-Tasking-Fähigkeit durch geeignete Interventionen zu verbessern, was perspektivisch das Sturzrisiko bei älteren Menschen verringern könnte.

4 Abstract

Although an inherent part of everyday life, motor-cognitive dual-tasking - the ability to perform a cognitive and motor task simultaneously - still has many open questions. These are further compounded by contradictions in existing findings, partly caused by the diversity of tasks used. Moreover, the mechanisms underlying these abilities are not well understood, and terms such as “attention” are often nebulous, with no clear distinction of the various attentional sub-processes. This is especially true of the age-related decline in dual-tasking abilities, in which the visual task demands have been shown to become increasingly exigent. This can have serious consequences for elderly adults, with the decline being linked to a higher risk of falls, which in turn can lead to hospital stays, decreased mobility, and decreased quality of life. A clearer understanding of the dual-tasking mechanisms affected by the aging process could therefore lead to the design of interventions aimed at reducing the risk of falls. Thus, to address these shortcomings, I conducted two studies, both presented in this dissertation. Study 1 introduced a novel paradigm to objectively measure motor-cognitive dual-task performance, whilst Study 2 used this new paradigm to investigate the impact of the aging process and of the cognitive load of a task on dual-tasking abilities. These studies were based on the Theory of Visual Attention (TVA). This mathematically formulated model allows parametric estimation of different aspects of attentional performance, thereby providing the means through which the mechanisms responsible for dual-task constraints can be assessed, and thus enabling the effects of the aging process to be quantified.

Study 1 aimed to create a novel paradigm that could test whether tasks are processed in a parallel or serial manner, and to see which attentional parameters would show a dual-task effect. Potential model violations of TVA were assessed, and it was hypothesised that high variance in the attentional data would be indicative of attentional switching between the two tasks, whilst low variance would support a parallel task processing view. To test these hypotheses, an original motor-cognitive dual-task paradigm was developed by combining the TVA-based whole report task with a simple, continuous, and repetitive motor task, thereby allowing attentional parameters and motor performance to be distinctly assessed. Each task was carried out separately as single-task conditions, and both tasks were also conducted simultaneously in the dual-task condition, with the paradigm being tested on 24 healthy middle-aged adults. Additionally, bootstrapped estimates and goodness-of-fit values were calculated to assess variance in attentional performance between the single-task and dual-task conditions, in order to see whether the performance of tasks was conducted in a continuous or discontinuous manner. Study 1 demonstrated that the visual processing rate and visual short-term memory (VSTM) storage capacity showed a dual-task-related

decline in middle-aged adults. Thus, during dual-tasking, the concurrent motor task reduced visual attentional capacity, leading to quantitatively less efficient processing of visual information. Moreover, bootstrapped data showed no difference in variance between conditions, indicating that there was no switching of attention between the two tasks. In other words, attentional resources were shared across both tasks simultaneously, indicating that the tasks were performed in parallel.

Having shown that this paradigm could distinctly measure dual-task performance, it was then used in Study 2 to test the hypotheses that older adults would have a lower performance in the dual-task condition relative to the younger adults, and that by manipulating the difficulty of the motor task - and therefore the task's cognitive load – even younger adults would show reduced dual-task performance. In Study 2, 30 older adults and 30 younger adults completed the paradigm outlined in Study 1. A further 30 younger adults performed a more complex version of the paradigm, in which the task load of the motor task had been increased by varying the complexity of the motor task. The results indicated that older adults performing the simple motor task, as well as younger adults performing the complex motor task, showed a selective decline in VSTM storage capacity in the dual-task condition, whilst younger adults performing the simple motor task displayed no such decrements. Thus, younger adults performing a more complex motor task showed reduced performance in a manner that was qualitatively similar to the decrement in older adults performing a less complex task.

Taken together, the studies show that even a relatively simple motor task utilises a central attentional capacity, suggesting that motor-cognitive dual-tasking is conducted in a capacity sharing manner. Furthermore, the VSTM appears to be the constraining mechanism which underlies dual-tasking ability, and it is this central capacity which is negatively impacted in a qualitatively similar manner by both increased age in older adults, as well as by the task load in younger adults. These findings provide insights into potential avenues for future interventions aimed at reducing the risk of falls in the elderly.

5 Introduction

To begin with, the context of the research will be presented, before looking at the overarching background of the studies - namely dual-task performance and how this is affected by the aging process - will be examined. Following this, outstanding questions and difficulties within the field of dual-tasking research will be explored, before expounding upon how these can be addressed through the use of the Theory of Visual Attention.

5.1 Context of the research

The two studies presented in this dissertation were conducted as part of the interdisciplinary DFG Priority Program (Schwerpunktprogramm) SPP 1772, "Human performance under multiple cognitive task requirements: From basic mechanisms to optimized task scheduling". This Priority Program is aimed at establishing a new integrative theoretical framework which is able to elucidate different aspects of human multi-tasking behaviour. To that end, a project entitled "Motor-cognitive dual-task performance: A neuro-cognitive approach investigating age-related differences based on the 'theory of visual attention' (TVA)" was created at the Jena University Hospital, with the aim of establishing a new dual-tasking paradigm based on TVA. This paradigm needed to not only take into consideration the existing difficulties in the field of motor-cognitive dual-tasking, but to also be able to explore the age-related decline in dual-tasking, going as far as to elucidate the mechanisms underlying this process. My Ph.D. position was created to investigate motor-cognitive dual-tasking from a cognitive and psychological standpoint, whilst a further Ph.D. position was established to address the questions from a neuroimaging perspective. This dissertation shall therefore focus on the two studies which were conducted to address open questions within the field of motor-cognitive dual-tasking. Study 1 tested the feasibility of a new paradigm, and once it was shown that this new dual-tasking paradigm is not only able to give clear and independent estimates of dual-task costs, but is also able to answer questions about the processing order of the two tasks, Study 2 was then carried out. This study was aimed at assessing the impact of age on dual-tasking abilities. Furthermore, by altering the complexity of the second task, it was also possible to check what effect the cognitive load of a task has on attentional processing.

5.2 Dual-tasking

Dual-tasking, namely the ability to carry out two tasks at the same time, is one of the fundamental aspects of modern everyday life. However, dual-tasking often leads to performance decrements (for example in the speed or accuracy) in either one or both of the tasks, a phenomenon known as dual-task interference or dual-task costs (for a review on multi-tasking see Fischer & Plessow, 2015). One of the most common forms of dual-tasking is the motor-cognitive dual-task, in which an individual must concurrently carry out a motor process whilst simultaneously performing a cognitive task (Al-Yahya et al., 2015), such as walking to a parking lot whilst also recalling where they parked their car, or paying attention to a conversation with someone whilst driving a car. However, despite the amount of research which has been done in the field of motor-cognitive dual-tasking, there are still many difficulties that have not yet been overcome, and several open questions which have yet to be answered, particularly with regards to how dual-tasking performance is affected by the aging process, and which mechanisms underlie the age-related decline in dual-task performance.

5.3 The impact of aging in dual-tasking

As a person ages, declines in motor and cognitive functions are common (Lindenberger, 2014), and this in turn can have repercussions on how well dual-tasking can be performed, with a multitude of studies reporting higher dual-task costs in older adults (for example Verhaeghen, 2015; Ruthruff & Lien, 2017). This can have serious ramifications for this age group, as this increase in dual-task costs is associated with an increased likelihood of falls in elderly populations, which can possibly impact the degree of everyday activity and overall independence, and can even lead to an increased mortality rate (Hawkes et al., 2012).

However, despite the importance of this subject, there is still much disagreement on how or why there are higher dual-task costs with increasing age. Some cognitive theories for example propose that the increased costs can be accounted for by general cognitive slowing, which would exacerbate the task demands (for example see Salthouse, 1996). However, such single factor theories cannot fully explain why dual-task costs are also affected by other factors, such as task order, or the cognitive load of the task. Another potential reason why dual-tasking costs are higher in this age group is that older adults have increased difficulty in automatising tasks (Maquestiaux et al., 2013). According to this viewpoint, older adults would require more attention to complete the two simultaneous tasks than younger adults would, as older adults would be less able to automatise the motor task, and therefore would need to dedicate more attentional resources to the additional motor task compared to the younger adults (Leone et al., 2017). As this additional motor task would require more attentional resources, there would be less resources available for Task 1, leading to higher dual-task costs for the two tasks. In other words, the attentional capacity would need to be shared by both tasks, thereby making the processing of both tasks in parallel less efficient than if the tasks were to be processed separately and in a serial manner.

Nevertheless, whilst there are multiple studies which corroborate this theoretical standpoint by showing that older adults require increased attentional resources when engaging in dual-tasking (see for example Broyd et al., 2009; Boisgontier et al., 2013; Leone et al., 2017), the precise attentional mechanisms are not entirely understood. This again highlights the need for a paradigm that can address questions regarding how attentional processes in dual-tasking are affected by age. Moreover, this must be done in a way that allows the motoric and cognitive age-related declines (Lindenberger, 2014) to be accounted for separately as well as overall.

5.4 Difficulties in dual-tasking research

Despite the multitude of studies on dual-tasking, there still remain several difficulties which need to be addressed, especially when viewing attention as the resource limitation which underlies dual-tasking costs. These shall be elucidated below.

5.4.1 Lack of differentiation of the term "attention"

It is generally accepted that attention, which is seen to be an essential cognitive resource or capacity, plays a key role in dual-tasking, and must be shared between the two tasks in order for performance of both tasks to be successful. Indeed, changes in attentional demands can be closely linked to some symptoms seen in patients. For example in several neurological disorders, movements become less automatised, meaning that greater amounts of attention are required to perform these movements (Fritz, Cheek, & Nichols-Larsen, 2015). This in turn means that in dual-tasking situations, there are greater demands on the limited capacity attentional resources, leading to increased dual-tasking costs. This in turn can have serious repercussions, such as for example an increased risk of falls.

Despite the importance of attentional processes to everyday functioning, one of the biggest drawbacks when looking at studies that examine attention in dual-tasking situations is that "attention" or "attentional resources" are typically used as an umbrella term, and are regarded as one single process. In reality, there are several sub-processes which underlie attention (for a comprehensive overview, see Pashler et al., 2001). Furthermore, the setup of many motor-cognitive dual-tasking experiments involve making similar motor responses to both the attentional and motor tasks, which can result in interference effects during the cognitive task (Verstraeten et al., 2016).

The presence of such confounds make disentangling the role of attention in motor-cognitive dual-tasking even more difficult.

Thus, a motor-cognitive dual-tasking paradigm ought to be able to clearly quantify attentional sub-processes separate from the motor task. Furthermore, this should be done in a manner that does not create motoric confounds in the responses made to each of the two tasks.

5.4.2 Parallel versus serial processing

In the dual-tasking literature, there is a pervasive disagreement on whether both tasks are conducted in a parallel or in a serial fashion. One prominent theory is the resource sharing account (see Tombu & Jolicoeur, 2004 for an overview), which posits that both tasks are executed in a parallel manner, but that there is an inherent limitation in the amount of processing capacity available for these tasks. Therefore, the limited attentional resources must be divided between Task 1 and Task 2. Depending on the difficulty of the tasks, as well as on the extent of an individual's available attentional resources, the two tasks are typically processed with less efficiency than if they had been completed one at a time, as the processing resources are shared between the two tasks. Thus, the dual-task costs arise from the decreased efficiency with which each of the two tasks are processed.

A different, albeit related, framework that has been proposed is the central capacity sharing model (see for example Navon & Miller, 2002; Tombu & Jolicoeur, 2004), which proposes that resources are only shared during the central processing stage. During other task stages, such as perception and motor response, both tasks can be processed in parallel. However, at the central response selection stage, tasks get processed successively in a serial fashion. This model postulates that this is due to a structural bottleneck, which can only process one task at a time. In other words, attention would be first be allocated to Task 1, before being switched to Task 2, then back to Task 1, and so on. This is a phenomenon known as attention switching.

As the overarching aim of my work is to gain an understanding of what mechanisms are affected by motor-cognitive dual-tasking - particularly in the context of aging -, any new paradigm created would need to be able to look at the precise mechanisms which underlie the dual-tasking processes, and thus be able to answer questions about whether tasks are processed in parallel or in a serial manner. Therefore, through the use of such a paradigm, it must be possible to assess dual-task performance from the bottom up - not just from a basic perceptual level, but also to a higher cognitive level. Only once such mechanisms are understood would it be feasible to design interventions, for example aimed at reducing the likelihood of falls in elderly adults.

5.4.3 Lack of objective and sensitive measures

A further difficulty in dual-tasking research is the inconsistencies in the observed results, which are most likely caused by the diversity of the tasks used to assess motor-cognitive dual-task performance. A recent review (see Verstraeten et al., 2016) stated that the more specific and objective the instrument used to assess these abilities was, the better the instrument was at evincing the correlation between motor and cognitive functions in dual-task situations.

This highlights the need for an objective measure which can be used not only to validate previous results, but also to set a foundation on which further studies can be based. Furthermore, this paradigm would ideally need to be simple enough so that it could be applied to a variety of participant cohorts, such as younger and older healthy adults, as well as in adults with brain damage or other disorders or illnesses. Additionally, the paradigm must also be sensitive enough to be able to quantify the degree of dual-task costs experienced by such a wide spectrum of participants.

5.5 The Theory of Visual Attention

These issues were addressed by combining the whole-report task based on the Theory of Visual Attention (TVA; Bundesen, 1990, see also Bundesen, Vangkilde, & Petersen, 2015) with a simple tapping task. TVA was chosen in this case as years of research have shown it to be well suited to assessing the efficiency of visual information uptake through the use of a simple, psychophysical whole report task, making it a strong foundation on which to build a new dual-tasking paradigm. Through its mathematical formulation, TVA can provide independent estimates of several important parameters of visual attention capacity using an exponential growth function to model observed data on the individual level. Moreover, by combining the TVA task with a concurrent motor task, it is possible to see how these attentional parameters are affected through motor-cognitive dual-tasking. The theory is strongly related to the biased competition account of attentional performance (Desimone & Duncan, 1995), and assumes that when a stimulus is displayed, it is processed in two distinct stages. First, visual input is matched to existing long-term memory representations, and is provided with evidence values that depend on the strength of the memory representations of that element. Based on this, an attentional weighting (*w*) is given to each element based on the strength of the evidence values obtained. In the second wave, each element races to enter the limited visual short-term memory (VSTM) capacity, with the selection process terminating once the VSTM is full

(Bundesen, 1990; Bundesen, Vangkilde, & Petersen, 2015). In other words, the elements which received higher weighting based on the first wave of processing are able to race with a faster speed, and therefore have a higher chance of being encoded into the VSTM. This process is depicted in Figure 1 below. As can be seen from this figure, the elements X, U, and S receive the highest attentional weighting, allowing these elements to complete the processing race the fastest, and therefore get encoded into the limited capacity of the VSTM.

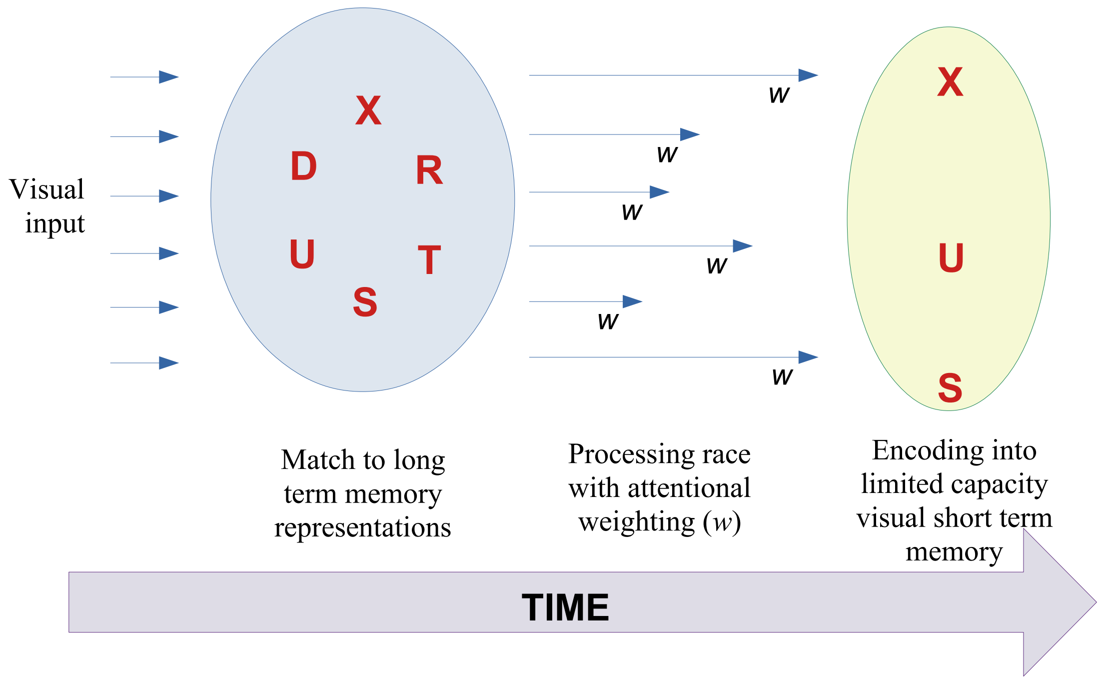


Figure 1: The biased competition account of attentional performance

Typically, the VSTM capacity is around three to four elements in young, healthy participants, and only stimuli that are held in the VSTM store are then available for further cognitive processing, such as a reporting of the letters seen (Luck & Vogel, 1997). Thus, attention is regarded as a limited resource which can be distributed in parallel across multiple stimuli within a visual task: when multiple items are presented, their selection is dependent on how large the VSTM capacity is.

Using the simple psychophysical TVA-based whole report task, multiple visual attentional parameters can be inferred within a single assessment in which participants verbally report as many target letters as they are able to from target arrays, with the reported letters then being recorded by the experimentor (Finke et al., 2005). Using the accuracy rates of the reported letters, one can estimate the probability of letter identification using an exponential growth function, which in turn yields parameter estimates of different aspects of processing capacity, representing the efficiency of visual information uptake (Bundesen, 1990). These parameters include the visual threshold, *t0*, which is the point in time at which a participant starts to consciously process visual stimuli; the processing speed, *C*, which is the number of visual stimuli across a target array which can be processed per second; and parameter *K*, which is indicative of the size of a participant's VSTM storage capacity, and which is formally defined as the highest number of objects which can be maintained in parallel by a participant's VSTM (Bundesen, 1990). These parameters reflect origin, slope, and asymptote, respectively, of the exponential growth function by which the individual whole report performance is modelled (see Kyllingsbæk, 2006; Habekost, 2015, for a tutorial overview). Below is one such exponential growth function showing the modeled attentional parameters for a young healthy participant taken from Study 2:

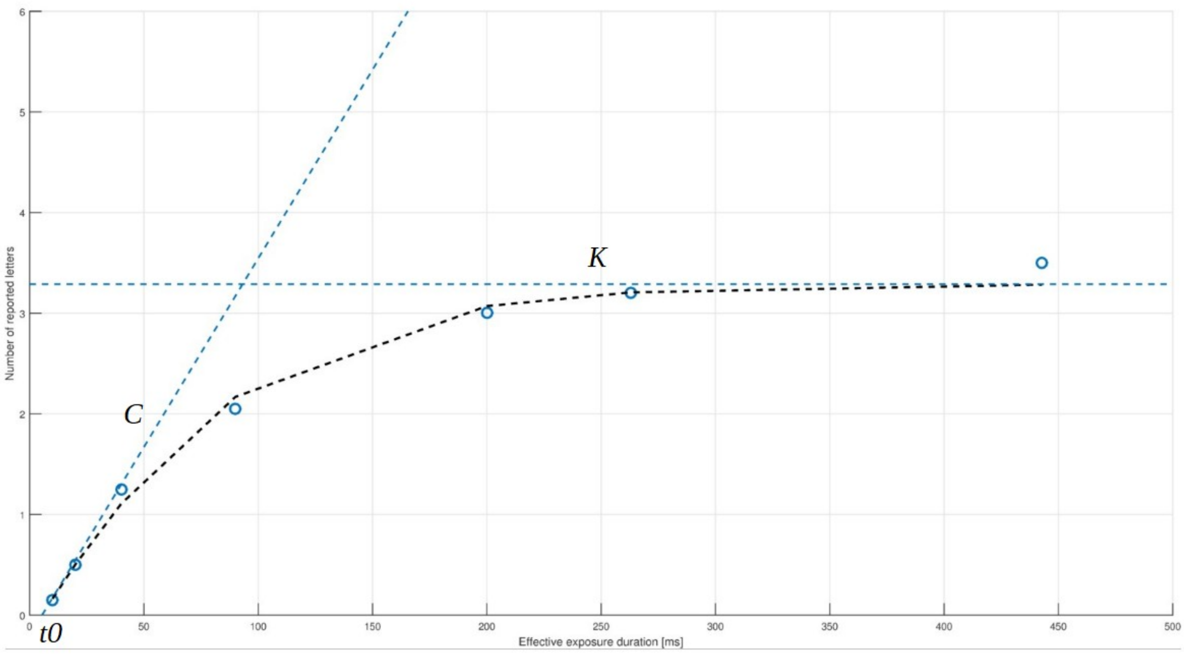


Figure 2: Example of modelled TVA parameters

In Figure 2, on the x axis shows the effective exposure duration is in milliseconds whilst the y axis depicts the number of reported letters. The blue circles represent actual data points, whilst the dotted black line shows the modelled data. As can be seen, there is a high degree of overlap between the observed and the modelled data, indicating high goodness-of-fit. In this particular example, the goodness-of-fit was over 96%, meaning that less than 4% of the observed data was not explainable through the TVA model. The time-point at which information starts to enter the visual system is the visual threshold *t0,* which in this case is at around 11ms. The steepness of the slope of the growth function yields the *C* parameter, the processing speed. In the example in Figure 2, the processing speed is approximately 36, indicating that this participant can process around 36 stimuli per second.

The asymptote of the growth function represents the *K* parameter, or the size of the VSTM storage capacity, and in this case lies just over 3, illustrating that this participant is on average able to hold approximately three elements in their VSTM.

Not only does the TVA paradigm provide a way of addressing the short-comings in dual-tasking research that were previously discussed in this chapter, but TVA can also be used to gain information about the processing efficiency of visual information in a way that does not require any motor components. This makes it possible to clearly separate the effect of a concurrent motor task on visual attentional parameters without having any motor confounds. A further point which makes this theory an attractive solution for approaching dual-tasking research is the unifying aspect of the theory. Whilst TVA is most often used in human experimental psychological research, there have also been findings based not only on neuroimaging data, but also on single-cell recordings in primates (Bundesen et al., 2015). Thus, TVA is able to integrate both cognitive and neural theories of attention into one unified theory, which is highly important in trying to localise the neuroanatomical underpinnings of cognitive mechanisms. Additionally, TVA-based paradigms offer a simple yet powerful tool with which to test various participant cohorts, ranging from younger to older healthy adults, as well as to multiple clinical populations (see Habekost, 2015, for an overview).

6 Aims and Hypotheses

The aim of this project was to explore motor-cognitive dual-tasking from a new angle whilst also addressing several main difficulties: 1) the disagreement between whether the tasks are processed in parallel or serially; 2) the lack of sensitive yet objective ways of measuring dual-task costs; and 3) the lack of distinction between the sub-processes that underlie attention. Once it was shown that existing difficulties could be addressed through the novel use of the TVA in dual-tasking, one particularly interesting use of this new paradigm was to explore which cognitive mechanisms underlie the age-related decline in dual-task abilities. Insights gained from such a study could in turn potentially lead to new ways of assessing the relevance of existing intervention methods aimed at reducing the risk of falls in elderly adults, or could even lead to the development of new intervention strategies. The aim of this integrative paradigm was to not only incorporate an approach to existing challenges in motor-cognitive dual-tasking research, but also to address more theoretical open questions, such as which processes underlie the increased dual-task costs in older adults, or how dual-task costs are affected by the cognitive load of a task. These issues were addressed in two separate studies.

Study 1 - The goal of this study was to create an objective and reliable tool that was sensitive enough to quantify dual-tasking costs, and which could later be used to address the main question regarding the cognitive mechanisms affected by the age-related decline in performance. Hence, a novel dual-task paradigm was developed based on TVA which allowed the distinct measurement of both the attentional parameters and the motor task performance. The aim of this study was therefore 1) to precisely measure how different attentional parameters are affected by motor-cognitive dual-tasking; 2) to see whether the results could disentangle whether tasks are processed in a parallel or serial fashion; and 3) to see whether this paradigm would be sensitive enough to be able to quantify dual-task costs. I conducted this work at the Jena University Hospital, under the supervision of Dr. P. Bublak.

Study 2 - The aim of this second study was to use the paradigm created in Study 1 to: 1) explore age-related differences in motor-cognitive dual-tasking; and 2) to see whether varying the cognitive load of the secondary motor task would have an influence on dual-tasking costs in younger subjects. This study was conducted in cooperation with the Ludwig Maximilian University, Munich, in which I and Melanie Penning (also a Ph.D. candidate) share all aspects of the project equally, thereby sharing first authorship of the resulting publication.

7 Publications

7.1 Motor-cognitive dual-task performance: effects of a concurrent motor task on distinct components of visual processing capacity, Künstler ECS, Finke K, Günther A, Klingner CM, Witte OW, Bublak P., Psychological Research, 82, 1, 177-185, 2018.

Psychological Research (2018) 82:177–185
https://doi.org/10.1007/s00426-017-0951-x

ORIGINAL ARTICLE

Motor-cognitive dual-task performance: effects of a concurrent motor task on distinct components of visual processing capacity

E. C. S. Künstler[1] · K. Finke[1] · A. Günther[1] · C. Klingner[1] · O. Witte[1] · P. Bublak[1]

Received: 27 December 2016 / Accepted: 22 November 2017 / Published online: 1 December 2017

Abstract
Dual tasking, or the simultaneous execution of two continuous tasks, is frequently associated with a performance decline that can be explained within a capacity sharing framework. In this study, we assessed the effects of a concurrent motor task on the efficiency of visual information uptake based on the 'theory of visual attention' (TVA). TVA provides parameter estimates reflecting distinct components of visual processing capacity: perceptual threshold, visual processing speed, and visual short-term memory (VSTM) storage capacity. Moreover, goodness-of-fit values and bootstrapping estimates were derived to test whether the TVA-model is validly applicable also under dual task conditions, and whether the robustness of parameter estimates is comparable in single- and dual-task conditions. 24 subjects of middle to higher age performed a continuous tapping task, and a visual processing task (whole report of briefly presented letter arrays) under both single- and dual-task conditions. Results suggest a decline of both visual processing capacity and VSTM storage capacity under dual-task conditions, while the perceptual threshold remained unaffected by a concurrent motor task. In addition, goodness-of-fit values and bootstrapping estimates support the notion that participants processed the visual task in a qualitatively comparable, although quantitatively less efficient way under dual-task conditions. The results support a capacity sharing account of motor-cognitive dual tasking and suggest that even performing a relatively simple motor task relies on central attentional capacity that is necessary for efficient visual information uptake.

Introduction

If we allocate undivided attention to a task, its execution will often be more successful as compared to situations when our attention is distracted by a concurrent task. Thus, it is everyday experience that paying attention to the visual environment is affected by the concurrent execution of a motor task. Consider driving a car whilst repeatedly pressing the buttons of your car stereo device in search of your favourite radio program or CD track. In such a situation, your monitoring of the traffic events outside will likely be rendered less efficient compared to a condition when you are focussed on the visual task alone. Empirical data corroborate this view. For example, Mioni et al. (2016) found temporal discrimination thresholds in the visual but not the auditory modality to be elevated by performing a concurrent finger tapping task in young healthy subjects. Similarly, Fuller and Jahanshahi (1999) reported that, in patients with schizophrenia, the performance of a task requiring visual-selective attention declined during concurrent finger tapping. These data suggest that even relatively simple motor tasks can significantly affect the efficiency of visual processing.

One approach to understand the performance decline typically observed under dual-task conditions, when two continuous tasks have to be executed simultaneously, is a resource sharing account (see Tombu & Jolicoeur, 2004, for an overview). This framework assumes that two tasks can be performed in parallel, but that the amount of processing capacity is strictly limited. Due to the limited resources, the available processing capacity has to be shared between the two tasks, rendering task processing of both tasks less efficient. The decrease of processing efficiency under dual-task conditions, compared to the processing of each single task in isolation, is observed as the dual-task cost. Several versions of the resource sharing model have been proposed. Kahneman's (1973) original proposal suggested a more or less undifferentiated pool of mental resources that can be allocated to different task demands. Navon (1984), and Wickens (2002) assumed multiple resources that can be

✉ E. C. S. Künstler
Erika.Kuenstler@med.uni-jena.de

[1] Hans Berger Department of Neurology, Jena University Hospital, Am Klinikum 1, 07747 Jena, Germany

shared across tasks, giving rise to dual-task costs whenever two or more task processes or stages draw from the same specific resource. A special case are central capacity sharing models (Navon & Miller, 2002; Tombu & Jolicoeur, 2004) which accept the idea of multiple task stages, but assume resource sharing at central processing stages only. These models consider the structural bottleneck account of dual-task costs, with its implication of serial task processing at central stages (Pashler, 1994), as a special case of capacity sharing, when task 1 and task 2 get all of the available capacity, respectively, in serial succession. A model that encompasses aspects of both the structural bottleneck, and of the resource sharing account, has been proposed by Logan and Gordon (2001) in their 'executive control of the theory of visual attention' (ECTVA) model.

The 'theory of visual attention' (TVA) introduced by Bundesen (1990; see also Bundesen, Vangkilde, & Petersen, 2015, for a recent update) is a framework well suited for assessing how the efficiency of visual information uptake is affected by a concurrent motor task. TVA conceptualizes visual processing capacity as a set of attentional parameters. These parameters can be estimated, on the individual level, by modelling a subject's performance in a simple psychophysical task, i.e., whole report of briefly presented letter arrays. In short, TVA assumes that visual information uptake is accomplished across two processing waves. During the first, unselective wave, evidence values are computed during a massive parallel processing of the visual input, where objects from the display are matched to long-term memory representations. In the second, selective wave of processing, the available attentional capacity is distributed across the objects in the visual field, and weighted according to the evidence values. All objects compete with each other in a race towards visual short-term memory (VSTM) which has a limited storage capacity of about four elements in healthy, young, participants. Objects receiving more attentional weight race with a faster speed and gain higher probability to be encoded into VSTM. Encoded objects are selected and available for further processing in the cognitive system. Thus, in TVA, the efficiency of visual information uptake is represented by three parameters reflecting the perceptual threshold (parameter $t0$), the rate of visual processing (parameter C), and the storage capacity of VSTM (parameter K). These parameters reflect origin, slope, and asymptote, respectively, of the exponential growth function by which the individual whole report performance is modelled according to the equations provided by TVA (see Kyllingsbæk, 2006; Habekost, 2015, for a tutorial overview).

Based on TVA, it is possible to individually describe attentional parameters representing the efficiency of visual information processing. Compared to 'classical' response time based measures, a number of important advantages arise with respect to the analysis of dual-task effects. It is not only possible to assess the effects induced by a concurrent motor task on visual information uptake by quantifying, for each individual participant, whether and to what degree changes of the perceptual threshold, rate of information uptake, and VSTM storage capacity are invoked. In addition, TVA-based analysis also allows for a comparison between single- and dual-task conditions according to qualitative aspects related to task processing. In TVA, it is assumed that the parameter visual processing speed C and VSTM storage capacity K are indexing processes that are relatively constant, within a given individual, across comparable stimulus and task conditions. Indeed, they were interpreted as having a latent trait character (e.g., Finke et al., 2012). However, it might be possible that, when measured in a dual-task scenario, these parameters reflect variable performance from moment to-moment, traded off in a time-sharing manner. In other words, in the dual-task condition, participants might start and stop the entire task process in which the TVA parameter estimates are embedded, depending on whether or not the participants were paying attention to the visual task. Then, the C estimate, for example, rather than reflecting a constant rate of information uptake across the dual-task condition, might be an average of actual C and a non-operating task (where C could possibly even equal 0). Therefore, two statistical analyses were run to explore whether, in dual-task conditions, the TVA parameter estimates actually reflect a relatively constant performance that can be validly modelled using the TVA-fitting process, or rather provide an overall average across very low versus optimal performance. First, goodness of fit measures were obtained for each participant that reflect the degree to which variance in the empirical performance in the different whole report conditions can be predicted by the individual TVA parameter estimates. Second, the variability of the individual parameter estimates under single- and dual-task conditions was assessed by a bootstrapping procedure (Efron & Tibshirani, 1993) to investigate the possibility of a broader distribution of the estimates under dual-task conditions.

Effects of a concurrent visual task have been recently assessed within a TVA-based framework by Poth, Petersen, Bundesen, & Schneider, (2014). These authors found a reduction of visual processing speed, but no effects on the perceptual threshold and the storage capacity of the VSTM. Our study combines—to the best of our knowledge, for the first time—the TVA approach with a continuous motor task in a dual-task procedure. We assessed whether visual processing speed is also affected under a concurrent non-visual task, and whether VSTM storage capacity would be affected as well. As part of this special issue, this attempt can offer new insight into how visual processing is affected by performance of a concurrent motor task. It also offers novel possibilities to assess qualitative differences between single- and dual-task conditions.

Methods

Participants

A total of 24 right-handed participants (10 female), aged between 40 and 71 years ($M = 57.0$; SD = 9.5), took part in this study. All were right-handed (verified by the Edinburgh Handedness Inventory; EHI; Oldfield, 1971) and had normal or corrected-to-normal vision. On average, they received $M = 11.5$ years of education (SD = 1.8), and had an IQ of $M = 107.1$ (SD = 9.9), as estimated by a German vocabulary test (MWT-B; Lehrl, 1999). All participants were without any history of neurological or psychiatric disease. The study was approved by the Ethics Committee of the Jena University Hospital, and all participants gave written informed consent prior to participation, in accordance with the Declaration of Helsinki. Each participant received a reimbursement of €30.

Procedure

Participants underwent a single session which lasted approximately 2 h, with 40 min used for questionnaires and screening tests, and the remaining time allotted to the experimental conditions, with breaks being taken as needed.

Tapping task

The tapping task used a simple sequence which consisted of using the index finger of the dominant hand to press the "1" key, and the middle finger of this same hand to press the "2" key on a separate numeric keyboard. This "1, 2" sequence was then tapped repetitively at a subjectively preferred speed. As all participants were right handed, the sequence tapped was the same for each participant. Following the methodology described by Kane and Engle (2000), this tapping task consisted of three blocks: the first block, which lasted 30 s, familiarised the participant with the sequence. If poorly performed, this block could be repeated. If successfully executed, the second block commenced, during which the average tapping speed was calculated over a duration of 60 s. If the wrong key was pressed, auditory feedback in the form of a beep was provided. If this block was also successfully completed, the participant could then go on to the final block. Here, the average tapping speed calculated in the second block was added to a tolerance buffer of 150 ms and was used as the cut-off speed for the participant's subsequent performance. If the participant was too slow by taking longer to press a key than the time stipulated by this average tapping speed, or pressed the wrong key, auditory feedback was again provided. This final block lasted for 3 min. This time-span was chosen as 3 min reflects the average length of a block in the whole report task. All participants were asked whether they could tap without any discomfort for this period and none of them experienced any problems. Each tap made by the participant in this final block was recorded in a text file, along with the time stamp of when the tap was made, which key was pressed, the correct response, and how long it took for the key to be pressed. This allowed for error rates and tapping speeds to be established for each participant post hoc, as well as allowing for a comparison between the time stamps of each response on each task to be made.

Whole report task

The whole report task was run using Matlab (MathWorks, 2012), using Psychtoolbox (Brainard, 1997). Participants received task instructions on-screen, along with two examples to elucidate the instructions. Following this, a pre-test consisting of 12 triples of trials divided into 4 blocks, with 12 trials per block, was run. This pre-test familiarised the participant with the task, and identified the appropriate exposure durations for each participant using an adaptive staircase model. Each triple consisted of two trials that were not used for adjustment. These were either unmasked with exposure duration of 200 ms or masked with exposure duration of 250 ms. One trial in each triple was critical for adjustment; this was masked and initially displayed for 100 ms. If at least one letter in such a critical trial was reported correctly, the exposure duration was decreased by 10 ms in the following critical trial. This was repeated until a final exposure duration was identified at which the participant could not even report one letter correctly. This exposure duration was determined as the lowest exposure duration and was combined with four longer exposure durations during the remainder of the experiment, which were picked from a pre-defined list based on the value of the lowest exposure duration. In 18 participants, the exposure durations used were 10, 20, 40, 90, and 200 ms. A further three participants had exposure durations of 20, 40, 60, 120, and 210 ms, whilst one participant had exposure durations of 30, 50, 80, 130, and 220 ms. Finally, two participants were tested using exposure durations of 40, 60, 100, 150, and 230 ms. In five unmasked conditions, stimuli were followed by a mask, to avoid visual persistence effects. The mask consisted of red-and-blue scattered squares of 1.3° size appearing on each stimulus location for 500 ms. Furthermore, to enhance variability of exposure durations, two unmasked conditions were additionally used, i.e., the second shortest and the longest exposure durations were presented both masked and unmasked. In unmasked trials, visual persistence increases the duration of information uptake by several hundred milliseconds (Sperling, 1960; Dick, 1974). This duration is estimated by parameter μ in TVA-based fitting of whole report performance, a parameter which only serves the valid estimation of the remaining parameters here, and is of no additional interest for this study. This resulted in seven effective exposure conditions, with each condition having 20 trials. The whole experiment thus consisted of 140 trials, which were divided into 4 blocks. Such exposure duration variability allowed measuring a broad range of whole report performance. Lower exposure durations allow valid estimations of the perceptual threshold *t*0 at lower exposure durations, which is also decisive for that of the rate of information uptake in ms at *t*0, i.e., for estimating visual processing speed *C*. Higher exposure durations are necessary for receiving precise estimates of the asymptote level of performance, i.e., of VSTM storage capacity *K*. An example of a trial sequence is given in Fig. 1.

As can be seen from Fig. 1, a fixation point was presented on the screen for a duration of 1000 ms. Following this, six different isoluminant letters were presented equidistantly in a circle around the fixation point. These target letters were either all red or all blue [CIE red = (0.49, 0.515, 0.322), CIE blue = (0.49, 0.148, 0.068)], and were selected randomly from a pre-specified set of letters (excluding the letters *I*, *Q*, and *Y*). The size of these letters was 1.5 cm by 1.5 cm, with the luminance being set to 0.49 cd/m^2, thereby ensuring that both red and blue targets had the same level of task difficulty. In masked trials, the masks consisted of 2.0 cm by 2.0 cm squares of overlapping blue [Colour space: CIE $L \times a \times b$ blue = (17.95; 45.15; − 67.08)] and red [CIE $L \times a \times b$ red = (28.51; 46.06; 41.28)] flecks. After this, the screen went blank, and at this point, the participant had to verbally report as many target letters as possible, in any order. It was emphasised that this was not a speeded task, thereby allowing each participant to take as much time as necessary in making the responses. The researcher, who was seated to the side and slightly behind the participant, then entered the reported letters via a keyboard before proceeding to the next trial. The reported letters, as well as the timestamps of each trial, were exported to a text file. After each block, participants received visual, on-screen feedback as to their accuracy on the letters they actually reported. In order to avoid both too liberal and too conservative responses, participants were encouraged to aim for an accuracy rate of 70–90%, indicated by a green area on the accuracy bar. If their accuracy was below 70%, participants were asked to only report those letters they were fairly confident of having seen. If the accuracy was over 90%, participants were encouraged to be less conservative by reporting more target letters, even if they did not feel entirely confident.

Dual-task

The task order was counterbalanced, with 12 participants completing the single-task condition before the dual-task condition, and 12 participants completing it afterwards. In

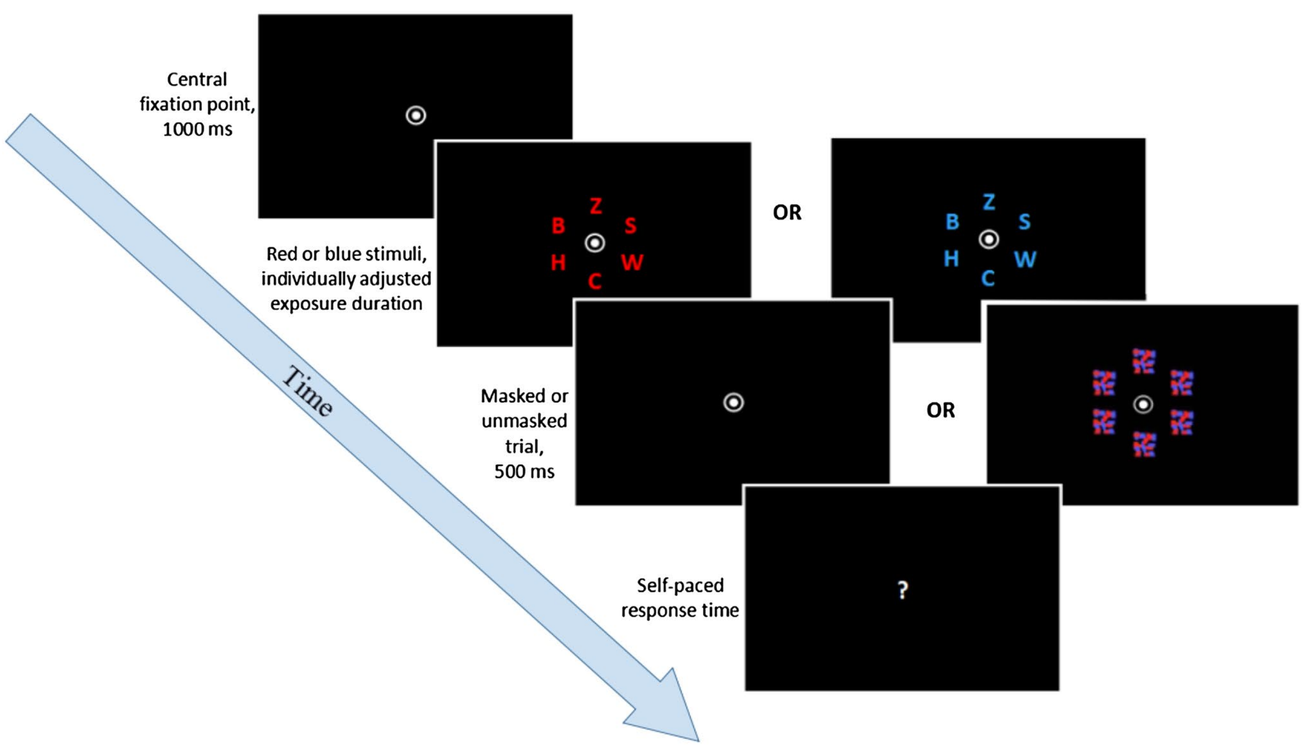


Fig. 1 Whole report trial sequence

the dual-task, all participants started with the training and speed adjustment blocks of the tapping task before the whole report paradigm was subsequently started. During the dual-task, it was ensured that the participants did not visually monitor their tapping on the keyboard, but instead constantly fixated on the screen. This screen was adjusted for each participant, such that the central fixation point was at eye level. Due to the set-up of the apparatus, participants' hands were located below the periphery of their visual field. Thus, to visually monitor their tapping, they would have had to move their heads to be able to see their hands (a mere shifting of the gaze downwards would not have been sufficient). The experimenter specifically monitored this, and ensured that no participant looked away from the central fixation point throughout the dual-task condition.

Parameter estimation

Data obtained through the whole report paradigm were analysed using the LIBTVA script developed by Dyrholm (2012) and run through Matlab (MathWorks, 2012) to obtain a TVA-based maximum likelihood fit for the data of each participant. This fitting method uses the observed data points to extrapolate the probabilistic parameters, utilising the fixed-capacity independent race model (see Shibuya & Bundesen, 1988). Moreover, to assess the data in which both tasks were successfully executed, dual-task trials in which a tapping error had occurred were excluded from the analysis. This yielded information regarding the goodness of fit, and the various visual attentional parameters of each participant, and how they were affected by motor-cognitive dual-tasking.

In addition to the exact parameter estimates, 200 bootstrapping estimates were derived (Efron & Tibshirani, 1993) to obtain quantitative estimates of the robustness of the maximum likelihood estimates produced by the TVA fitting (see Habekost & Bundesen, 2003). To that end, the original dataset was resampled by drawing 140 "new" trials, at random, with replacement, from the original sample of 140 trials. The algorithm was repeated 200 times (for each experimental condition and participant) and a TVA-based maximum likelihood fit was computed for each of the resulting 200 bootstrapping samples. The standard estimates of these bootstrapping estimates may be taken as quantitative estimates of the standard errors of the original parameter estimations (Habekost & Bundesen, 2003). Note that, as during resampling, each original trial can be drawn 0, 1, 2, …, or up to n times, resampling an original mixture of trials with fluctuating, "normal" and "0" rates, of information should result in increased standard errors of the bootstrapping estimates. On the other hand, rather constant rates of information uptake across the dual-task condition should lead to a low probability of producing extreme deviations from the mean also during the bootstrapping process that equals that of the standard, single task, condition. Note also that the same arguments apply to the estimation of the whole set of parameters (i.e., also to $t0$ and K estimates).

Calculation of dual task costs

To normalise the dual-task costs (see Boisgontier et al., 2013), the following formula was used when an increase in the metric was indicative of a dual-task cost (such as in the $t0$ parameter): DTC = [(DT − ST)/ST] × 100; when a decrease in the metric indicated a dual-task cost (as for the C and K parameters), then DTC = [(ST − DT)/ST] × 100 was used, instead (whereby DTC = dual-task costs, ST = single task performance, and DT = dual-task performance).

Apparatus

To minimise distractions, the tests were administered in a dimly lit- and sound-attenuated room. The entire experiment was run on a Fujitsu Lifebook E series laptop, with a separate numeric keyboard used for the tapping task. However, for the presentation of stimuli, an ASUS VG248 17 inch monitor with a refresh rate of 100 Hz, a resolution of 1024 × 768 pixels. To ensure a viewing distance of 60 cms, both the seat on which the participant sat as well as the table on which the screen was placed were not moveable. Furthermore, the distance between the participant and the screen was demarcated with tape.

Results

Tapping results

Tapping performance in the single task was consistently high, with an average accuracy of 97.9% (SD = 3.9). There was no significant decline in the accuracy with which participants were able to complete the tapping task in the dual-task condition, although a tendency was found ($t(23) = 1.41$, $p = .09$). Tapping accuracy dropped to 96.7% (SD = 3.2) under dual-task conditions. Based on the above-mentioned formulas for normalising dual-task costs across participants, there was an average dual-task cost of 1.3% (SD = 4.5) in the dual-task condition.

Whole report results

Accuracy of letter report as a function of effective exposure duration was modelled for each participant and each experiment condition by a TVA-based function that represented the maximum-likelihood fit to the data (Dyrholm et al., 2011; Kyllingsbæk, 2006). As can be seen in Fig. 2 below, in the single-task condition, participants had an

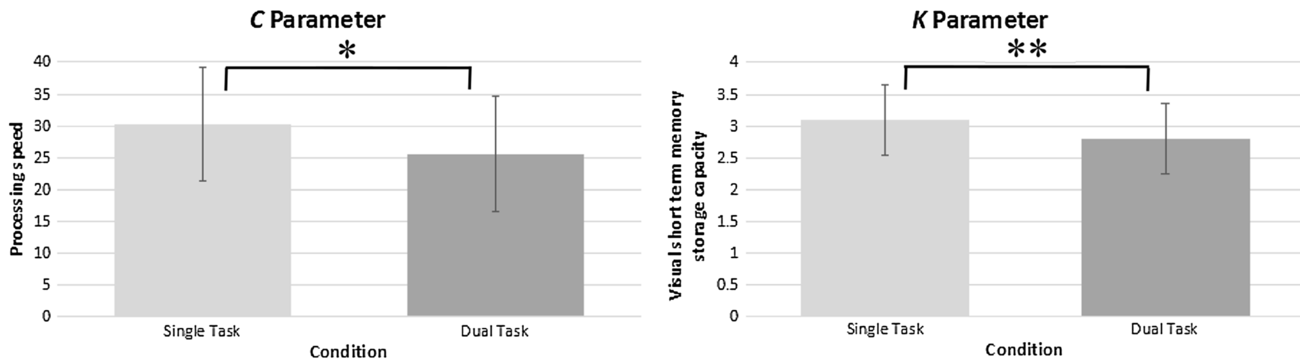


Fig. 2 Single-task and dual-task results for parameter visual processing speed *C* and visual short-term memory storage capacity *K* respectively

average *C* value of 30.3 elements per second (SD = 8.1), whilst in the dual-task scenario, this parameter dropped to an average of 25.6 elements per second (SD = 10.0). A one-sided t test showed this difference to be significant (t (23) = 2.24, $p = .02$, $d = 0.52$). For VSTM storage capacity, participants had an average *K* parameter of 3.1 elements in the single task (SD = 0.6), and a mean *K* of 2.8 elements in the dual-task condition (SD = 0.5). A one-sided t test indicated this as a significant decline (t (23) = 4.07, $p < .001$, $d = 0.63$). Normalised dual-task costs in processing speed and VSTM storage capacity were also calculated, revealing an average cost of $M = 11.6\%$ (SD = 33.9) for the *C* parameter, and $M = 9.47\%$ (SD = 11.6) for the *K* parameter. As can be seen from Fig. 3, a decline in the *C* parameter occurred in 18, and a decrease in the *K* parameter in 19 of the 24 participants. In this figure, dual-task performance is plotted against performance in the single task. Thus, all data points falling within the gray triangle represent dual-task costs, whilst those falling within the white triangle represent a dual-task gain.

The parameter *t0*, or perceptual threshold, i.e., the minimum exposure duration at which participants start to process stimuli, was 17.4 ms (SD = 11.9) in the single task, whilst in the dual-task condition, the *t0* was 15.5 ms (SD = 10.1). This difference between the single-task- and dual-task conditions was not significant ($t(23) = 1.14$, $p = .13$).

Goodness-of-fit measures revealed that there was a close correspondence between the empirical mean scores in the different whole report conditions and the values that would be predicted based on the TVA parameter estimates. Average squared Pearson product-moment correlation coefficients of $R^2 = 0.98$ (SD = 0.02) in the single task and $R^2 = 0.97$ (SD = 0.03) in the dual task clearly indicated that, in both conditions, most of the variance in the empirical data was explained by the TVA model.

Resampling each original dataset with 200 bootstrapping iterations did not indicate any tendency for higher standard deviations for the resulting bootstrapping estimates of parameter processing speed *C* (single task: $M = 5.29$, SD = 2.38; dual task: $M = 3.97$, SD = 2.45) or VSTM storage capacity *K* (single task: $M = 0.12$, SD = 0.04, dual task: $M = 0.12$, SD = 0.04). Figure 4 shows the distribution of bootstrapping estimates for parameter *C*, separately for the single- and the dual-task condition for a representative participant (whose estimates most closely resembled the mean group estimates in the single-task- and the dual-task conditions). Thus, there is no indication of increased variability in the bootstrapping estimates.

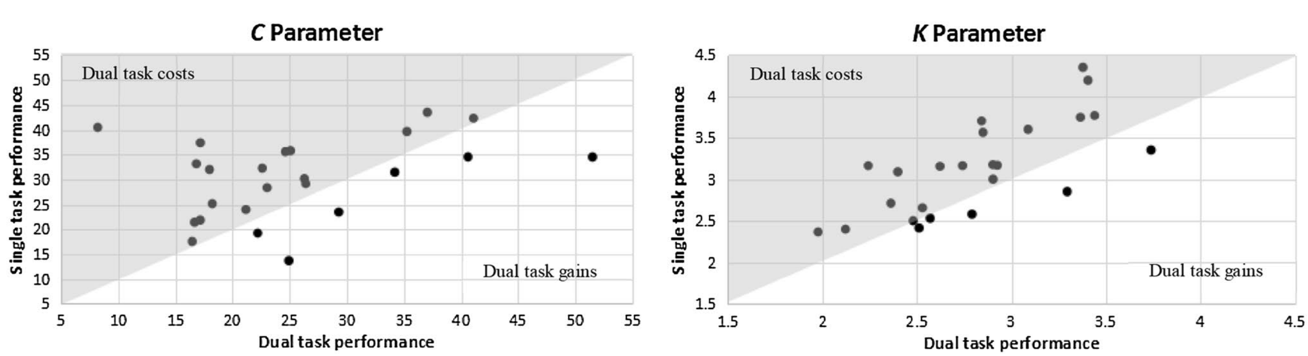


Fig. 3 Individual dual-task costs in visual processing speed *C* and visual short-term memory storage capacity *K*

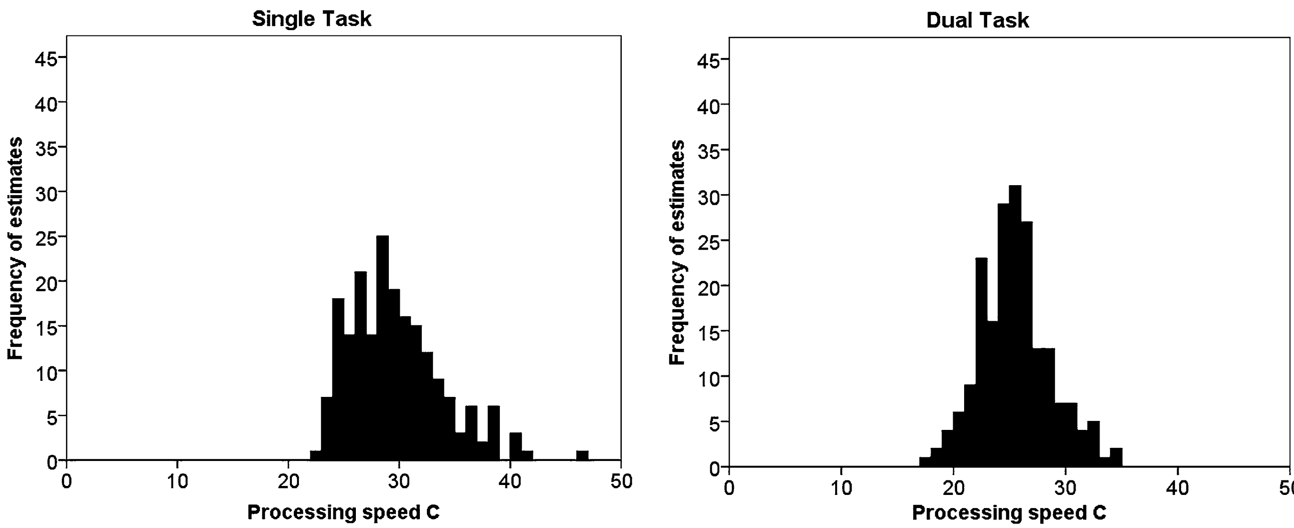


Fig. 4 Distribution of a representative participant's estimates for parameter visual processing speed *C* as obtained by bootstrapping

Discussion

In this study, we combined a concurrent motor task, in the form of a repetitive finger tapping, with a visual task assessing the efficiency of visual information uptake. Based on TVA (Bundesen, 1990), parameter estimates were derived, both under single- and dual-task conditions, that reflected distinct components of visual processing capacity; that is, the perceptual threshold, the speed of visual processing, and the storage capacity of VSTM. Additionally, goodness-of-fit values were obtained for each condition to check whether parameters were validly estimated under both single- and dual-task conditions. Moreover, by applying a bootstrapping procedure, quantitative estimates of the reliability of the parameter estimates in each condition were obtained to test for possibly increased fluctuation of visual attentional performance in dual-task compared to single-task conditions.

Our results showed that concurrent tapping affected visual processing in a significant way. Both the speed of visual processing, and VSTM storage capacity declined under dual-task- compared to single-task conditions. In contrast, the perceptual threshold remained unaffected. These results suggest that a concurrent motor task taps attentional aspects of visual-processing capacity. Participants seem to process information at a lower rate and also to store less pieces of information in VSTM, but are not less sensitive for stimulus registration at minimal exposure durations.

The effect on processing capacity is remarkable when considering the fact that the tapping task was performed on a very high level, with more than 96% accuracy, under both single- and dual-task conditions. Obviously, then, tapping was not a very demanding task and subjects were readily able to keep motor performance in the dual-task condition on a level comparable to the single-task condition. Nevertheless, this rather easy task with only a minor cognitive demand was sufficient to significantly reduce efficiency of visual information uptake in participants at middle to higher age.

The analysis of goodness-of-fit values for the single- and dual-task conditions indicated that a very high variance of the empirical data was explained by the TVA parameter model estimates in both conditions. Moreover, bootstrapping analyses of the parameter estimates showed that the robustness of these estimates was comparable between single- and dual-task conditions. These results clearly do not suggest that the dual-task condition created a higher trial-to-trial variability in the way the participants approached the task. Instead, they support the assumption of the TVA-based fitting that relatively constant parameters underlie whole report performance of a given individual—also across the entire duration of the dual task.

These data are appealing for two reasons. First, they suggest that performing a concurrent motor task relies on attentional resources that are necessary for visual information uptake. Second, they are compatible with a capacity sharing account of motor-cognitive dual-tasking and justify the assumption that both tasks share a common central resource. Given the very short, near-threshold, exposure durations that are most critical for estimating visual processing speed *C*, these results would be difficult to reconcile with an attention switching account. Contrary to the prediction made by a switching account of dual tasking, there was no evidence of a time-based trade-off in processing the visual task under dual-task conditions, such that participants would switch between a state of paying attention (with a "normal" processing rate at the level of the single task), and a state of not paying attention to the display (with a rate of processing approaching 0). Such behaviour would be reflected in both a violation of the TVA model, giving rise to a decline in the goodness-of-fit, and in an increase of the variability of the bootstrapping estimates. Our analyses showed that this was not the case.

Of course, time-sharing accounts cannot be completely ruled out on the basis of our present findings. After all, there are lots of ways for costs of more difficult or higher-demand central processing to influence the time course of other processes (e.g., costs of switching between monitoring different tasks relative to task difficulty). Therefore, additional studies with experimental settings tailored to investigate this issue in more detail would be required. For example, combining TVA-based whole report with a "classical" psychological refractory period (PRP) paradigm could allow for more fine-grained temporal distinctions.

Our results also render another explanation for our data rather unlikely, namely that participants visually monitored the tapping device in the dual-task condition. The consistency with respect to both model fitting and bootstrapping estimates across single- and dual-task conditions speaks against such an assumption. Arguably, as participants would need to shift not only eye fixation but also turn their heads towards the tapping device, this should result in a marked change of visual threshold estimates (whereby trials with low-exposure duration in particular would be affected) and in reduced parameter robustness in general. Taken together, the high comparability between single- and dual-task conditions with respect to goodness-of-fit and bootstrapping estimates is in line with a resource sharing account predicting qualitatively similar but quantitatively less efficient visual processing in the dual compared to the single task.

Within the framework of TVA, parameter *C* reflects the amount of attentional capacity that can be allocated to the processing of objects in the visual field (Bundesen, 1990; Bundesen et al., 2015). Accordingly, a reduction of *C* would indicate that the amount of attentional capacity is decreased by the presence of a concurrent motor task. A plausible explanation would be that the motor task receives attentional weighting which leaves less attentional capacity available for visual processing. In other words, the concurrent motor task acts as sort of a distractor receiving attentional capacity. Two conclusions can be drawn from such an assumption. First, the decrease of processing speed assessed by the whole report task can be regarded as a quantification of the amount of attentional capacity that is used by the concurrent motor task. Second, due to the non-visual nature of the motor task, this suggests that central attention rather than visual attentional capacity is shared between the concurrent tasks. That is, the attentional capacity as conceptualized by TVA reflects, at least to some degree, central attentional resources instead of purely visual processing capacity. This has already been suggested by clinical studies in which processing speed has been associated with global cognitive ability (Bublak et al., 2011), or with a non-visual task reflecting central attentional capacity (Kluckow, Rehbein, Schwab, Witte, & Bublak, 2016). Note, however, that this is the first study to suggest a relationship between TVA-based visual processing speed and central attentional capacity in healthy subjects. While Poth et al. (2014) also found a reduction of processing speed under the influence of a concurrent visual task, this interference could be interpreted as a competition of visual attentional resources. Nevertheless, it must also be noted that both tasks involve a spatial component insofar as the TVA task utilises six stimuli spread out across the visual field, whilst the tapping task relies on the learning of a sequence which is spatially organised. Thus, it is also possible that rather than drawing on a general central attentional capacity, the tasks more specifically tap into a form of spatial attention. However, it is not possible to distinguish the degree to which the attentional changes found in this paper are reflective of either spatial attention or a more general attentional capacity.

The *K* parameter reflects VSTM storage capacity in TVA, which represents object categorisations that are available for further processing. Essentially, and in accordance with the ECTVA framework of Logan and Gordon (2001), this is a stage of response selection, which results in naming of the letters in the case of whole report. In the presence of a concurrent motor task, response selection is made more demanding by the fact that not only do letters have to be named, but also that finger movements need to be selected. Here, executive control is necessary, and our results suggest that this stage is also characterized by resource sharing. A possible explanation could be that when more representations have to be maintained in parallel in a passive store such as VSTM, the reliability of these representations is reduced, owing to decay or interference (see e.g., Jonides et al., 2008), and response selection is rendered more difficult.

A limitation of our study is that our investigation involved subjects of middle to higher age. Therefore, the results need first to be replicated in younger subjects, before their applicability can be reliably evaluated. However, our results can provide a first step towards a deeper understanding why motor-cognitive dual-task effects seem to be especially pronounced under concurrent visual processing demands in the elderly (Boisgontier et al., 2013). Furthermore, they set a valuable framework for neuropsychological studies in patients with lesions in brain regions relevant for cognitive-motor functions, which are currently underway.

Acknowledgements This research was supported by a Grant within the Priority Program, SPP1772 from the German Research Foundation (Deutsche Forschungsgemeinschaft, DFG), Grant number

SPP 1772/1—BU 1327/4-1 (to PB) and by a DFG Grant, number FI 1424/2-1 (to KF). We would like to thank Natan Napiórkowski for programming the experiment.

Compliance with ethical standards

Funding This research was supported by a Grant within the Priority Program, SPP1772 from the German Research Foundation (Deutsche Forschungsgemeinschaft, DFG), Grant number SPP 1772/1—BU 1327/4-1.

Conflict of interest E. C. S. Künstler declares that she has no conflict of interest. K. Finke declares that she has no conflict of interest. A. Günther declares that he has no conflict of interest. C. Klingner declares that he has no conflict of interest. O. Witte declares that he has no conflict of interest. P. Bublak declares that he has no conflict of interest.

Ethical approval All procedures performed in studies involving human participants were in accordance with the ethical standards of Jena University Hospital, and with the 1964 Helsinki Declaration and its later amendments. The study was approved by the Ethics Committee of the Jena University Hospital.

Informed consent Informed written consent was obtained from all individual participants included in the study.

References

Boisgontier, M. P., Beets, I. A. M., Duysens, J., Nieuwboer, A., Krampe, R., & Swinnen, S. P. (2013). Age-related differences in attentional cost associated with postural dual-tasks: Increased recruitment of generic cognitive resources in older adults. *Neuroscience & Biobehavioral Reviews, 37*, 1824–1837.

Brainard, D. H. (1997). The Psychophysics Toolbox. *Spatial Vision, 10*, 433–436.

Bublak, P., Redel, P., Sorg, C., Kurz, A., Förstl, H., Müller, H. J., Schneider, W. X., & Finke, K. (2011). Staged decline of visual processing capacity in mild cognitive impairment and Alzheimer's disease. *Neurobiology of Aging, 32*, 1219–1230.

Bundesen, C. (1990). A theory of visual attention. *Psychological Review, 97*, 523–547.

Bundesen, C., Vangkilde, S., & Petersen, A. (2015). Recent developments in a computational theory of visual attention (TVA). *Vision Research, 116*, 210–218.

Dick, A. O. (1974). Iconic memory and its relation to perceptual processing and other memory mechanisms. *Perception & Psychophysics, 16*, 575–596.

Dyrholm, M. (2012). LIBTVA user guide. Retrieved from http://cvc.psy.ku.dk/resources/matlab-toolbox-for-modeling/. Accessed 29 Nov 2017.

Dyrholm, M., Kyllingsbæk, S., Espeseth, T., & Bundesen, C. (2011). Generalizing parametric models by introducing trial-by-trial parameter variability: The case of TVA. *Journal of Mathematical Psychology, 55*, 416–429.

Efron, B., & Tibshirani, R. J. (1993). *An Introduction to the Bootstrap*. Dordrecht: Springer.

Finke, K., Matthias, E., Keller, I., Müller, H. J., Schneider, W. X., & Bublak, P. (2012). How does phasic alerting improve performance in patients with unilateral neglect? A systematic analysis of attentional processing capacity and spatial weighting mechanisms. *Neuropsychologia, 50*, 1178–1189.

Fuller, R., & Jahanshahi, M. (1999). Concurrent performance of motor tasks and processing capacity in patients with schizophrenia. *Journal of Neurology, Neurosurgery, and Psychiatry, 66*, 668–671.

Habekost, T. (2015). Clinical TVA-based studies: A general review. *Frontiers in Psychology, 6*, 290–301.

Habekost, T., & Bundesen, C. (2003). Patient assessment based on a theory of visual attention (TVA): Subtle deficits after a right frontal-subcortical lesion. *Neuropsychologia, 41*, 1171–1188.

Jonides, J., Lewis, R. L., Nee, D. E., Lustig, C. A., Berman, M. G., & Moore, K. S. (2008). The mind and brain of short-term memory. *Annual Review of Psychology, 59*, 193–224.

Kahneman, D. (1973). *Attention and effort*. Englewood Cliffs: Prentice-Hall International.

Kane, M. J., & Engle, R. W. (2000). Working-memory capacity, proactive interference, and divided attention: Limits on long-term memory retrieval. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 26*, 336–358.

Kluckow, S. W., Rehbein, J. G., Schwab, M., Witte, O. W., & Bublak, P. (2016). What you get from what you see: Parametric assessment of visual processing capacity in multiple sclerosis and its relation to cognitive fatigue. *Cortex, 83*, 167–180.

Kyllingsbæk, S. (2006). Modeling visual attention. *Behavioural Research Methods, 38*, 123–133.

Lehrl, S. (1999). *Mehrfachwahl-Wortschatz-Intelligenztest: Manual mit Block MWT-B*. Balingen: Spitta Verlag.

Logan, G. D., & Gordon, R. D. (2001). Executive control of visual attention in dual-task situations. *Psychological Review, 108*, 393–434.

MATLAB and Statistics Toolbox Release. (2012). The MathWorks, Inc., Natick.

Mioni, G., Grassi, M., Tarantino, V., Stablum, F., Grondin, S., & Bisiacchi, P. S. (2016). The impact of a concurrent motor task on auditory and visual temporal discrimination tasks. *Attention, Perception, and Psychophysics, 78*, 742–748.

Navon, D. (1984). Resources—A theoretical soupstone? *Psychological Review, 91*, 216–234.

Navon, D., & Miller, J. (2002). Queuing or sharing? A critical evaluation of the single-bottleneck notion. *Cognitive Psychology, 44*, 193–251.

Oldfield, R. C. (1971). The assessment and analysis of handedness: The Edinburgh Inventory. *Neuropsychologia, 9*, 97–113.

Pashler, H. (1994). Dual-task interference in simple tasks: Data and theory. *Psychological Bulletin, 116*, 220–244.

Poth, C. H., Petersen, A., Bundesen, C., & Schneider, W. X. (2014). Effects of monitoring for visual events on distinct components of attention. *Frontiers in Psychology, 5*, 930–943.

Shibuya, H., & Bundesen, C. (1988). Visual selection from multielement displays: Measuring and modeling effects of exposure duration. *Journal of Experimental Psychology: Human Perception and Performance, 14*, 591–600.

Sperling, G. (1960). The information available in brief visual presentations. *Psychological Monographs: General and Applied, 74*, 1–29.

Tombu, M., & Jolicoeur, P. (2004). Virtually no evidence for virtually perfect time-sharing. *Journal of Experimental Psychology: Human Perception and Performance, 30*, 795–810.

Wickens, C. D. (2002). Multiple resources and performance prediction. *Theoretical Issues in Ergonomic Science, 3*, 159–177.

7.2 Dual Task Effects on Visual Attention Capacity in Normal Aging, Künstler ECS, Penning MD, Napiórkowski N, Klingner CM, Witte OW, Müller HJ, Bublak P, Finke K., Frontiers in Psychology, 9, 1564–1576, 2018.

frontiers in Psychology

ORIGINAL RESEARCH
published: 03 September 2018
doi: 10.3389/fpsyg.2018.01564

Check for updates

Dual Task Effects on Visual Attention Capacity in Normal Aging

Erika C. S. Künstler[1*†], Melanie D. Penning[2†], Natan Napiórkowski[2], Carsten M. Klingner[1], Otto W. Witte[1], Hermann J. Müller[2], Peter Bublak[1‡] and Kathrin Finke[1,2‡]

[1] Hans Berger Department of Neurology, Jena University Hospital, Jena, Germany, [2] Department of Psychology, Ludwig-Maximilians-Universität München, Munich, Germany

Older adults show higher dual task performance decrements than younger adults. While this is assumed to be related to attentional capacity reductions, the precise affected functions are not specified. Such specification is, however, possible based on the "theory of visual attention" (TVA) which allows for modeling of distinct attentional capacity parameters. Furthermore, it is unclear whether older adults show qualitatively different attentional effects or whether they show the same effects as younger adults experience under more challenging conditions. By varying the complexity of the secondary task, it is possible to address this question. In our study, participants performed a verbal whole report of briefly presented letter arrays. TVA-based fitting of report performance delivered parameters of visual threshold t_0, processing speed C, and visual short-term memory (VSTM) storage capacity K. Furthermore, participants performed a concurrent motor task consisting of continuous tapping of a (simple or complex) sequence. Both TVA and tapping tasks were performed under single and dual task conditions. Two groups of 30 younger adults each performed either the simple or complex tapping, and a group of 30 older adults performed the simple tapping condition. In older participants, VSTM storage capacity declined under dual task conditions. While no such effect was found in younger subjects performing the simple tapping sequence under dual task conditions, the younger group performing the complex tapping task under dual task conditions also showed a significant VSTM capacity reduction. Generally, no significant effect on other TVA parameters or on tapping accuracy was found. Comparable goodness-of-fit measures were obtained for the TVA modeling data in single and dual tasks, indicating that tasks were executed in a qualitatively similar, continuous manner, although quantitatively less efficiently under dual- compared to single-task conditions. Taken together, our results show that the age-specific effects of motor-cognitive dual task interference are reflected by a stronger decline of VSTM storage capacity. They support an interpretation of VSTM as central attentional capacity, which is shared across visual uptake and concurrent motor performance. Capacity limits are reached earlier, and already under lower motor task complexity, in older compared to younger adults.

Keywords: visual attention, healthy aging, dual-tasking, theory of visual attention, multi-tasking

OPEN ACCESS

Edited by:
Celine R. Gillebert,
KU Leuven, Belgium

Reviewed by:
Mario Bonato,
Università degli Studi di Padova, Italy
Thomas Alrik Sørensen,
Aalborg University, Denmark

***Correspondence:**
Erika C. S. Künstler
erika.kuenstler@med.uni-jena.de

† These authors share first authorship

‡ These authors share senior authorship

Specialty section:
This article was submitted to Cognition, a section of the journal Frontiers in Psychology

Received: 28 February 2018
Accepted: 06 August 2018
Published: 03 September 2018

Citation:
Künstler ECS, Penning MD, Napiórkowski N, Klingner CM, Witte OW, Müller HJ, Bublak P and Finke K (2018) Dual Task Effects on Visual Attention Capacity in Normal Aging. Front. Psychol. 9:1564. doi: 10.3389/fpsyg.2018.01564

INTRODUCTION

Aging is associated with a decline of sensory and motor functions, as well as distinct cognitive abilities (Lindenberger, 2014). Moreover, consistent evidence shows that dealing with cognitive demands in parallel to a motor task is more difficult for subjects of a higher age (McDowd and Craik, 1988; Kramer and Larish, 1996; Verhaeghen and Cerella, 2002; Woollacott and Shumway-Cook, 2002; Verhaeghen, 2011; Ruthruff and Lien, 2017). Thus, not only do cognitive and motor skills both decline over the life span (Ketcham and Stélmach, 2001; Park and Reuter-Lorenz, 2009; McAvinue et al., 2012; Habekost et al., 2013), but dual tasking seems to add an additional deteriorating factor (Verhaeghen et al., 2002, 2003) that renders even the execution of seemingly easy tasks vulnerable through the introduction of a secondary task (Boisgontier et al., 2013; Künstler et al., 2017). That is, dual tasking requirements seem to represent a specific challenge for elderly adults, which in turn leads to exacerbated performance deterioration. These particular difficulties of older adults in dual tasking situations are especially relevant because they have been linked to a higher risk of falls (Faulkner et al., 2007). However, the reasons for these stronger dual task effects in aging are still not entirely clear.

Dual task interference is observed when performance of one or both tasks within a dual task situation declines compared to the performance of each single task carried out separately (Kahneman, 1973). Two of the most influential attentional explanations for the dual task effect are the bottleneck account and the central capacity sharing model (see Tombu and Jolicoeur, 2004, for an overview). According to the bottleneck account, the dual task related decline in performance arises from the fact that two tasks cannot be executed simultaneously but have to be carried out in a sequential manner, at least at some stage of processing (Pashler, 1994). In contrast, the capacity sharing account assumes simultaneous task performance, but suggests that the overall amount of attentional resources available for performance is strictly limited (e.g., Navon and Miller, 2002). Due to this limitation, attentional capacity has to be shared between the two tasks, giving rise to a trade-off in task performance. As long as the individual's capacity limit is not reached, both tasks can be performed concurrently without a drop-off in either task. Only when the task demand exceeds said limit, one or both of the tasks will be affected. Capacity sharing models consider serial task processing at central stages (Pashler, 1994) as a special case of capacity sharing, whereby first Task 1 and then Task 2 gets all of the available capacity. However, Logan and Gordon (2001) offered a model combining aspects from both the resource sharing and the bottleneck account in their "executive control of the theory of visual attention" (ECTVA) framework.

The "theory of visual attention" (TVA; Bundesen, 1990; see Bundesen et al., 2015 for a current overview) can itself be applied as a framework to assess processing capacity under a dual task condition. TVA is a mathematically formalized theory which has strong relations to the biased competition account of attentional processing. With the Neural Theory of Visual Attention (NTVA) Bundesen et al. (2005) sought to describe single cell data based on TVA, thereby attempting to provide a deeper understanding of how TVA could possibly be explained from a neural standpoint. TVA disentangles processing capacity into a set of distinct parameters determining the efficacy of an individual's visual information uptake. These parameters can be estimated by modeling participants' performance on a simple psychophysical whole report task (e.g., Sperling, 1960). In this task, an array of letter stimuli is briefly presented; TVA proposes that these stimuli are encoded in two distinct processing waves. The first, unselective wave processes the visual information in parallel, allocating evidence values to objects based on the extent to which long-term memory representations match the objects in the display. The second, selective wave distributes limited capacity attention across the objects, with attentional weighting being allocated based on the evidence values. The objects then race to be encoded in the fixed capacity visual short-term memory, which is typically limited to approximately three to four elements in younger, healthy participants. This VSTM storage capacity is intimately related to the concept of visual working memory capacity, as applied by Luck and Vogel (2013) and proposed to be a central index of overall cognitive ability (however, see Aben et al., 2012 for an opposing view). Only those objects which are encoded into the VSTM store are consciously represented, and are therefore available for further actions, such as verbal report.

Performance in the whole report task is modeled, according to the equations set out by TVA (see Kyllingsbaek, 2006; Habekost, 2015, for a comprehensive overview), by an exponential growth function that relates accuracy of letter report to the effective stimulus exposure duration. The origin, the slope, and the asymptote of this function are determined by three parameter estimates provided by TVA: the perceptual threshold, t_0, reflects the time-point at which conscious visual stimulus processing starts; the processing rate C indexes the number of visual elements which can be processed per second; and parameter K estimates the size of the storage capacity of the visual short-term memory, given as the maximum number of elements which can be maintained in parallel. TVA has several advantages in the dual tasking context (see Habekost, 2015, for an overview on the methodological merits of TVA-based measurement): Importantly, to the best of our knowledge, TVA-based testing furthermore is the only methodology that permits a mathematically *independent quantification* measurement of the parameters perceptual threshold, processing speed, and capacity of VSTM. Thus, firstly, it reveals cognitively specific information on which aspect(s) of visual attentional processing is or are affected by the concurrent second task. Secondly, it allows precise measurements of how strongly each parameter is affected. Furthermore, as the TVA whole report paradigm does not rely on motor speed or button presses, the effects of a concurrent manual motor task can be assessed simultaneously, without motor confounds. Finally, by analyzing goodness of fit parameters, qualitative comparisons between single- and dual-task performance can be made, giving insights into how the tasks are processed.

In a recent study Künstler et al. (2017) assessed motor-cognitive dual task interference by combining the TVA-based whole report task with a simple motor task (alternating tapping with two fingers of the dominant hand) in middle- to higher-aged individuals. The results revealed a decline of visual attentional capacity under dual task conditions. Importantly, goodness-of-fit and reliability measures in both single and dual task conditions showed that participants performed on the visual task in a qualitatively similar (i.e., continuous), although quantitatively less efficient way under dual task as compared to single task conditions. Taken together, the results supported a capacity sharing account of motor-cognitive dual-tasking and suggested that even performing a relatively simple motor task relies on central attentional capacity that is necessary for efficient visual information uptake.

In the present study, we apply this method to analyse the effects of aging on motor-cognitive dual-task performance. We investigate which attentional capacity aspects are disproportionately affected in older compared to younger adults when performing a concurrent motor task consisting of the continuous tapping of a simple sequence. In an additional group of younger participants, the complexity of the tapping sequence was increased. This was done due to the evidence that older subjects require more attention for the execution of simple motor tasks, which younger subjects can perform more or less effortlessly (Boisgontier et al., 2013). That is, we tested the hypothesis that more pronounced effects in the older group are attributable to the motor demand being more challenging for them. Taken together, by quantifying the dual-task decrement in older and younger adults, we firstly want to specify the exact attentional parameters that are more prone to dual-task decline in older compared to younger adults. Secondly, by comparing the dual-task decrements of older adults induced by a simple tapping sequence to the decline induced by a more complex sequence in younger adults, we want to assess whether older adults show the same dual-task effects as younger adults facing a more challenging dual-task scenario.

METHODS

This study combined a TVA whole report paradigm with a simple or complex continuous tapping task as the secondary task. In order to establish the effect of task load, 30 younger participants completed a simple tapping task condition (referred to as the "younger simple group"), while 30 younger adults performed a more complex tapping sequence as the secondary task (the "younger complex group"). Then, to look at the effects of aging, the performance of the 30 younger adults who executed the simple tapping sequence was compared to the performance of 30 older adults who completed the same task (the "older adults group"). This allowed us to explore the decline in dual-task abilities as a function of age. Lastly, to test whether younger participants experience a qualitatively similar decline in attentional processing under more complex conditions, we compared the performance of the older adults to that of the younger adults who completed the complex tapping task.

Participants

We tested a total of 90 participants, split into three groups of 30 participants each, who were recruited at the Department of Psychology, Ludwig Maximilians Universität, in Munich and the Department of Neurology, Jena University Hospital, in Jena, Germany: An older group aged between 50 and 78 years, one younger group aged between 19–35 years performing a simple tapping sequence and another younger group with an age of 18–34 years performing a complex tapping sequence. All participants had normal or corrected to normal vision and no history of neurological or psychiatric disorders. The older participants were tested for signs of beginning dementia (MMSE; all values $\geq$ 27; all values $\geq$ 26; and MOCA; Folstein et al., 1975; Nasreddine et al., 2005). Handedness was assessed with the Edinburgh Handedness Inventory (Oldfield, 1971) and vocabulary as an estimate of crystallized intelligence with the "Mehrfachwahl-Wortschatz-Test" (MWT-B; Lehrl, 1977). Due to changes in educational and occupational standards over the years, we created a sociodemographic score based on vocabulary (an estimate of crystallized intelligence), number of school years, and occupation (please see the **Supplementary Material** for a full overview of how this score was constructed). This sociodemographic score indicated that there were no significant differences between the various groups. The study was approved by the Ethics Committees of the Jena University Hospital and of the Ludwig-Maximilians-Universität München, and all participants gave written informed consent prior to participation, in accordance with the Declaration of Helsinki. Each participant received monetary remuneration. Relevant demographic data for each group are listed in **Table 1**.

Apparatus

In both locations, the data was collected in dimly lit- and sound-attenuated rooms so as to minimize distractions. Stimuli were presented on ASUS VG248 17-inch monitors with a refresh rate of 100 Hz and a resolution of 1920 × 1080 and a viewing distance of 60 cm. The tapping task was conducted on external keyboards attached to the computer on which the experiments were run. The height of the screen was adjusted for each participant,

TABLE 1 | Demographic data and sociodemographic score for younger participants who performed the simple or complex tapping sequence and for older participants who performed the simple tapping sequence.

Variable	Older (*N* = 30)	Younger simple (*N* = 30)	Younger complex (*N* = 30)
Gender (N): m/f	16/14	18/12	13/17
Handedness: r/a	29/1	30/0	30/0
Age (years): Mn/SD/range	65.0/7.6/50–78	26.1/3.8/19–35	25.7/4.1/18–34
Sociodemographic score: Mn/SD/range	7.4/1.3/5–9	6.7/1.4/4–9	7.2/1.1/5–9

Demographics include gender (number), handedness (number), age, and sociodemographic score.
M, male; f, female; r, right; a, ambidextrous; Mn, Mean; SD, standard deviation.

such that the center of the screen was directly at eye level. Because of the setup of the apparatus, the keyboard was located below participants' visual periphery. Thus, to visually monitor their tapping performance, participants would have had to move their heads downwards so as to see their hands. Not only were participants instructed to not look down, and to continuously maintain fixation at the center of the screen, but their compliance was also monitored by the examiner.

Procedure

All participants completed a single session which lasted around 60 min. Approximately 20 min were spent on questionnaires aimed at obtaining demographic information. The remaining 40 min were allocated to the tapping tasks and TVA based whole report, with breaks being taken as needed. The task order was counterbalanced between participants, such that half of all participants began with the two single tasks before commencing to the dual-task condition, while the other half started with the dual-task condition, before completing the two single tasks. In this case, the single tapping was always first performed first.

Tapping Task

This task was carried out using the dominant hand to continuously tap a given sequence. The simple sequence consisted of using the index and middle fingers to press the "1" and "2" keys respectively, while the more complex sequence required the use of the index, middle, ring, and pinky fingers to press the "F4," "F3," "F2," and "F1" keys (with the keyboard turned upside down to reduce interference from other keys) respectively (see **Figure 1** for a diagrammatic representation of these two sequences). The more complex sequence was deduced from an unpublished pilot study in which we tested the effects of varying sequence complexities in younger participants. The complex sequence used in the current study was found to be moderately challenging, but manageable for most participants.

The allocated sequence was then tapped at a subjectively preferred pace for a prespecified amount of time. As per the methodology used by Kane and Engle (2000), the single condition of the tapping task consisted of three blocks. The first block spanned 30 s, and was used to familiarize the participant with the sequence to be tapped. If performance on this block was unsatisfactory, the block could be repeated. However, if the performance on the first block was above 80% accuracy, the participant could go on to the second block, which lasted 60 s, during which time the average tapping speed was calculated. In this block, if the wrong key was pressed, auditory feedback in the form of a beep was given to the participant. If this block was performed below 80% accuracy, it could be repeated. However, if performance was satisfactory, the participant could proceed to the third block. Here, the average tapping speed calculated in the second block was added to a buffer of 150 ms. This was then used as the cut-off speed for the third block. Thus, if a participant took longer than this cut-off speed to press a key, or if the wrong key was pressed, a beep was again used as auditory feedback. This final block lasted 3 min, as this time-frame is equivalent to the average duration of a block in the whole report task. It was also a reasonable duration which should not lead to discomfort or hand cramps for the participants according to experience from a previous study (Künstler et al., 2017). A text file was created which recorded the time stamps and tapping speed for each key press, along with information about which key was pressed. This information allowed the *post-hoc* calculation of each participant's speed and accuracy, and also allowed the time-stamps to be compared between tasks in the dual-tasking condition. The average tapping accuracy and standard deviations for all groups and conditions can be found in **Table 2**[1].

Whole Report Task

This task was run in Matlab[2], using Psychtoolbox (Brainard, 1997). The experiment consisted of a total of 140 trials. At the start of each trial, a fixation point was displayed in the center of the screen for 1,000 ms. Subsequently, six isoluminant letters appeared around the fixation point, displayed equidistantly in an invisible circle. These letters were drawn at random from a predefined set of letters (all letters of the alphabet, excluding I, Q, and Y), with the size being set to 1.5 by 1.5 cm. These letters were either all blue [Color space: CIE L × a × b blue = (17.95; 45.15; —67.08)] or red [CIE L × a × b red = (28.51; 46.06; 41.28)], with a luminance of 0.49cd/m2. In 40 trials, the stimuli were masked. Once the screen went blank, participants were tasked with verbally reporting as many of the observed letters as possible; an unspeeded task, thereby allowing each participant as much time as necessary. The responses were then typed in by the researcher, who was seated behind the participant, before going on to the next trial. The timestamps of the responses, as well as the responses made, and the correct responses were exported to a text file. Following each block, participants received accuracy feedback on-screen, indicating what percentage out of the letters actually reported was correct. Performance between 70 and 90% was seen as optimal. If the accuracy rate dropped below 70%, participants were asked to be more conservative in their answers. If their accuracy was above 90%, participants were asked to try reporting more letters. A diagrammatic representation of a trial sequence can be found in **Figure 2**. The mean accuracy for this criterion in the single and dual task conditions was 87.6 ($SD = 4.7$) and 86.4 ($SD = 4.2$) for the older group, 86.5 ($SD = 6.6$) and 85.8 ($SD = 6.4$) for the younger simple group, and 87.5 ($SD = 5.8$) and 85.1 ($SD = 5.6$) for the younger complex group.

Initially, the task instructions were displayed on-screen, followed by two examples. Subsequently, a pretest, consisting of 12 triples of trials, was run over the course of four blocks. This served to familiarize the participants with the task, as well as to individually adjust the exposure duration to each participant through the use of a Bayesian adaptive staircase model. Two of the trials in each triple were not used for adjustment; one was unmasked with exposure duration of 200 ms, while the other was masked and presented for 250 ms. This long exposure duration

[1] For this study, we only analyzed tapping accuracy as a measure for effects of the dual task situation on the motor task. For the interested reader, average tapping speed and standard deviations as well as individual values and the distribution of tapping speed can be found in the **Supplementary Materials in Tables 1, 4 and Figures 5–7**.

[2] MATLAB and Statistics Toolbox Release. (2012). The MathWorks, Inc., Natick.

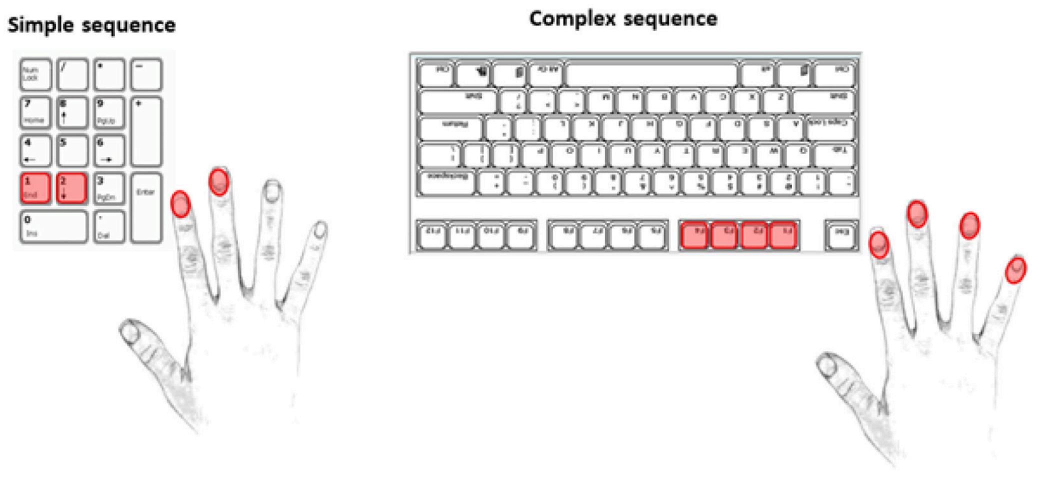


FIGURE 1 | Simple and complex tapping sequences. Used keys and fingers are marked in red.

TABLE 2 | Tapping accuracy and TVA parameter values across all conditions and groups.

Parameters	Older		Younger simple		Younger complex	
	Single Task	Dual Task	Single Task	Dual Task	Single Task	Dual Task
Tapping accuracy: Mn/SD/N	97.5/4.6/30	96.4/3.3/29	98.8/1.4/29	98.8/1.2/30	96.2/4.6/29	96.3/3.2/30
WR minimum EDs: Mn/SD/N	12.0/4.8/30	14.0/7.2/30	10.0/0.0/30	10.0/0.0/30	11.0/4.0/30	10.7/3.7/30
WR maximum EDs: Mn/SD/N	202.3/5.0/30	204.3/7.3/30	200.7/2.5/30	200.7/2.5/30	201.7/4.6/30	201.3/4.3/30
Parameter *K:* Mn/SD/N	3.1/0.6/30	2.8/0.6/30	3.7/0.7/30	3.7/0.7/30	3.8/0.8/30	3.5/0.8/30
Parameter *C:* Mn/SD/N	31.7/ 9.2/30	28.6/12.8/30	34.3/16.6/30	31.4/14.2/30	31.2/15.4/30	30.2/14.3/30
Parameter *t0:* Mn/SD/N	11.9/13.5/30	12.4/13.9/30	−1.8/15.1/30	−3.0/ 13.1/30	−1.4/15.2/30	−3.1/15.9/30

Mn, Mean; SD, standard deviation; N, sample size; WR, Whole Report; ED, exposure duration.

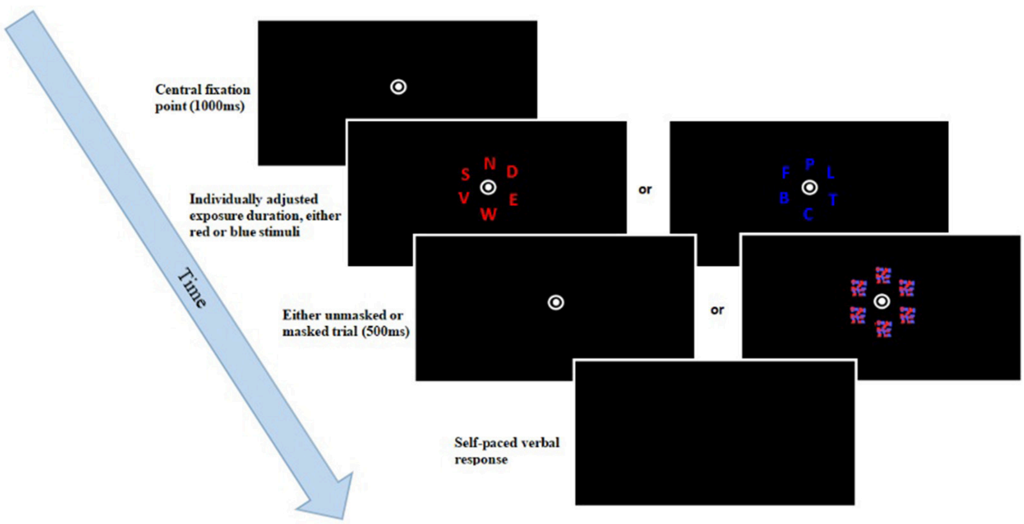


FIGURE 2 | TVA whole report trial sequence. After the presentation of a fixation point, six either red or blue letters were briefly displayed, followed by a mask in some of the trials. Participants had to name all letters they had recognized.

was only used to familiarize the participant with the task; in the experiment itself, shorter, and adjusted exposure durations were used. Only one trial in each triple was critical for exposure adjustment; this was masked and initially displayed for 100 ms. If at least one letter in such a critical trial was reported correctly, the exposure duration was decreased by 10 ms in the following critical trial. This was repeated until a final exposure duration was identified at which the participant was unable to report any letter correctly. This was then taken to be the lowest exposure duration, and was used together with four other pre-set exposure durations, which were picked based on the lowest, individually adjusted exposure duration. Stimuli in five conditions, using the different exposure durations, were masked. These masks, which comprised a red/blue mesh of overlapping flecks, were 2 by 2 cm in size, and covered the stimuli for 500 ms. They were used to avoid visual persistence effects, as visual information in unmasked trials typically persists by several hundred milliseconds (Sperling, 1960; Dick, 1974). In addition to these five masked conditions, two unmasked conditions were used, using the second shortest and the longest exposure duration, giving rise to a total of seven effective exposure duration conditions. Such a broad spectrum of exposure durations is necessary to measure a wide range of performance, allowing for the estimation of different parameters. For example, t_0, the perceptual threshold, is calculated based on performance changes at lower exposure durations close to the minimum individual effective exposure duration. Exact quantification of t_0 is in turn needed to determine the rate of information uptake at t_0, indexed by parameter C. However, the computation of the VSTM storage capacity, which is demarcated by the asymptote of performance or parameter K, requires higher exposure durations. For each of the seven effective exposure conditions, 20 trials were included in the study, resulting in a total of 140 trials, divided into four experimental blocks. The obtained data could then be further analyzed through the LibTVA script (Dyrholm, 2012) in Matlab[2] which calculated a maximum likelihood fit for the data, according to the principles of TVA. This was done for each participant, and utilizes observed data to extrapolate probabilistic parameters, based on the fixed capacity independent race model (see Shibuya and Bundesen, 1988). Our model had eight degrees of freedom: Five for parameter K and one each for parameters C, $t0$, and μ ("iconic memory buffer," of no particular interest to this study). The average minimum and maximum exposure durations for each group and condition can be found in **Table 2**.

Dual-Task

In this condition, participants completed the whole report task while simultaneously and continuously tapping. Participants initially performed the familiarization and speed adjustment blocks of the tapping task, after which the whole report paradigm was started. This was then followed by the simultaneous execution of both tasks concurrently, while participants' gaze remained fixated to the center of the screen. The timestamps of the data points of both tasks were compared. If the participant made a mistake in the tapping task, then the corresponding trial in the whole report task was excluded from the analysis. This was done in order to examine attentional parameters only in those trials where the tapping was successfully executed. On average, 5.7 ($SD = 6.9$) trials were excluded in the older simple group, 3.1 ($SD = 4.3$) trials were excluded in the younger simple group and 9.0 ($SD = 7.2$) trials were excluded in the younger complex group. **Supplementary Table 4** shows how the exclusion of trials affected Goodness-of-Fit values.

Goodness of Fit

As the whole report results were obtained through a mathematical model, we wanted to ensure that the observed data was closely mirrored by the estimated parameters. To this end, we did a Goodness of Fit analysis. These Goodness of Fit values give an indication of how much of the variance of the empirically observed data is explained by the model estimates provided by TVA. Thus, the higher the explained variance, the more closely the parameter estimates match the actual data obtained.

Furthermore, these Goodness of Fit results also provided an estimation of how robust these estimates were between the single and dual task conditions. More precisely, TVA posits that the processes indexed by the parameter estimates remain stable across comparable conditions. Violations of this assumption, e.g., due to the switching between tasks, would be expected to result in a lower Goodness of Fit in the dual task condition.

RESULTS

The accuracy of the letter whole report was modeled as a function of effective exposure duration for each participant and task condition (single whole report task condition, dual task condition), from which parameters K (VSTM storage capacity in number of objects), C (visual processing speed in objects/s) and t_0[3] (visual threshold in ms) were derived. For the tapping task, overall accuracy was computed for each task condition (single tapping task condition, dual task condition). The means and standard deviations of these parameter estimates are given for each group in **Table 2**.

We computed separate repeated-measures ANOVAs for tapping accuracy and TVA parameters. For comparison of older participants performing the simple tapping sequence to either younger participants performing the simple tapping sequence or younger participants performing the complex tapping sequence we included the factors Age Group (older vs. younger) and Task Condition (single task vs. dual task). Three tapping accuracy values were missing (one from each group) due to technical errors. For the sake of interest, several further analyses can be found in the **Supplementary Materials**, including a comparison between the two younger groups. Furthermore, for individual values of TVA parameters and tapping accuracy see **Supplementary Table 4**, while the individual variability in TVA parameter K is provided in **Supplementary Figures 2–4**.

[3]Possibly due to subjects' inappropriate guessing during letter report, or to inefficient masking, TVA-based modeling provided negative $t0$ values in multiple cases. We handled this problem by calculating our analyzes in two alternative ways: first, based on the model fit providing negative t0 values; second, based on a model fit constraining the minimum t0 value to zero. Both analyses generally revealed the same effects and group interactions. The data are provided in the **Supplementary Materials in Tables 2, 3 and 5**.

Older Group Performing the Simple Tapping Sequence vs. Younger Group Performing the Simple Tapping Sequence

To look for age effects on tapping accuracy and TVA parameters in a dual task situation a comparison was run between older and younger participants who both performed the simple tapping sequence.

Tapping

For tapping accuracy (see **Table 2**), we found a significant main effect of Age Group [$F_{(1, 56)} = 7.06$, $p = 0.01$; $\eta_p^2 = 0.11$]. The main effect of Task Condition [$F_{(1, 56)} = 1.56$, $p = 0.22$; $\eta_p^2 = 0.03$], and the interaction [$F_{(1, 56)} = 2.06$, $p = 0.16$; $\eta_p^2 = 0.04$] were not significant. Thus, younger and older participants differed in their general tapping accuracy, but neither group's tapping accuracy was affected by the concurrent visual task. Results are depicted in **Figure 3**.

Whole Report

For VSTM storage capacity *K* (see **Table 2**), we found significant main effects of Age Group [$F_{(1, 58)} = 19.91$, $p < 0.001$, $\eta_p^2 = 0.26$] and Task Condition [$F_{(1, 58)} = 17.05$, $p < 0.001$, $\eta_p^2 = 0.23$], and a significant interaction [$F_{(1, 58)} = 10.01$, $p = 0.002$, $\eta_p^2 = 0.15$; see **Figure 4**]. *Post-hoc* pairwise *t*-tests with Bonferroni-correction demonstrated that there was a significant decline in VSTM storage capacity in the older group induced by the tapping [$t_{(29)} = 4.49$, $p < 0.001$, $d = 0.52$], while, as described before, the younger group performing the same, simple tapping sequence did not show this effect [$t_{(29)} = 0.83$, $p = 0.41$, $d = 0.06$].

For processing speed *C* (see **Table 2**) no significant main effect of Age Group was found [$F_{(1, 58)} = 0.76$, $p = 0.39$; $\eta_p^2 = 0.01$]. There was a trend for an effect for Task Condition, indicating lower performance in the dual-task compared to the single-task condition across groups [$F_{(1, 58)} = 3.37$, $p = 0.07$; $\eta_p^2 = 0.06$]. The interaction was not significant [$F_{(1, 58)} = 0.002$, $p = 0.97$; $\eta_p^2 < 0.0014$]. Thus, there was no indication for a general age effect or for an increased dual task effect with increased age.

Similar effects as for processing speed were also found for the perceptual threshold parameter t_0 (see **Table 2**). There was only a significant effect for Age Group [$F_{(1, 58)} = 20.09$, $p < 0.001$; $\eta_p^2 = 0.26$], while the main effect for Task Condition [$F_{(1, 58)} = 0.06$, $p = 0.81$; $\eta_p^2 = 0.001$] and the interaction [$F_{(1, 58)} = 0.27$, $p = 0.60$; $\eta_p^2 = 0.005$] were not significant. Thus, significantly higher thresholds for older compared to younger adults were found in both task conditions, while there was no evidence for an age-specific dual task decrement for visual threshold t_0.

Older Group Performing the Simple Tapping Sequence vs. Younger Group Performing the Complex Tapping Sequence

Older participants' performance was also compared to that of the younger participants who completed the complex tapping sequence to see whether younger participants would show comparable effects as older participants under a more challenging dual-task condition.

Tapping

No significant main effect of Age Group [$F_{(1, 56)} = 0.79$, $p = 0.38$; $\eta_p^2 = 0.01$] or Task Condition [$F_{(1, 56)} = 0.99$, $p = 0.33$; $\eta_p^2 = 0.02$] was found on tapping performance. The interaction [$F_{(1, 56)} = 1.05$, $p = 0.31$; $\eta_p^2 = 0.02$] was also not significant. Thus, neither older participants nor younger adults performing a complex tapping sequence showed dual-task effects on motor performance induced by an additional visual attention task (see **Table 2**, **Figure 5**).

Whole Report

For VSTM storage capacity *K* (see **Table 2**), we found significant main effects of Age Group [$F_{(1, 58)} = 15.69$, $p < 0.001$, $\eta_p^2 = 0.21$] and Task Condition [$F_{(1, 58)} = 35.87$, $p < 0.001$, $\eta_p^2 = 0.38$], but no significant interaction [$F_{(1, 58)} = 0.17$, $p = 0.68$, $\eta_p^2 = 0.003$]. Thus, the older group showed a general reduction compared to the younger one in VSTM storage capacity *K*, and, across groups, dual task effects occurred. However, no indication was found for an enhanced dual task effect in VSTM storage capacity in the older group when a younger group had to perform a more challenging motor task. **Figure 6** shows comparable reductions of VSTM storage capacity *K* for both age groups.

For parameter visual processing speed *C* (see **Table 2**), we did not find any significant effects [Age Group: $F_{(1, 58)} = 0.03$, $p = 0.88$; $\eta_p^2 < 0.001$; Task Condition: $F_{(1, 58)} = 1.94$, $p = 0.17$; $\eta_p^2 = 0.03$; Interaction: $F_{(1, 58)} = 0.48$, $p = 0.49$; $\eta_p^2 = 0.008$]. Thus, older and younger participants did not differ in visual processing speed, and none of the groups were affected by the secondary task.

We found a significant main effect for Age Group for visual threshold t_0 (see **Table 2**) [$F_{(1, 58)} = 17.42$, $p < 0.001$, $\eta_p^2 = 0.23$], but no other significant effects [Task Condition: $F_{(1, 58)} = 0.18$, $p = 0.68$; $\eta_p^2 = 0.003$; Interaction: $F_{(1, 58)} = 0.49$, $p = 0.49$; $\eta_p^2 = 0.008$]. The visual threshold was significantly higher in the older group compared to the younger group performing the complex tapping sequence, but there were no indications for a difference in t_0 between the single and dual task conditions in the younger or older groups.

Goodness of Fit

To test to what degree the empirical data obtained in the different experimental whole report conditions was explained by the TVA-based modeling, Goodness-of-fit measures were obtained. They showed that there was a close correspondence between the empirical data (mean accuracy scores) obtained in the different experimental conditions of the whole report and the values that would be predicted based on the TVA parameter estimates. The average Pearson product-moment correlation coefficients are listed in **Table 3**. They show for each participant group, and very similarly in single and dual task conditions, that at least 96% of the variance in the observed data is explained by the TVA model parameters. Across all participants, the model explained at least

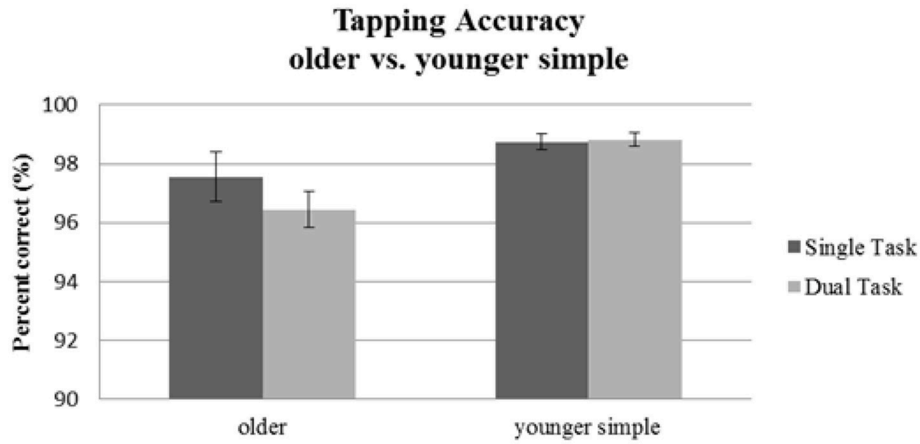


FIGURE 3 | Tapping accuracy as indicated by percentage of correct taps for the older group performing the simple tapping sequence vs. the younger group performing the simple tapping sequence. Error bars indicate standard errors of the mean.

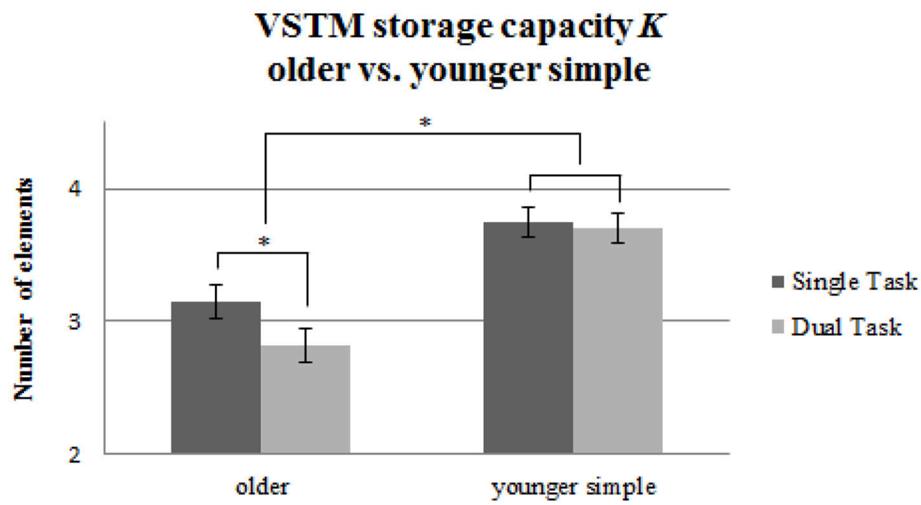


FIGURE 4 | VSTM capacity *K* measured in maximum number of recognized letters for the older group performing the simple tapping sequence vs. the younger group performing the simple tapping sequence. Error bars indicate standard errors of the mean. Significant differences are denoted by an asterisk (*).

89% of the variance. For individual Goodness-of-fit measures see **Table 4** in the Supplementary Materials.

DISCUSSION

This study was aimed at specifying which aspects of visual attention capacity are disproportionately affected in elderly individuals in motor-cognitive dual task situations. To that end, we investigated the influence of a concurrent tapping task on the performance of a visual attention task (whole report) in older and younger participants, whilst additionally modulating the difficulty of the motor task performed by the younger adults. TVA model-based fitting of whole report performance provided estimates of separate visual attention capacity parameters.

When older participants performed a simple tapping task concurrently with the visual attention task, their VSTM storage capacity declined. However, when younger participants performed the same simple tapping sequence under dual task conditions, attention capacity did not show any significant decrement. However, in another group of younger participants performing a more challenging tapping task under dual task conditions, their VSTM storage capacity declined significantly as well. Tapping accuracy—although generally at a lower level in the older group than in the younger group performing the simple tapping task—remained unaffected by the load incurred by the dual task.

A comparison between the older participants performing the simple tapping, and the younger participants performing the complex tapping task, revealed that the effect of an additional tapping task on VSTM storage capacity was equally pronounced in both groups, although older adults, overall, had lower VSTM storage capacity than younger participants.

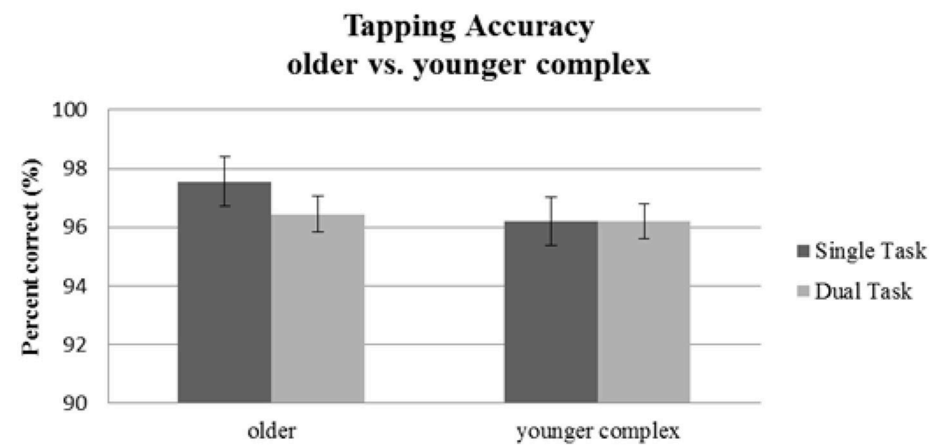


FIGURE 5 | Tapping accuracy as indicated by percentage of correct taps for the older group performing the simple tapping sequence vs. the younger group performing the complex tapping sequence. Error bars indicate standard errors of the mean.

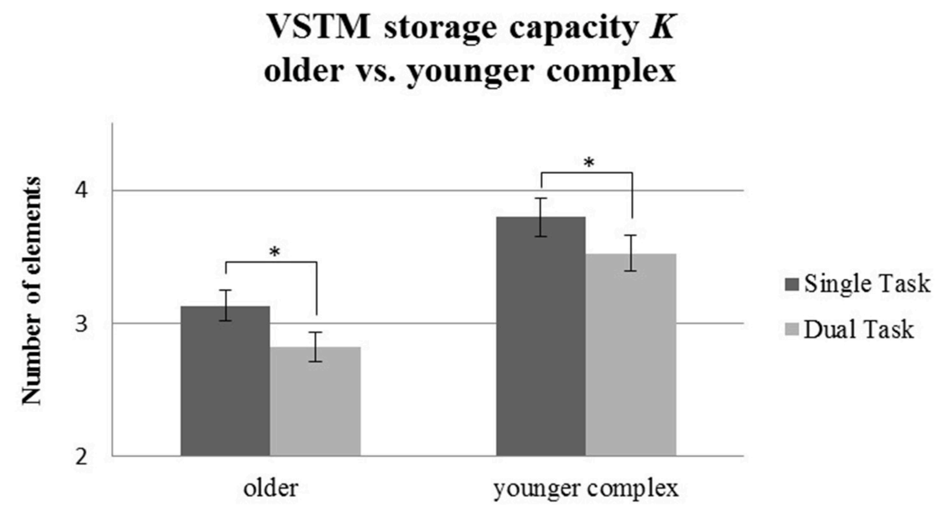


FIGURE 6 | VSTM capacity *K* measured in maximum number of recognized letters for the older group performing the simple tapping sequence vs. the younger group performing the complex tapping sequence. Error bars indicate standard errors of the mean. Significant differences are denoted by an asterisk (*).

Similar to McAvinue et al. (2012) we found that older participants had a lower VSTM storage capacity, a higher visual threshold and—at least numerically—a lower perceptual processing speed than younger participants. These results are typical of older adults with normal or corrected-to-normal eyesight (see also Habekost et al., 2013; Espeseth et al., 2014). The fact that we did not see significant differences in perceptual processing speed seems to be driven by high standard deviations.

Taken together, these results shed considerable light on the nature of motor-cognitive dual task interference: Firstly, concurrent performance of a motor task seems to affect visual attention capacity quite selectively by way of reducing VSTM storage capacity. It was especially the number of items that could be maintained within VSTM that declined under dual task conditions. This was true both for older subjects performing the simple tapping, and for younger subjects performing the more complex tapping task. The remaining parameters obtained from TVA-based fitting were not significantly affected. That is, the perceptual threshold and the visual processing rate did not decline under dual-task compared to single-task conditions in any age group.

Secondly, the effect of the motor task on VSTM storage capacity appears to be more pronounced in older participants. Whilst the simple tapping sequence put only a minor demand on younger participants, this same task caused considerable dual task effects in the older adults. The VSTM decrement found in these older participants more or less equaled the decline revealed in younger adults performing the more complex tapping task. The aging effect thus seems to reflect the fact that a simple motor task is more challenging for older participants. In other words, even a simple motor program consisting of a sequence of concurrent finger tapping significantly decreased VSTM storage

TABLE 3 | Correlations between observed and modeled data: Goodness-of-Fit values (Pearson-product-moment correlation *r*) for single and dual-task-conditions for all three groups.

	Single Task	Dual Task uncorrected	Dual Task corrected
Older: Mn/SD/Range	0.97/0.02/0.896–0.997	0.96/0.02/0.901–0.996	0.96/0.03/0.901–0.998
Younger Simple: Mn/SD/Range	0.98/0.02/0.907–0.996	0.98/0.01/0.944–0.998	0.98/0.01/0.944–0.998
Younger Complex: Mn/SD/Range	0.98/0.02/0.922–0.998	0.98/0.02/0.905–1.00	0.98/0.02/0.906–1.0

Mn: Mean; SD: standard deviation

capacity in older adults, an effect which was only present to the same extent in younger adults when they performed a more complex motor task. Overall, the results of this study support capacity sharing accounts of dual tasking (e.g., Navon and Miller, 2002), implicating the VSTM storage capacity as being the limiting attentional capacity which is shared across the two tasks. Thus, as long as the capacity limits of the VSTM are not reached, the performance of both tasks remains unaffected. However, when the task demands exceed the limits of this capacity, such as when the task demands are increased, then the performance on the tasks is reduced.

In sum, our results show that the age-specific effects of motor-cognitive dual task interference are based on a stronger decline of VSTM storage capacity.

Our results are largely consistent with recent data presented by Künstler et al. (2017) who used the same method in a group of middle to higher aged subjects and combined the whole report task with the simple tapping task. In this study, a decrement of both VSTM storage capacity and processing rate was found under dual task conditions. The effect was more pronounced for VSTM, however, and a direct investigation of which parameter more strongly reflects the dual task related decline was not possible in this study. In line with these results, we found a clear decline of VSTM storage capacity in older subjects and in younger subjects performing a more complex tapping task, while the effects on processing rate were much weaker, and non-significant. Moreover, we were able to show that the age-related decline of attention capacity under motor-cognitive dual-task conditions is selectively reflected by parameter VSTM.

An important result of the Künstler et al. (2017) study was the demonstration that the performance of the whole report task, which was used to assess visual attention capacity, was qualitatively comparable under both single and dual task conditions. This was shown, for instance, by the fact that goodness-of-fit measures were comparable under both conditions. In this way, the valid applicability of the TVA-model—which assumes parameter estimates to remain constant across the task—under both single and dual task conditions was proven. Consequently, a conjecture that the whole report task would be performed in a non-continuous manner under dual task conditions (for example by switching attention between the two tasks) was not supported. Analogously, comparable goodness-of-fit measures across the single and the dual task conditions were obtained also in the present study. This in turn corroborates that participants performed both tasks simultaneously and continuously, as evidenced by the high correlations between the observed and the predicted data, also obtained in the present study. Thus, in congruence with the previous study, we would suggest that the results of the present study indicate that both tasks were executed simultaneously and in a qualitatively similar, although quantitatively less efficient way under the dual task as compared to single task condition.

The results of the present study are in line with earlier studies showing that motor-cognitive dual task interference is increased in aging (Kramer and Larish, 1996; Verhaeghen et al., 2002, 2003; Woollacott and Shumway-Cook, 2002; Boisgontier et al., 2013; Schaefer, 2014). They are also congruent with other studies which have indicated that increased task demands are linked with decreased spatial awareness during dual tasking (Lisi et al., 2015).

However, by referring to an explicit theoretical framework modeling attentional processing capacity, it was possible for the present study to specifically attribute the capacity limitation to the constraint in VSTM storage capacity.

To explain these findings, in the previous study (Künstler et al., 2017) we proposed that, when it comes to dual task situations, the VSTM represents a stage of response selection, at which verbal output is required in the whole report task, whilst simultaneously preparing the finger movement output for the tapping task. A similar view was proposed by Klapp (1976) who considered short-term memory as a stage of motor-response programming where response commands are temporarily stored. Under motor-cognitive dual-task conditions, when several response commands have to be maintained in parallel, the probability of interference at this stage is increased by cross-talk effects, resulting in a performance decline. Due to the fact that aging is associated with an overall decline of VSTM storage capacity, the reliability of maintained representations would be reduced in this group, giving rise to an even higher probability of interference (Jonides et al., 2008).

Of course, these assumptions are speculative and need to be investigated in future studies. However, they are in line with both a resource sharing perspective on short-term memory (Franconeri et al., 2013), as well as with the view that processing capacity limitations are mainly dependent on interference control and inhibition (Kane and Engle, 2002), which appears to be significantly reduced in older subjects (Mccabe et al., 2005).

It could be argued that our results might best be accounted for within Baddeley's multicomponent working memory model (see Baddeley, 2012, for a recent review). According to this view, motor-kinetic information from the finger tapping task and visual information from the whole report task would both be represented within the same slave system, namely the visuospatial sketch pad (VSSP). Doing both tasks in parallel would, therefore, increase the load on the VSSP compared to when each of the tasks is performed separately. A possible decrease in VSSP during aging (e.g., Kessels et al., 2010) would then mean that older participants have a higher load on modality specific resources than younger participants, while a more complex tapping pattern would mean a higher load even for younger participants. We consider such an explanation as less likely, for the following reasons. First, there is of course strong evidence that observed kinesthetic movement information (Baddeley, 2012) mentions gestures and dance as examples) is represented within the viewer's sketchpad. However, whether this is also true for motor programs representing sequential finger movements that are not directly observed remains equivocal. Moreover, Logie's seminal work (Logie, 1995) has shown that the VSSP itself can be subdivided into a visual and a spatial subsystem, with movement related information only tapping into the latter. This would be inconsistent with the assumption of a modality specific interference within the VSSP. In line with this assumption, recent ERP data of Katus and Eimer (2018) implies that tactile and visual working memory representations are distinct, i.e., modality-specific, and are not transferable across different sensory modalities

In conclusion, our results indicate that tasks are processed in parallel under conditions of motor-cognitive dual tasking, and that VSTM storage capacity is a core function involved in the dual task decrement, which is particularly exacerbated during aging. Whilst younger adults only show difficulties when the complexity of the secondary task is increased, older adults already show qualitatively similar decrements in the VSTM capacity when performing a simple secondary motor task.

AUTHOR CONTRIBUTIONS

EK, MP, HM, KF, and PB contributed to the design of the study. NN contributed the necessary programming of the experiments used in this study. EK and MP collected the data, analyzed the results, and wrote the manuscript. KF and PB both supervised the data analysis and the writing of the manuscript. OW, CK, PB, and KF contributed to the data discussion. OW, PB, and CK contributed to the funding application. EK and MP contributed equally as first authors, whilst PB and KF both contributed equally as senior authors.

ACKNOWLEDGMENTS

This research was supported by a Grant within the Priority Program, SPP1772 from the German Research Foundation (Deutsche Forschungsgemeinschaft, DFG), Grant number SPP 1772/1—BU 1327/4-1.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpsyg.2018.01564/full#supplementary-material

REFERENCES

Aben, B., Stapert, S., and Blokland, A. (2012). About the distinction between working memory and short-term memory. *Front. Psychol.* 3:301. doi: 10.3389/fpsyg.2012.00301

Baddeley, A. (2012). Working memory: theories, models, and controversies. *Annu. Rev. Psychol*. 63, 1–29. doi: 10.1146/annurev-psych-120710-100422

Boisgontier, M. P., Beets, I. A., Duysens, J., Nieuwboer, A., Krampe, R. T., and Swinnen, S. P. (2013). Age-related differences in attentional cost associated with postural dual-tasks: increased recruitment of generic cognitive resources in older adults. *Neurosci. Biobehav. Rev.* 37, 1824–1837. doi: 10.1016/j.neubiorev.2013.07.014

Brainard, D. H. (1997). The psychophysics toolbox. *Spat. Vis.* 10, 433–436. doi: 10.1163/156856897X00357

Bundesen, C. (1990). A theory of visual attention. *Psychol. Rev.* 97, 523–547. doi: 10.1037/0033-295X.97.4.523

Bundesen, C., Habekost, T., and Kyllingsbaek, S. (2005). A neural theory of visual attention: bridging cognition and neurophysiology. *Psychol. Rev.* 112:291. doi: 10.1037/0033-295X.112.2.291

Bundesen, C., Vangkilde, S., and Petersen, A. (2015). Recent developments in a computational theory of visual attention (TVA). *Vis. Res.* 116, 210–218. doi: 10.1016/j.visres.2014.11.005

Dick, A. O. (1974). Iconic memory and its relation to perceptual processing and other memory mechanisms. *Percept. Psychophys.* 16, 575–596. doi: 10.3758/BF03198590

Dyrholm, M. (2012). *LIBTVA User Guide*. Available online at: http://cvc.psy.ku.dk/resources/matlab-toolbox-for-modeling/ (Accessed Nov 29, 2017).

Espeseth, T., Vangkilde, S. A., Petersen, A., Dyrholm, M., and Westlye, L. T. (2014). TVA–based assessment of attentional capacities–associations with age and indices of brain white matter microstructure. *Front. Psychol.* 5:1177. doi: 10.3389/fpsyg.2014.01177

Faulkner, K. A., Redfern, M. S., Cauley, J. A., Landsittel, D. P., Studenski, S. A., Rosano, C., et al. (2007). Multitasking: association between poorer performance and a history of recurrent falls. *J. Am. Geriatr. Soc.* 55, 570–576. doi: 10.1111/j.1532-5415.2007.01147.x

Folstein, M. F., Folstein, S. E., and McHugh, P. R. (1975). "Mini-mental state". A practical method for grading the cognitive state of patients for the clinician. *J. Psychiatr. Res.* 12, 189–198. doi: 10.1016/0022-3956(75)90026-6

Franconeri, S. L., Alvarez, G. A., and Cavanagh, P. (2013). Flexible cognitive resources: competitive content maps for attention and memory. *Trends Cogn. Sci.* 17, 134–141. doi: 10.1016/j.tics.2013.01.010

Habekost, T. (2015). Clinical TVA-based studies: a general review. *Front. Psychol.* 6, 290–301. doi: 10.3389/fpsyg.2015.00290

Habekost, T., Vogel, A., Rostrup, E., Bundesen, C., Kyllingsbaek, S., Garde, E., et al. (2013). Visual processing speed in old age. *Scand. J. Psychol.* 54, 89–94. doi: 10.1111/sjop.12008

Jonides, J., Lewis, R. L., Nee, D. E., Lustig, C. A., Berman, M. G., and Moore, K. S. (2008). The mind and brain of short-term memory. *Ann. Rev. Psychol.* 59, 193–224. doi: 10.1146/annurev.psych.59.103006.093615

Kahneman, D. (1973). *Attention and Effort*. Englewood Cliffs, NJ: Prentice-Hall International.

Kane, M. J., and Engle, R. W. (2000). Working-memory capacity, proactive interference, and divided attention: limits on long-term memory retrieval. *J. Exp. Psychol.* 26, 336–358. doi: 10.1037/0278-7393.26.2.336

Kane, M. J., and Engle, R. W. (2002). The role of prefrontal cortex in working-memory capacity, executive attention, and general fluid intelligence: an individual-differences perspective. *Psychon. Bull. Rev.* 9, 637–671. doi: 10.3758/BF03196323

Katus, T., and Eimer, M. (2018). Independent attention mechanisms control the activation of tactile and visual working memory representations. *J. Cogn. Neurosci.* 30, 644–655. doi: 10.1162/jocn_a_01239

Kessels, R. P., Meulenbroek, O., Fernández, G., and Olde Rikkert, M. G. (2010). Spatial working memory in aging and mild cognitive impairment: effects of task load and contextual cueing. *Aging Neuropsychol. Cogn.* 17, 556–574. doi: 10.1080/13825585.2010.481354

Ketcham, C. J., and Stélmach, G. E. (2001). "Age-related declines in motor control," in *Handbook of Psychology of Aging, 5th Edn.*, eds J. Birren and K. W. Schaie (San Diego, CA: Academic Press), 313–348.

Klapp, S. T. (1976). Short-term memory as a response preparation state. *Mem. Cogn.* 4, 721–729. doi: 10.3758/BF03213240

Kramer, A. F., and Larish, J. L. (1996). "Aging and dual-task performance," in *Aging and Skilled Performance*, eds W. A. Rogers, A. D. Fisk, and N. Walker (Hillsdale, NJ: Lawrence Erlbaum Associates), 83–112.

Künstler, E. C. S., Finke, K., Günther, A., Klingner, C., Witte, O., and Bublak, P. (2017). Motor cognitive dual-task performance: effects of a concurrent motor task on distinct components of visual processing capacity. *Psychol. Res.* 82, 177–185. doi: 10.1007/s00426-017-0951-x

Kyllingsbaek, S. (2006). Modeling visual attention. *Behav. Res. Methods* 38, 123–133. doi: 10.3758/BF03192757

Lehrl, S. (1977). *Mehrfachwahl-Wortschatz-Intelligenztest*. Erlangen: Manual zum MWT-B.

Lehrl, S. (1999). *Mehrfachwahl-Wortschatz-Intelligenztest: Manual mit Block MWT-B*. Balingen: Spitta Verlag.

Lindenberger, U. (2014). Human cognitive aging: corriger la fortune? *Science* 346, 572–578. doi: 10.1126/science.1254403

Lisi, M., Bonato, M., and Zorzi, M. (2015). Pupil dilation reveals top–down attentional load during spatial monitoring. *Biol. Psychol.* 112, 39–45. doi: 10.1016/j.biopsycho.2015.10.002

Logan, G. D., and Gordon, R. D. (2001). Executive control of visual attention in dual-task situations. *Psychol. Rev.* 108, 393–434. doi: 10.1037/0033-295X.108.2.393

Logie, R. H. (1995). *Essays in Cognitive Psychology. Visuo-Spatial Working Memory*. Hillsdale, NJ.

Luck, S. J., and Vogel, E. K. (2013). Visual working memory capacity: from psychophysics and neurobiology to individual differences. *Trends Cogn. Sci.* 17, 391–400. doi: 10.1016/j.tics0.2013.06.006

McAvinue, L. P., Habekost, T., Johnson, K. A., Kyllingsbæk, S., Vangkilde, S., Bundesen, C., et al. (2012). Sustained attention, attentional selectivity, and attentional capacity across the lifespan. *Atten. Percept. Psychophys.* 74, 1570–1582. doi: 10.3758/s13414-012-0352-6

Mccabe, D. P., Robertson, C. L., and Smith, A. D. (2005). Age differences in Stroop interference in working memory. *J. Clin. Exp. Neuropsychol.* 27, 633–644. doi: 10.1080/13803390490919218

McDowd, J. M., and Craik, F. I. M. (1988). Effects of aging and task difficulty on divided attention performance. *J. Exp. Psychol. Hum. Percept. Perform.* 14, 287–280. doi: 10.1037/0096-1523.14.2.267

Nasreddine, Z. S., Phillips, N. A., Bédirian, V., Charbonneau, S., Whitehead, V., Collin, I., et al. (2005). The montreal cognitive assessment, MoCA: a brief screening tool for mild cognitive impairment. *J. Am. Geriatr. Soc.* 53, 695–699. doi: 10.1111/j.1532-5415.2005.53221.x

Navon, D., and Miller, J. (2002). Queuing or sharing? A critical evaluation of the single-bottleneck notion. *Cogn. Psychol.* 44, 193–251. doi: 10.1006/cogp.2001.0767

Oldfield, R. C. (1971). The assessment and analysis of handedness: the edinburgh inventory. *Neuropsychologia* 9, 97–113. doi: 10.1016/0028-3932(71)90067-4

Park, D. C., and Reuter-Lorenz, P. (2009). The adaptive brain: aging and neurocognitive scaffolding. *Annu. Rev. Psychol.* 60, 173–196. doi: 10.1146/annurev.psych.59.103006.093656

Pashler, H. (1994). Dual-task interference in simple tasks: data and theory. *Psychol. Bull.* 116, 220–244. doi: 10.1037/0033-2909.116.2.220

Ruthruff, E., and Lien, M. C. (2017). "Aging and attention," in *Encyclopedia of Geropsychology*, ed N. A. Pachana (Singapore: Springer), 166–172.

Schaefer, S. (2014). The ecological approach to cognitive–motor dual-tasking: findings on the effects of expertise and age. *Front. Psychol.* 5:1167. doi: 10.3389/fpsyg.2014.01167

Shibuya, H., and Bundesen, C. (1988). Visual selection from multielement displays: measuring and modeling effects of exposure duration. *J. Exp. Psychol.* 14, 591–600. doi: 10.1037/0096-1523.14.4.591

Sperling, G. (1960). The information available in brief visual presentations. *Psychol. Monogr.* 74, 1–29. doi: 10.1037/h0093759

Tombu, M., and Jolicoeur, P. (2004). Virtually no evidence for virtually perfect time-sharing. *J. Exp. Psychol. Hum. Percept. Perform.* 30, 795–810. doi: 10.1037/0096-1523.30.5.795

Verhaeghen, P. (2011). Aging and executive control: reports of a demise greatly exaggerated. *Curr. Dir. Psychol. Sci.* 20, 174–180. doi: 10.1177/0963721411408772

Verhaeghen, P., and Cerella, J. (2002). Aging, executive control, and attention: a review of meta-analyses. *Neurosci. Biobehav. Rev.* 26, 849–857. doi: 10.1016/S0149-7634(02)00071-4

Verhaeghen, P., Cerella, J., Semenec, S. C., Leo, M. A., Bopp, K. L., and Steitz, D. W. (2002). Cognitive efficiency modes in old age: performance on sequential and coordinative verbal and visuospatial tasks. *Psychol. Aging* 17, 558–570.

Verhaeghen, P., Steitz, D. W., Sliwinski, M. J., and Cerella, J. (2003). Aging and dual-task performance: a meta-analysis. *Psychol. Aging* 18:443. doi: 10.1037/0882-7974.18.3.443

Woollacott, M., and Shumway-Cook, A. (2002). Attention and the control of posture and gait: a review of an emerging area of research. *Gait Posture* 16, 1–14. doi: 10.1016/S0966-6362(01)00156-4

Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

8 Discussion

Through the findings in Study 1, the newly established paradigm showed to be a sensitive measure of motor-cognitive dual-task performance. Based on this, Study 2 not only showed that the findings of Study 1 were reproducible, but also that through minor adjustments to the second task, the paradigm can also be adapted to answer further questions of interest, especially regarding the effect of aging on dual-tasking abilities. Each of these studies shall now be addressed individually, before looking at the research from a more global perspective.

8.1: Study 1

In light of the pervasive difficulties found within dual-tasking research, and bearing in mind that the overarching objective of the DFG SPP was to create a new and integrative framework from which to understand multi-tasking, the aim of the initial study was to create and test a paradigm which would not only address these difficulties, but would also provide a new perspective into motor-cognitive dual-tasking. This was done by combining the TVA-based whole report with a simple, continuous, repetitive motor task. As described in Chapter 6, the aims of Study 1 were: 1) to precisely measure how different attentional parameters would be affected by motor-cognitive dual-tasking; 2) to see whether the tasks are processed in a parallel or serial fashion; and 3) to see whether this paradigm would be sensitive enough to be able to quantify dual-task costs. Each of these points shall be separately addressed below.

8.1.1: Visual processing capacity declines in the presence of a concurrent motor task

The primary objective of Study 1 was to see whether different attentional parameters representing visual processing capacity would be affected by motor cognitive dual-tasking. Here, the use of TVA had several distinct advantages. Most importantly, to the best of my knowledge, this is the only paradigm which allows these visual attentional sub-processes to be quantified in a mathematically independent manner and within the same task. Moreover, this was done using an approach which does not rely on any motor responses. In other words, this paradigm not only distinguishes between different attentional sub-processes, but it also allows these parameters, as well as the motor responses of the second task, to each be measured independently. Thus, as there are no motor confounds in the visual attention task, it is possible to clearly quantify the dual-task costs related to each task separately. This allowed the parameters of both the visual task and the motor task to be precisely quantified in isolation, even when both tasks are conducted simultaneously, thereby making it possible to make exact assertions about how the concurrent motor task cognitively affects the visual attention task. Indeed, this assumption is supported by the goodness-of-fit values, showing that at least 97% of the variance observed in data was explainable through the TVA model. This in turn makes this paradigm ideal for comparing single- and dual-task performance.

The accuracy results of the tapping task in the single- and dual-task conditions were nearly identical, both averaging near 97%. As there was no significant decline in the accuracy of the motor task between the single-task and the dual-task condition, it can be assumed that the motor task received the same amount of attentional weighting in both instances. In terms of the visual attention task, there was a significant drop in the processing speed and the VSTM storage capacity between the single- and dual-task conditions. However, there was no change in the perceptual threshold from one condition to the next. These findings show that in both conditions, the amount of time necessary to register the presence of visual input was the same. However, following this, there were significant differences in the rate at which this visual information was processed and how much information could be stored in the VSTM. More specifically, in the dual-task condition, participants were no longer able to process visual information as quickly, nor store as much information in the VSTM, as compared to the single-task condition. This in turn shows that even though the cognitive load of the motor task was low and remained stable across both conditions, the strain of this added task was already sufficient to adversely affect the efficiency of visual information uptake by utilising shared cognitive resources.

8.1.2: Both cognitive and motor tasks are processed in a parallel, not serial manner

Due to the precision with which different visual attentional parameters could be estimated, it was also possible to make inferences as to how the tasks were processed in the dual-task condition. In other words, having a way to objectively measure the variance in attentional parameters between the single- and dual-task conditions provided a means through which the debate between parallel and serial processing could be addressed. This was done by creating new estimates for each participant via a bootstrapping procedure, thereby providing quantitative estimates of the standard errors in the observed data (Habekost & Bundesen, 2003). As the bootstrapped estimates were obtained using a resampling technique, these estimates were even more sensitive to fluctuations in attentional performance than the original observed data. In other words, if there were trials where the participant was not paying attention to the task at hand - for example, if the attention was completely “switched” to the motor task -, then such trials had the possibility of being re-sampled multiple times during the bootstrapping procedure. This in turn would become evident as a lowered robustness of the bootstrapped estimates, manifesting as high trial-to-trial variation.

As pointed out in 5.4.2, if there was a high degree of fluctuation within the bootstrapped estimates, this would be indicative of the presence of trials in which the participant was not paying attention to the TVA task. More specifically, if the tasks were being performed in a serial fashion, then attentional resources would be switched between Task 1 and Task 2. This would mean that there would be instances in the visual attention task during which attention would be allocated to the tapping task. In other words, as attention would be allocated to the motor task (Task 2), then the visual task (Task 1) would not receive any attentional resources at that point in time. This would mean that the decline in visual attentional performance seen between the single- and dual-task condition could be the result of this time-based trade-off in attention, caused by the switching of attention between the two tasks. However, there was no difference in the amount of standard deviation in the bootstrapped data between the single- and the dual-task condition. This demonstrated that there was no switching of attention in the dual-task condition. This was again confirmed by the goodness-of-fit data, which indicated that 97% of the variance observed in the data was explained by the TVA model, which in turn assumes that visual processing occurs solely in a parallel manner.

Taken together, the bootstrapping data and the goodness-of-fit values provide unequivocal evidence that both the motor task and the visual attention task received attentional resources simultaneously. This in turn is in line with the findings of Logan and Gordon (2001), who proposed an "executive control of the theory of visual attention" (ECTVA), which combines both the theory of a structural bottleneck with the resource sharing account of dual-tasking. According to this view, the parameters estimated by TVA are subordinate, and are controlled by an executive process. Thus, resources may be shared in parallel at a more basic level, but at a higher, structural level, further processing of information is limited by a structural bottleneck. This in turn would be a very attractive model, as it would be able to use a new approach in order to unify the previously divided standpoints on whether dual-tasks are performed in a parallel or serial manner. As the overarching goal of this DFG SPP is to establish a new integrative theoretical framework which is able to elucidate different aspects of human multi-tasking behaviour, a paradigm which is able to coincide both the structural bottleneck theories with resource sharing accounts would be highly attractive.

Therefore, put briefly, these findings indicate that the paradigm was not only capable of distinguishing between different attentional parameters, but was also sensitive enough to be able to precisely quantify the dual-task costs of each task in an independent manner. This in turn lead to valuable information about how tasks are processed in a motor-cognitive dual-tasking manner:

Study 1 clearly indicates that, at a basic level, there is a limited cognitive reserve which gets shared between both the visual attention task as well as the motor task, which are processed in a parallel fashion.

8.1.3: The new paradigm is a sensitive and objective measure of dual-tasking effects

As previously outlined, one of the goals of this project was to create a paradigm which would be simple enough so that it could be used in a wide variety of participant populations. However, despite its simplicity, the paradigm also needed to be sensitive enough to be able to quantify dual-task costs. The results in Study 1 indicate that although the paradigm is exceedingly simple for the participant, it is nevertheless sensitive enough to not only quantify different attentional sub-components, but also to be able to disentangle dual-task costs related to each task separately. The results of this study demonstrated that this new paradigm was capable of objectively measuring dual-task costs, despite its simplicity.

However, despite these very promising results, this paradigm needed to be tested further. In order for a paradigm to be successful in providing consistent results, it must also be flexible enough to be easily adapted to answer remaining questions. Among these open questions, one especially important one is the influence of the aging process on motor-cognitive dual-tasking abilities, as this can have very serious ramifications for elderly adults in the form of an increased likelihood of falls. This question was therefore addressed in Study 2.

8.2: Study 2

Once the paradigm had been established as a viable tool through which motor-cognitive dual-tasking costs could be independently quantified, Study 2 was conducted in order to address some of the open questions in this field. More specifically, the paradigm was subtly altered to see whether there was a qualitative relationship between the age-related increase in dual-task costs and the higher amount of dual-task costs associated with a greater cognitive task load. This was done by using the original paradigm in a younger as well as in an older adult cohort. Additionally, a further younger adult group completed a more difficult version of the motor-cognitive dual-task paradigm. Together, this allowed for a qualitative comparison between the cognitive mechanisms which underlie age-related and cognitive load-related declines in dual-tasking performance. The results corroborated those of Study 1, again showing that the addition of a concurrent motor task leads to dual-task costs in the visual attention task. More importantly, through Study 2, it was possible to disentangle precisely which parameter underlies the performance of a motor-cognitive dual-task, and how this dual-tasking is affected by both age and task load.

8.2.1: The age effect is reflected by less cognitive resources being available for the simultaneous performance of the two tasks

In order to test for age-related effects in motor-cognitive dual-tasking, performance of the older adult group was compared to that of the younger adult group. Both groups were tested with the same paradigm used in Study 1. Results indicated that whilst the baseline tapping accuracy was lower in the older group, both groups' tapping performance was not affected by the concurrent visual task. Whilst processing speed and visual threshold were also unaffected, the older adults experienced a significant decrease in VSTM storage capacity in the dual-tasking condition as compared to younger adults. These results showed whilst the VSTM storage capacity is already lower in older adults even in the single-task condition, older adults have increased dual-tasking costs here when compared to younger adults, with these costs manifesting as a further reduction of the VSTM. Thus, the addition of the motor task to the cognitive task affects the efficiency with which visual information is processed in older adults. However, in younger adults the cognitive load of this simple motor task was too small to affect visual information processing. Taken together, this indicates that the effect of age on motor-cognitive dual-tasking is that the motor task is rendered more difficult, and that the available cognitive resources are not sufficient to support both tasks simultaneously.

The greater difficulty in carrying out the simultaneous motor task may well be caused by the age-related increased difficulty in automatising tasks, which would mean that older adults need more attention for performing a concurrent motor task than younger adults (for a review, see Leone et al., 2017). Given that difficulty in automatising tasks is associated with an increased likelihood of falls in older populations, such research is also of clinical importance. A deeper grasp of how the demands of dual tasking impact on the performance of either task is an imperative first step toward understanding which cognitive mechanisms are most strained under motor-cognitive dual-task conditions. Such an understanding could in turn support the development of therapeutic measures aimed at decreasing fall likelihood in elderly adults, thereby increasing the independence and quality of life of those at high risk for falls.

8.2.2: Increased task load in younger adults results in a qualitatively similar decline in performance as the age-related decline seen in older adults

To see whether increased dual-task costs related to aging were qualitatively similar to the decreased dual-task performance observed when younger adults perform a more cognitively demanding second task, the cognitive load of the motor task was increased in the second group of younger adults, and was then compared to the performance of the older adults doing the less demanding task. Both groups performed equally well at the motor task in both conditions. However, in the dual-task condition, both groups showed a reduced VSTM storage capacity, again showing that the number of items that could be held by the VSTM was decreased through the addition of a concurrent motor task. These results not only confirm the findings of Study 1, which support the capacity sharing account of dual-tasking, but also suggest that the increased age-related dual-task costs occur in a qualitatively similar manner as the increased dual-task costs seen in younger adults facing a more challenging motor-cognitive dual-task situation. These results are important, as they clearly and quantitatively show that the addition of a concurrent motor task reduces the number of items that can be held in the VSTM storage capacity, and that higher task loads in younger adults are qualitatively similar to the age effect seen in older adults.

8.3: Open questions and future research

Together Studies 1 and 2 have shown that not only can this new paradigm be used to clearly distinguish between motor dual-task costs and cognitive dual-task costs, but that this is a sensitive tool to assess independent motor-cognitive dual-tasking costs at a basic perceptual level. However, some open questions remain. For example, how are dual tasks processed at a higher processing level, and which cognitive architecture is involved?

Due to the simplicity yet stability and adaptability of the paradigm presented in this dissertation, the task design can easily be altered to address such questions. For example, as this paradigm is designed to measure dual-task related changes at a basic perceptual level, it can be complimented through the addition of designs aimed at detecting changes at a processing level, such as the Psychological Refractory Period (PRP) paradigm (Pashler, 1994; Welford, 1952). The PRP paradigm typically consists of two discrete choice discrimination tasks, Task 1 and Task 2, which are presented with variable temporal intervals (i.e., stimulus onset asynchrony, SOA). Typically such experiments find that the response time to Task 2 increases with decreasing SOA, whilst the response time to Task 1 typically remains unaffected by SOA manipulation. This prolongation of the response time to Task 2 in conjunction with shorter SOAs is called the PRP effect (Pashler, 1994), and is typically explained via the central bottleneck model, which posits that perception and motor response operate in parallel to the other processing stages. However, response selection is a central stage that operates only for one task at a time, and is constrained by a bottle-neck (Pashler, 1994; Schubert, 1999, 2008). By combining the PRP and TVA paradigms into a dual-task paradigm, it would be possible to investigate whether response selection influences visual attention processing, indicating that they rely on a common capacity limitation (see also Reimer, Strobach, & Schubert, 2016). Put in a broader perspective, Section 8.1.2 showed that at a basic level, resources are shared across the tasks. However, if it could be shown that higher cognitive processing is subject to a structural bottleneck, then this novel dual-task paradigm could prove quintessential in showing how the bottleneck theory could be integrated with the resource sharing account into a unified framework of dual-tasking behaviour which could have decisive ramifications not only on how existing literature is understood, but also in how the topic of motor-cognitive dual-tasking is approached by future studies. Given that this establishment of a new integrative theoretical framework of human multi-tasking behaviour is at the heart of the DFG SPP, this research would be a quintessential step forward.

In addition to this, this paradigm can also be used to test neuropsychological theories of motor-cognitive dual-tasking. For example, whilst there is typically much disagreement in neuroimaging research about dedicated cognitive architecture underlying dual-tasking, a recent review (Leone et al., 2017) found that the cerebellum consistently shows activation in studies assessing motor-cognitive dual-tasking. One such study suggested that the cerebellum integrates the neural networks responsible in the execution of each task into a singular dual-task related network, suggesting that the anterior lobe in conjunction with the cerebellar vermis is essential to performance (Wu et al., 2013). This theory would also be able to explain the age-related increase in dual-task costs. For example, Sullivan and Pfefferbaum (2006) suggest that the age-related disruption of the cerebellar circuitry may be the underlying cause for many of the decreases in performance of executive functions that appear with age. Thus, it is entirely possible that the cerebellum plays a role in the coordination and distribution of attentional resources across the two tasks in motor-cognitive dual-tasking, and that it is precisely this mechanism which deteriorates with age, leading to an age-related increase in dual-task costs. Therefore, in a current project, the same paradigm from Study 1 was used in a sample of 26 patients with isolated cerebellar stroke as well as in a 26 healthy, age-matched controls. Behavioural and neuroimaging data from this study suggest that the cerebellum is indeed vital in allocating attention across tasks in a motor-cognitive dual-tasking situation (Künstler et al., in preparation). In addition, the application of the motor-cognitive dual-task presented in this dissertation could also be important for the assessment of other patient groups. For example, multiple sclerosis patients would be a relevant target population, as this disease is known to involve not only cerebellar function, but also frontal lobe functions. Moreover, a recent study by Fischer and colleagues (2019) has shown that visual processing capacity declines early in this disease. Thus, using this paradigm to test such patient groups could lead to valuable insigts into what effect the disease has on motor-cognitive dual-tasking, and how this could affect the functioning of these patients in their everyday lives.

Taken together, the paradigm tested in Studies 1 and 2 has not only already provided answers to some fundamental questions within the field, but also has the potential to be used in answering other outstanding questions in motor-cognitive dual-tasking. Moreover, this paradigm has the potential to be able to do so from a multi-directional approach, integrating behavioural, neuroimaging, and neuropsychological results, and thereby possibly providing the groundwork for a more integrative framework of dual-tasking.

8.4: Global discussion

As stated in 5.1, these two studies were conducted as part of the project "Motor-cognitive dual-task performance: A neuro-cognitive approach investigating age-related differences based on the 'theory of visual attention' (TVA)", which formed part of a DFG SPP. In this project, the use of this novel TVA-based paradigm not only addressed the question of age-related differences in motor-cognitive dual-tasking, but was also able to provide valuable insights into how such tasks are performed at a basic perceptual level by quantifying the changes in the attentional parameters involved. The relevance of these findings is particularly important in both the potential assessment of existing therapeutic interventions aimed at reducing the risk of falls in elderly adults, as well as in possibly designing interventions aimed specifically at combating this increased risk of falls. As an example, Reinhart & Nguyen (2019) report that through use of non-invasive stimulation designed to synchronise long-range theta band activity, they were able to reverse the age-associated decline in working memory. As the studies presented in this dissertation show that working memory (as indexed by parameter K) is not only affected by the aging process, but also plays a key role in motor-cognitive dual-tasking abilities, it is possible to hypothesise that such stimulation may also help those at an increased risk of falls.

As indicated in 5.4.3, this paradigm was specifically designed so as to be applicable to a large variety of different participant cohorts. In other words, as this test is straightforward and easy to carry out, this paradigm can be used in not just healthy adults, but also in patient groups. This is of great importance, as this paves the way for further studies involving patients with specific lesions, which will in turn lead to valuable findings about the neural correlates which underlie the behavioural results observed in dual-tasking, as many neuroimaging studies are contradictory or inconclusive. For example, the use of this paradigm in patients with isolated cerebellar strokes has lead to valuable findings about the role of the cerebellum in motor-cognitive dual-tasking. Moreover, as the paradigm can be easily altered, it can be used to address a whole range of further questions in the field of motor-cognitive dual-tasking.

Whilst TVA has over the years been shown to be a robust and valuable method, there are some critiques which may be levelled against this paradigm. Firstly, it is possible that the lower parameters observed in older adults may be due to physiological changes in the visual system rather than because of age-related differences in cognitive processes. Increased age is often associated with changes in the physiology of the eye and visual system, for example being linked to changes in the curvature of the cornea, or increased hardness of the lens (for a review, see Salvi, Akhtar, & Currie, 2006). Although such age-related changes could lead to a reduced capacity for the intake of visual information in elderly participants, this factor has little impact on the TVA-based assessment. Not only was participation in the experiments limited to those with normal or corrected-to-normal vision, but in addition to this, the exposure durations were individually adjusted for each participant (for a detailed explanation of this procedure, please see the section entitled "Whole Report Task" in Paper 2), meaning that the length of time at which the stimuli were displayed was adjusted so that all participants performed at a comparable level. In other words, had physiological changes in the visual system caused older adults to be slower in the uptake of information, this would be counterbalanced by presenting the letters at longer exposure durations. In addition to this, as Study 1, and to some degree Study 2, make direct within-subject comparisons between the single and dual task conditions, the acuity of the visual system remained the same across the conditions, and thereby did not influence the results in these cross-condition comparisons. Secondly, a further critique which could be made of the dual-tasking paradigm, and as mentioned in Paper 1, is that visual monitoring of the tapping task could have been a possible confound which could have accounted for the observed results. This visual monitoring would have resulted in the switching of attention between the motor and the cognitive task, which would have led to trials in which no attention was allocated to the cognitive task, resulting in an overall lowered performance in the dual-task. However, the data in Study 1 conclusively showed that this was not the case (see Paper 1 for a detailed discussion), indicating that both tasks were executed simultaneously, thereby clearly showing that no visual monitoring of the tapping task took place. One last point to note about the methodology is that although this dual-tasking paradigm itself is completely new, it is based on a combination of well-established paradigms which are supported by many years of research. Thus although the results cannot be compared directly to existing research using the same paradigm, it is nevertheless based on well-tested paradigms, attesting to the reliability of the individual tasks.

Aside from the paradigm, one possible critique of the methodology of Study 1 is that the sample size was fairly small. However, the sample size is comparable to other studies of an explorative nature, especially given the age-group of the participants. Furthermore, the results of Study 1 were replicated by Study 2, which had a much larger sample size, indicating an adequate sample size in Study 1. As an additional point, care was taken in both studies to obtain data in dimly-lit and sound-attenuated environments following a standardised testing procedure. This meant that participants were not distracted from the tasks, ensuring that the data contained as few confounds as possible, and thereby enhancing the reliability of the data. In Study 2, in which data was collected in both Jena and Munich, it was ensured that the tests were run on the exact same brand of computer screen using the same settings, to further ensure that the stimuli were perceptually identical in both locations.

In summary, although there are a few possible critiques of the studies, each of these points can be reneged, often for multiple reasons. Together, these two studies have provided vital groundwork on which further studies can be - and indeed already have been - based. To sum-up, through the paradigm's ability to combine information from different approaches whilst simultaneously being able to precisely quantify changes in discrete mechanisms, this paradigm provides a reliable, precise and yet versatile tool with which questions of motor-cognitive dual-tasking can be comprehensively explored.

9 Conclusion

Study 1, to the best of my knowledge, was the first time that TVA had been combined with a continuous motor task. This newly created paradigm provided a robust and sensitive method which could separately untangle the dual-task costs related to both the visual attention task and the motor task whilst ensuring that there were no mutual confounds of either task.

This paradigm was used to show that the attentional resources which are utilised by visual information processing are also allocated to a concurrent motor task, meaning that even a very simple motor task already detracts valuable attentional resources away from the cognitive visual attention task. Thus, the parallel processing of a motor task led to a decrease in the efficiency with which participants were able to process visual information. More specifically, the processing rate of visual information decreased in the dual-task condition, as did the amount of information which could be held in the limited VSTM storage capacity.

Furthermore, this paradigm was able to demonstrate that both tasks are processed in parallel, thereby supporting a cognitive resource sharing account of dual-tasking. Overall, this paradigm shows potential in being able to contribute to a new integrative theoretical framework which is able to explain different aspects of human multi-tasking behaviour. Furthermore, these findings also make important theoretical contributions which can be applied to everyday life. For example, these findings could shed light on theoretical topics, such as whether tasks are conducted in a serial or parallel fashion, or even to practical topics, such as the dangers of multi-tasking whilst driving. Most importantly, Study 1 showed that this new paradigm could successfully measure both motor and cognitive dual-task-costs in an independent manner whilst still being able to address several key short-comings in dual-tasking research. This indicated the potential of this paradigm in addressing other open questions within the literature.

To this end, Study 2 was aimed at exploring the age-related decline in motor-cognitive dual-tasking ability, as well as the nature of the increased dual-task costs seen when the cognitive load of the motor task becomes more challenging. The results illustrated that although older adults already had a reduced VSTM storage capacity from the outset, this was further exacerbated by the addition of a simultaneous motor task, meaning that fewer items could be held in the VSTM storage capacity when a concurrent motor task had to be performed. Younger adults performing the exact same task did not show any such dual-task costs. This seems to suggest that the task load of the two tasks was small enough for the younger adults so that both tasks could be carried out without any decrements in performance in this group.

The younger adults performing a similar paradigm in which the cognitive load of the motor task had been increased also showed a reduction of the VSTM storage capacity in the dual-task condition. This indicates that the increase in dual-task costs experienced by this cohort occurred in a manner which was qualitatively similar to the increased dual-task costs seen in the older adults performing the less demanding motor task. Put another way, the age-related decline seen in dual-tasking performance seems to be indicative of the second task being more demanding for older adults than for younger adults performing the same task. These findings suggest provide an understanding of how dual-tasking is affected by age, thereby providing possible avenues for interventions aimed at reducing the likelihood of falls in elderly at-risk populations.

Taking these two studies together, this paradigm shows promise as a means for investigating motor-cognitive dual-task performance in healthy populations of a wide range of ages, and shows potential for use in patient cohorts. Both elderly adults as well as patient groups are at-risk for increased likelihood of falls, making it imperative that the cognitive mechanisms that underlie dual-tasking performance be better understood. Due to the versatility and simplicity of this paradigm, it is possible to not only address questions regarding very basic perceptual processing under dual-task conditions, but also to explore more far-reaching aspects of dual-tasking performance from multiple approaches, thereby gaining pertinent insights into why dual-tasking becomes more difficult with increased age or with neurological damage. This in turn has ramifications for practical uses of this paradigm, and opens up new avenues from which therapies and interventions aimed at decreasing the risk of falls could be devised. From a theoretical standpoint, this paradigm has proven to be successful in addressing several key debates in dual-tasking literature, and furthermore allows results to be integrated into an overarching and unified framework. To conclude, this new paradigm has shown potential in addressing not only theoretical, but also practical issues that are at the heart of dual-tasking literature, and shows promise in answering remaining open questions in the field of motor-cognitive dual-tasking.

10 References

Al-Yahya, E., Johansen-Berg, H., Kischka, U., Zarei, M., Cockburn, J., & Dawes, H. (2015). Prefrontal cortex activation while walking under dual-task conditions in stroke: A multimodal imaging study. *Neurorehabilitation and Neural Repair, 10*, 1 - 9.

Boisgontier, M. P., Beets, I. A., Duysens, J., Nieuwboer, A., Krampe, R. T., and Swinnen, S. P. (2013). Age-related differences in attentional cost associated with postural dual-tasks: increased recruitment of generic cognitive resources in older adults. *Neuroscience & Biobehavioral Reviews, 37,* 1824 – 1837.

Broyd, S. J., Demanuele, C., Debender, S., Helps, S. K., James, C. J., & Sonuga-Barke, E. J. S. (2009). Default-mode brain dysfunction in mental disorders: A systematic review. *Neuroscience & Biobehavioural Reviews, 33,* 279 - 296.

Bundesen, C. (1990). A theory of visual attention. *Psychological Reviews, 97,* 523 – 547.

Bundesen, C., Vangkilde, S., and Petersen, A. (2015). Recent developments in a computational theory of visual attention (TVA). *Visual Research, 116,* 210 – 218.

Desimone R, & Duncan J. (1995). Neural mechanisms of selective visual attention. *Annual Review of Psychology, 18,* 193 – 222.

Finke, K., Bublak, P., Krummenacher, J., Kyllingsæk, S., Müller, H. J., & Schneider, W. X. (2005). Usability of a theory of visual attention (TVA) for parameter-based measurement of attention I: Evidence from normal subjects. *Journal of the International Neuropsychological Society, 11,* 832 – 842.

Fischer, R., & Plessow, F. (2015). Efficient multitasking: parallel versus serial processing of multiple tasks. *Frontiers in Psychology, 6,* 1366 - 1376.

Fischer, M., Köhler, W., Faiss, J. H., Hoffmann, F., Kunkel, A., Sailer, M., Schwab, M., Zettl, U. K., Bublak, P., & HIPPOCOMS Study Group. (2019). A smart peek: Processing of rapid visual displays is disturbed in newly diagnosed, cognitively intact MS patients and refers to cognitive performance and disease progression in late stages. *Journal of the Neurological Sciences, 401,* 118 - 124.

Fritz, N. E., Cheek, F. M., & Nichols-Larsen, D. S. (2015). Motor-Cognitive Dual-Task Training in Persons With Neurologic Disorders: A Systematic Review. *Journal of Neurologic Physical Therapy, 39,* 142 - 153.

Habekost, T., & Bundesen, C. (2003). Patient assessment based on a theory of visual attention (TVA): Subtle deficits after a right frontal-subcortical lesion. *Neuropsychologia, 41,* 1171 - 1188.

Hawkes, T. D., Siu, K.-C., Silsupadol, P., & Woollacott, M. H. (2012). Why does older adults' balance become less stable when walking and performing a secondary task? Examination of attentional switching abilities. *Gait and Posture, 35,* 159 – 163.

Künstler, E. C. S., Fuchs, B., Günther, A., Finke, K., Witte, O. W., Bublak, P., & Klingner, C. M. (in preparation). The role of the cerebellum in motor-cognitive dual-tasking: Evidence from cerebellar stroke patients.

Leone, C., Feys, P., Moumdjian, L., D'Amico, E., Zappi, M., & Patti, F. (2017). Cognitive motor dual-task interference: A systematic review of neural correlates. *Neuroscience and Biobehavioural Reviews, 75,* 348 – 360.

Lindenberger, U. (2014). Human cognitive aging: corriger la fortune? *Science, 346,* 572 – 578.

Logan, G. D., and Gordon, R. D. (2001). Executive control of visual attention in dual-task situations. *Psychological Review, 108,* 393 – 434.

Luck, S. J., & Vogel, E. K. (1997). The capacity of visual working memory for features and conjunctions. *Nature, 390,* 279 - 281.

Maquestiaux, F., Didierjean, A., Ruthruff, E., Chauvel, G., & Hartley, A. A. (2013). Lost ability to automatize task performance in old age. *Psychonomic Bulletin & Review, 20,* 1206 – 1212.

Navon, D., and Miller, J. (2002). Queuing or sharing? A critical evaluation of the single bottleneck notion. *Cognitive Psychology, 44*, 193 – 251.

Pashler, H. (1994). Dual-task interference in simple tasks: data and theory. *Psychological Bulletin, 116,* 220 – 244.

Pashler, H., Johnson, J.C., and Ruthruff, E. (2001). Attention and Performance. *Annual Review of Psychology, 52,* 629 – 651.

Reimer, C. B., Strobach, T., & Schubert, T. (2016). Concurrent deployment of visual attention and response selection bottleneck in a dual-task: Electrophysiological and behavioral evidence. *The Quarterly Journal of Experimental Psychology, 12,* 2460 – 2477.

Reinhart, R. M., & Nguyen, J. A. (2019). Working memory revived in older adults by synchronizing rhythmic brain circuits. *Nature neuroscience*, *22,* 820 – 827.

Ruthruff, E., and Lien, M. C. (2017). Aging and attention. In (Ed.), *Encyclopedia of Geropsychology* (pp. 166 – 172). Singapore: Springer.

Salthouse, T. A. (1996). The processing-speed theory of adult age differences in cognition. Psychological Review, 103, 403 - 426.

Salvi, S. M., Akhtar, S. & Currie, Z. Ageing changes in the eye (2006). *Postgraduate Medical Journal, 82*, 581 – 587.

Schubert, T. (1999). Processing differences between simple and choice reactions affect bottleneck localization in overlapping tasks. *Journal of Experimental Psychology: Human Perception and Performance, 25, 408 - 425.*

Schubert, T. (2008). The central attentional limitation and executive control. F*rontiers in Bioscience, 13,* 3569 - 3580.

Sullivan, E. V. & Pfefferbaum, A. (2006). Diffusion tensor imaging and aging. *Neuroscience & Biobehavioral Reviews, 30,* 749 - 761.

Tombu, M., and Jolicoeur, P. (2004). Virtually no evidence for virtually perfect time-sharing. *Journal of Experimental Psychology: Human Perceptual Performance, 30,* 795 – 810.

Verhaeghen, P. (2015). Aging and executive control: Reports of a demise greatly exaggerated. *Current Directions in Psychological Science, 20,* 174 – 180.

Verstraeten, S., Mark, R. & Sitskoorn, M. (2016). Motor and cognitive impairment after stroke: A common bond or a simultaneous deficit? *Stroke Research and Therapy, 1:* 1.

Welford, A. T. (1952). The psychological refractory period and the timing of high speed performance – A review and a theory. *British Journal of Psychology, 43,* 2 - 19.

Wu, T., Liu, J., Hallett, M., Zheng, Z., & Chan, P. (2013). Cerebellum and integration of neural networks in dual-task processing. *NeuroImage, 65,* 466 - 475.

11 Supplementary Data

11.1 Acknowledgments

Firstly, I would like to express my sincere gratitude to my supervisor, PD Dr. Peter Bublak, for the continuous support of my Ph.D study and related research, for his patience, motivation, and immense knowledge, which came to bear in all aspects of the work that went into making this dissertation possible. His guidance helped me in throughout my research and writing of this thesis.

My thanks also go out to PD Dr. Kathrin Finke for her insightful comments, suggestions and input, and also for arranging the collaboration which led to the second article being published.

I would also like to thank Dr. P. Bublak, Professor Dr. O. W. Witte, and PD Dr. C. Klingner for all their valuable comments and insights, as well as for their efforts in securing the grant necessary for this research. This research was supported by a Grant within the Priority Program, SPP1772 from the German Research Foundation (Deutsche Forschungsgemeinschaft, DFG), Grant number SPP 1772/1—BU 1327/4-1.

Last but not least, my heartfelt thanks go out to Nico Vössing ans Sarunas Dreseris for all of their encouragement and support, and for making sure my coffee mug was never empty.

11.2 List of Figures

11.3 Plagiarism Declaration / Ehrenwörtliche Erklärung

Hiermit erkläre ich, dass mir die Promotionsordnung der Medizinischen Fakultät der FriedrichSchiller-Universität bekannt ist,

ich die Dissertation selbst angefertigt habe und alle von mir benutzten Hilfsmittel, persönlichen Mitteilungen und Quellen in meiner Arbeit angegeben sind,

mich folgende Personen bei der Auswahl und Auswertung des Materials sowie bei der Herstellung des Manuskripts unterstützt haben:

- Herrn Dr. P. Bublak, Leiter der Arbeitsgruppe Neuropsychologie des Universitätsklinikums Jena
- Frau Dr. K. Finke, Psychologische Leitung des Gedächtniszentrum des Universitätsklinikums Jena
- Herrn Prof. O. Witte, Direktor der Klinik für Neurologie des Universitätsklinikums Jena

die Hilfe eines Promotionsberaters nicht in Anspruch genommen wurde und dass Dritte weder unmittelbar noch mittelbar geldwerte Leistungen von mir für Arbeiten erhalten haben, die im Zusammenhang mit dem Inhalt der vorgelegten Dissertation stehen,

dass ich die Dissertation noch nicht als Prüfungsarbeit für eine staatliche oder andere wissenschaftliche Prüfung eingereicht habe und

dass ich die gleiche, eine in wesentlichen Teilen ähnliche oder eine andere Abhandlung nicht bei einer anderen Hochschule als Dissertation eingereicht habe.

Jena, 05/12/2019

Ort, Datum   Unterschrift des Verfassers

11.4 Supplementary material for Study 2

Sociodemographic Score

Due to changes in educational and occupational standards over the years, we created a sociodemographic score based on vocabulary (an estimate of crystallized intelligence), number of school years, and occupation (either intended or obtained), with a maximum of 3 points being awarded per criterion. Thus, it was possible to obtain a minimum score of 3 and a maximum score of 9 points.

For the vocabulary score, each participant obtained a score based on his or her performance on the MWT-B (Lehrl, 1999), a German test which provides an estimate of crystallized intelligence. This was allocated as follows: 1 point for those below average; 2 points for those with an average score; and 3 points for those with an above average score. What was deemed to be below average, average, or above average was based on the norms set out in the MWT-B handbook (Lehrl, 1999).

Again, participants obtained a score between 1 and 3 based on their secondary school qualifications. Those completing a qualification which required 9 years of schooling obtained 1 point; those who completed a qualification which necessitates 10 years of education were awarded 2 points; and those who had a qualification which required 12 school years were given 3 points.

Finally, participants were scored according to their occupation. 1 point was given to those participants with menial jobs which did not require any further training or education; 2 points were given to those whose occupation required further training; 3 points were awarded to those participants with occupations requiring a university degree. University students were automatically awarded 3 points, even if they had not as yet completed their degree.

Older adults had a mean score of 7.4, with a standard deviation of 1.3, and a range of 5 to 9 points. The adults in the younger simple group (one value missing due to a missing IQ value) had a mean sociodemographic score of 6.7, a standard deviation of 1.4, and a range of 4 to 9 points. The younger complex group on the other hand had a mean score of 7.2, a standard deviation of 1.1, and a range of 5 to 9 points. There was no significant difference between the younger simple group and the older adults group (younger simple: *Mdn* = 7; older: *Mdn* = 7.5; $U = 319.0$, $p = .073$, $r^2 = .05$), nor between the younger complex group and the older adults group (younger complex: *Mdn* = 7; older: *Mdn* = 7.5; $U = 397.5$, $p = .424$, $r^2 = .01$). Please see Table 2 for the means and standard deviations of the scores for each group.

Younger group performing the simple tapping sequence vs. younger group performing the complex tapping sequence

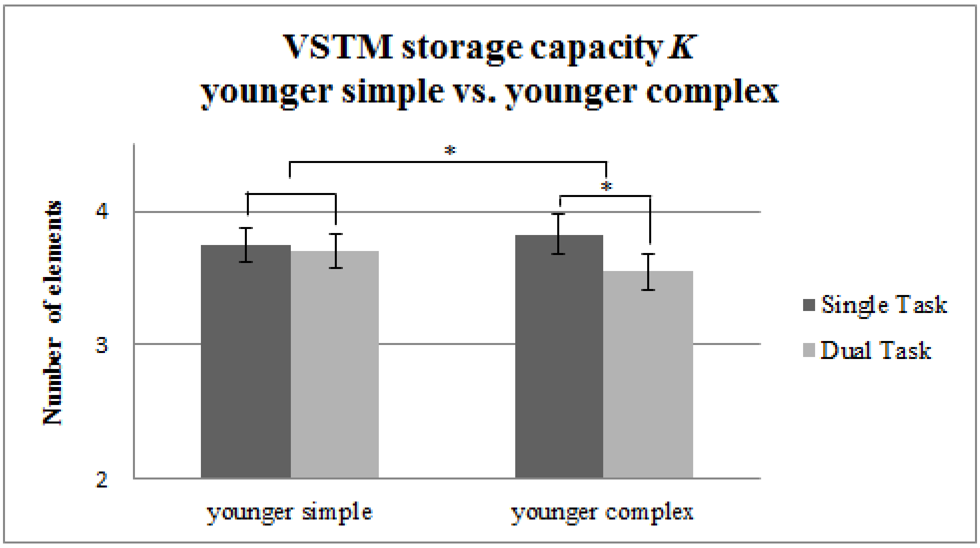
To explore the differences between a simple versus a more complex tapping sequence in younger participants – which should increase the difficulty of the task – a comparison was run between the two younger groups.

Tapping

The comparison of the younger simple and younger complex groups showed a significant main effect of Tapping Group [$F(1, 56) = 14.82$, $p < .001$; $\eta_p^2 = .21$], but no other significant effects [Task Condition: $F(1, 56) = .01$, $p = .91$; $\eta_p^2 < .001$; interaction: $F(1, 56) = .006$, $p = .94$; $\eta_p^2 < .001$]. While the higher tapping demands led to lower overall accuracy in the group performing the complex compared to the group performing the simple sequence type, there was no indication for any dual task effect in tapping throughout the groups.

Whole Report

For VSTM storage capacity *K*, there was no significant main effect of Tapping Group [$F(1, 58) = .0051$; $p = .94$, $\eta_p^2 < .001$]. There was a significant main effect of Task Condition [$F(1, 58) = 14.13$, $p < .001$, $\eta_p^2 = .20$] and a significant interaction between Task Condition and Tapping Group[$F(1, 58) = 4.77$, $p = .03$, $\eta_p^2 = .08$]. Pairwise post-hoc *t*-tests with Bonferroni-correction showed a significant dual task effect on VSTM storage capacity only in the group performing the complex tapping sequence [$t(29) = 3.98$, $p < .001$, d = 0.35], and not in the group performing the simple tapping sequence [$t(29) = .83$, $p = .41$, d = 0.06; see Supplementary Figure 1].



Supplementary Figure 1: VSTM capacity *K* measured in maximum number of recognized letters for the younger group performing the simple tapping sequence vs. the younger group performing the complex tapping sequence. Error bars indicate standard errors of the mean.

The respective ANOVA on processing speed *C* did not show any significant effects [Tapping Group: $F(1, 58) = .24$, $p = .62$; $\eta_p^2 = .004$; Task Condition: $F(1, 58) = 1.55$, $p = .22$; $\eta_p^2 = .03$; interaction: $F(1, 58) = .28$, $p = .60$; $\eta_p^2 = .005$]. Thus, visual processing speed was comparable across groups and was not affected by concurrent tapping.

For visual threshold t_0, there were no significant main effects for Tapping Group [$F(1, 58) = .05$; $p = .83$, $\eta_p^2 = .001$] or Task Condition [$F(1, 58) = .79$; $p = .38$, $\eta_p^2 = .01$]and no significant interaction [$F(1, 58) = .05$; $p = .83$, $\eta_p^2 = .001$]. Thus, across different groups, task and complexity conditions, visual threshold t_0 remained rather constant.

These results indicate that when a complex motor program was performed as part of a dual task, the younger complex group experienced a significant reduction in the storage capacity of VSTM as compared to the younger adults performing the simple tapping sequence. This is in line with previous findings, which also showed that increased complexity can result in higher dual task decrements (Boisgontier et al., 2013). Processing speed and visual threshold were, however, unaffected. As higher tapping demands induced a specific decline in VSTM storage capacity only, this suggests that VSTM plays a role in supporting both the cognitive as well as the motor task in a dual tasking situation. If the overall cognitive load induced by dual tasking situation is relatively low, VSTM is able to successfully and accurately support both tasks simultaneously, with both tasks being processed in parallel. However, the time-point at which visual information starts to be processed, and the speed with which such information is processed was not affected by the complexity of the secondary task.

Supplementary Table 1. Tapping speed (seconds per tap) across all conditions and groups.

	Single Task	**Dual Task**
Older: Mn/ SD/ N	.43/ .11/ 30	.45/ .13/ 29
Younger Simple: Mn/ SD/ N	.32/.11/29	.29/.09/30
Younger Complex: Mn/ SD/ N	.33/ .08/ 29	.33/ .08/ 30

Note. Mn: Mean; SD: standard deviation; N = sample size

Setting negative *t0*-values to 0

Perhaps due to subjects' inappropriate guessing during letter report, or to inefficient masking, TVA-based modeling provided negative *t0* values in multiple cases. We handled this problem by calculating our analyzes in two alternative ways: first, based on the model fit providing negative *t0* values; second, based on a model fit constraining the minimum *t0* value to zero. Both analyses generally revealed the same effects and group interactions. The data are provided in the Supplementary Tables 2, 3 and 5.

Supplementary Table 2. Results from repeated measures ANOVAs for TVA parameters *K* and *C* for all group comparisons (minimum *t0* = 0).

	Younger simple vs. older simple		**Younger complex vs. older simple**		**Younger simple vs. younger complex**	
	K	*C*	*K*	*C*	*K*	*C*
Task Condition						
F	18.24	6.58	39.23	2.07	16.05	1.02
df	1, 58	1, 58	1, 58	1, 58	1, 58	1, 58
***p*-value**	< .001**	.01*	< .001**	.16	< .001**	.32
η_p^2	.24	.10	.40	.04	.22	.02
Age Group/ Tapping Group						
F	17.74	2.67	13.63	1.16	.02	.10
df	1, 58	1, 58	1, 58	1, 58	1, 58	1, 58
***p*-value**	< .001**	.11	< .001**	.29	.90	.75
η_p^2	.23	.04	.19	.02	< .001	.002
Interaction						
F	9.42	.03	.07	2.72	4.86	1.44
df	1, 58	1, 58	1, 58	1, 58	1, 58	1, 58
***p*-value**	.003*	.87	.79	.11	.03*	.24
η_p^2	.14	< .001	.001	.05	.08	.02

Note. * $p < .05$; ** $p < .001$; df = degrees of freedom

Because of its non-normal distribution and thus a violation of assumptions that have to be met for the calculation of ANOVAs, non-parametric tests were used for the visual threshold t_0. The results of these calculations can be found in Supplementary Table 3. Individual values for all TVA parameters (minimum *t0* = 0) are presented in Supplementary Table 5.

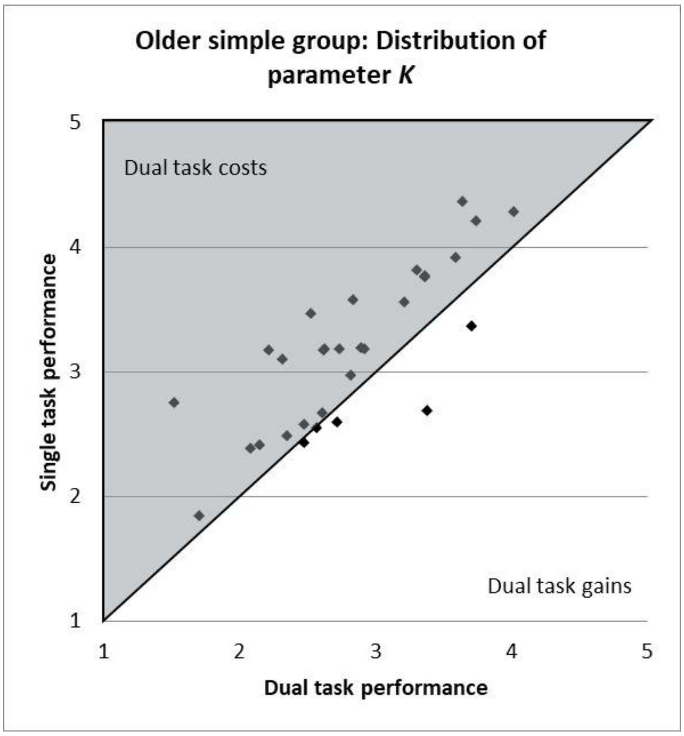
Supplementary Table 3. Results of Wilcoxon-Tests for all groups and of Mann-Whitney-*U*-Tests for all group comparisons for TVA parameter t_0 (minimum $t_0 = 0$).

	Wilcoxon-Test					
	Older simple		**Younger simple**		**Younger complex**	
Z	-.024		-1.415		-.362	
***p*-value**	.98		.16		.72	
r²	< .001		.07		.004	
	Mann-Whitney-*U* Test					
	Older simple vs. younger simple		**Older simple vs. younger complex**		**Younger simple vs. Younger complex**	
	single	*dual*	*single*	*dual*	*single*	*dual*
Md	os = 10.00 ys = .44	os = 11.35 ys = .17	os = 10.00 yc = 1.59	os = 11.35 yc = .81	ys = .44 yc = 1.59	ys = .17 yc = .81
U	173.0	189.0	152.0	189.0	443.5	438.0
***p*-value**	< .001**	< .001**	< .001**	< .001**	.92	.85
r²	.28	.26	.33	.26	< .001	< .001

Note. Md = Median; os = older simple group; ys = younger simple group; yc = younger complex group; ** $p < .001$

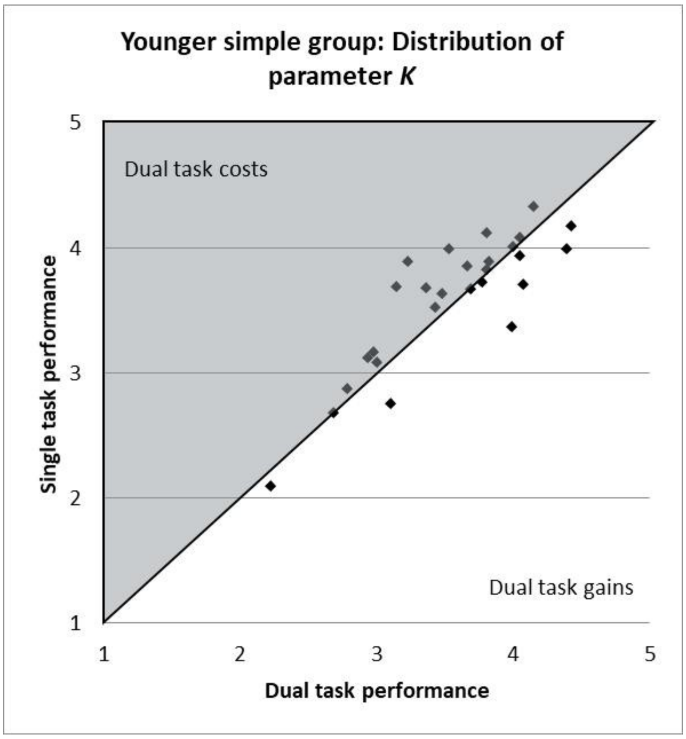
Supplementary figures 2 to 7: Distribution of individual *K* parameter scores (S2-S4) and tapping speed (seconds per tap; S5-S7) for each group

S2.



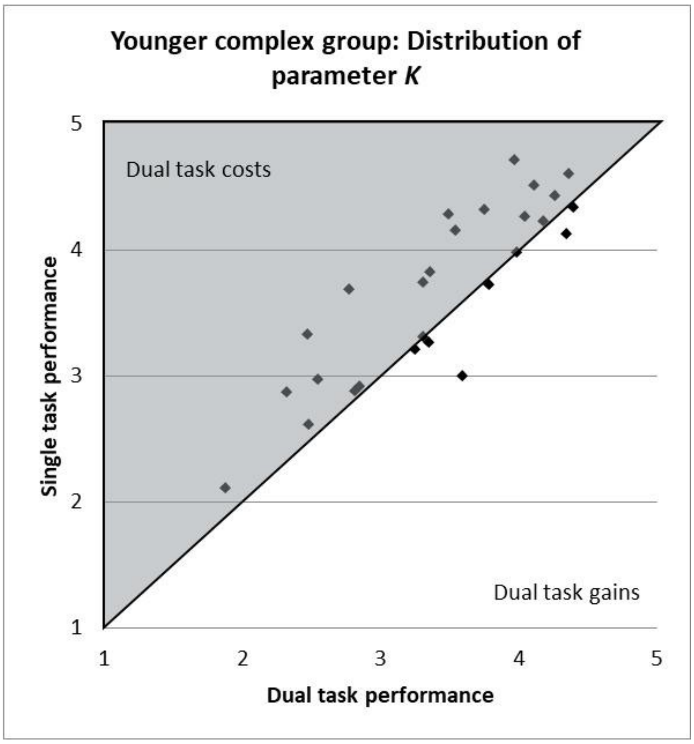
Older simple group: Distribution of parameter *K*
Dual task costs
Dual task gains
Single task performance
Dual task performance
1
2
3
4
5

S3.

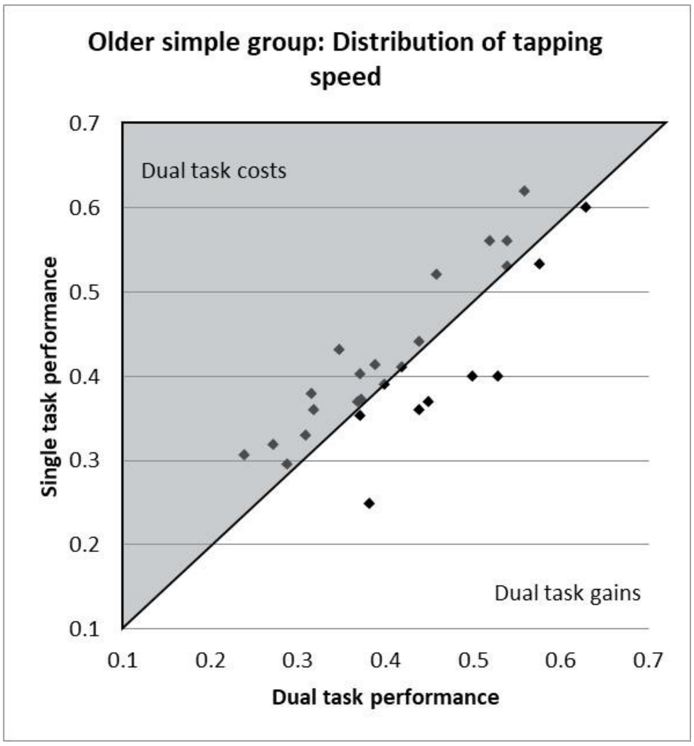


Younger simple group: Distribution of parameter *K*
Dual task costs
Dual task gains
Single task performance
Dual task performance
1
2
3
4
5

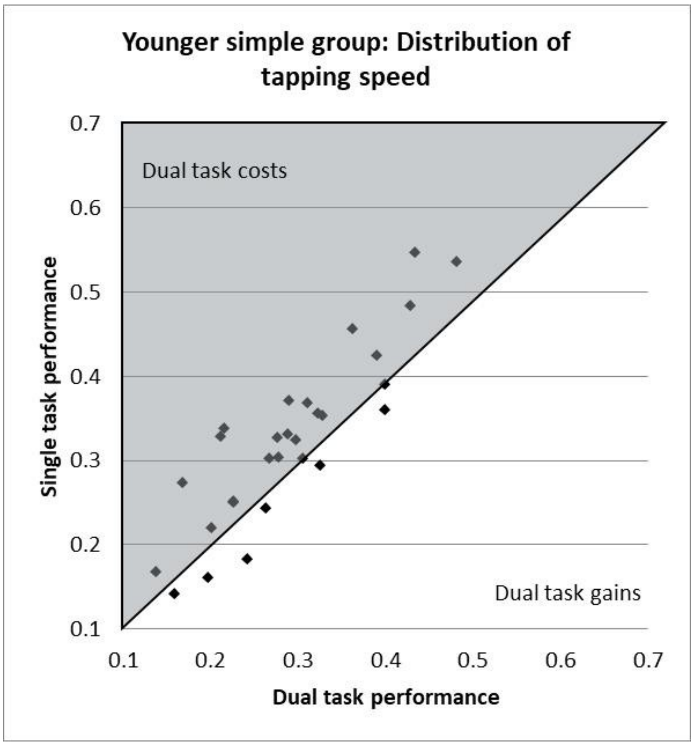
S4.


Younger complex group: Distribution of parameter *K*
Dual task costs
Dual task gains
Single task performance
Dual task performance
1
2
3
4
5

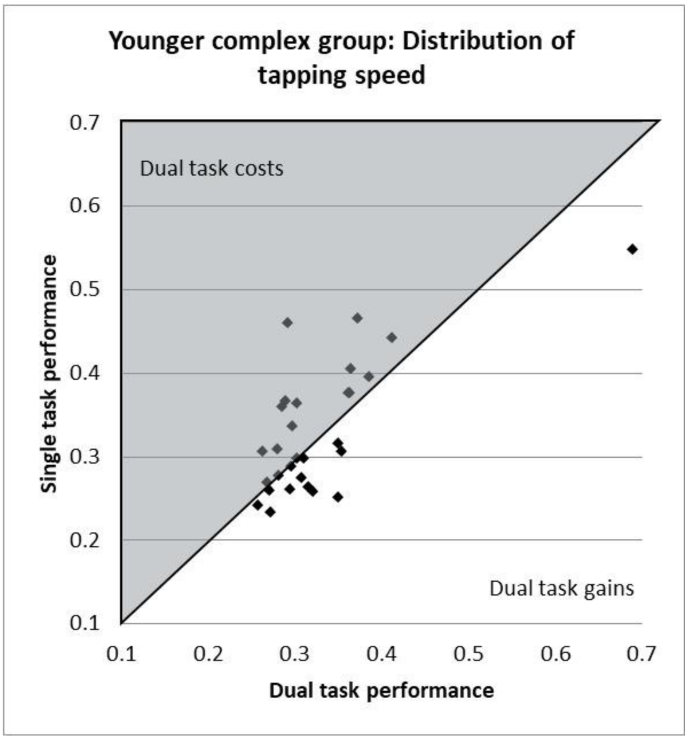
S5.


Older simple group: Distribution of tapping speed
Dual task costs
Dual task gains
Single task performance
Dual task performance
0.1
0.2
0.3
0.4
0.5
0.6
0.7

S6.


Younger simple group: Distribution of tapping speed
Dual task costs
Dual task gains
Single task performance
Dual task performance
0.1
0.2
0.3
0.4
0.5
0.6
0.7

S7.


Younger complex group: Distribution of tapping speed
Dual task costs
Dual task gains
Single task performance
Dual task performance
0.1
0.2
0.3
0.4
0.5
0.6
0.7