Age-related changes in visual attention capacity and the impact of cognitive training

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Abstract

Cognition declines over the lifespan, and a growing life expectancy warrants new solutions to ward off deficits for as long as possible. It is crucial to apply sensitive measures to assess specific deficits as well as potential for enhancement in cognitive function. In the studies presented in this dissertation, we used parametric assessment based on the Theory of Visual Attention (TVA, Bundesen, 1990) in healthy older adults to (1) investigate specific age-related motor-cognitive dual task decrements in visual attention capacity, (2) evaluate the specific effects of an alertness training program on latent visual processing speed and, (3) in combination with resting-state functional magnetic resonance imaging (rs-fMRI), identify a neural marker assessed before training to predict subsequent training-induced change in visual processing speed. In the area of deficits in visual attention capacity, evidence will be presented for (1) a specific dual task decrement in visual short-term memory capacity with a sufficiently complex secondary motor task in younger and older adults, and (2) complexity-dependent age effects in motor-cognitive dual tasking. In the area of enhancement of visual attention capacity, our studies show (3) a specific enhancement in latent visual processing speed caused by alertness training compared to an active and a passive control group, and (4) a specific relationship between more 'youth-like' intrinsic functional connectivity in the cingulo-opercular network assessed before training and higher subsequent alertness-training-related gain in visual processing speed. The presented results corroborate the applicability of TVA-based measurement in assessing specific age-related deficits as well as specific potential for enhancement. Our insights are critical for the future development of maximally efficient and personalized interventions to counteract cognitive decline.

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List of Abbreviations

ACTIVE	Advanced Cognitive Training for Independent and Vital Elderly
BOLD	Blood-Oxygen-Level-Dependent
DT	Dual Task
DTC	Dual Task Cost
ERP	Event-Related Potential
FC	Functional Connectivity
ICN	Intrinsic Connectivity Network
NTVA	Neural interpretation of TVA
PRP	Psychological Refractory Period
(RS-)FMRI	(Resting-state-) Functional Magnetic Resonance Imaging
ST	Single Task
TDCS	Transcranial Direct Current Stimulation
TVA	Theory of Visual Attention
UFOV	Useful Field of View
VSTM	Visual Short-Term Memory

1. General Introduction

Due to increasingly better healthcare, we reach higher and higher ages. This growing life expectancy takes its toll, reflected also in growing rates of cognitive decline through to pathological aging (Patterson, 2018; Zaninotto, Batty, Allerhand, & Deary, 2018). Consequences for those affected include a reduction in quality of life, loss of independence and even a higher risk of mortality (Pusswald et al., 2015; Anstey, Luszcz, Giles, & Andrews, 2001; Njegovan, Man-Son-Hing, Mitchell, & Molnar, 2001). Apart from the well-known age-related memory decline, losses can be found in most cognitive functions, such as working memory, executive functions or processing speed, most of which seem to deteriorate starting in our twenties (Park, 2002; Anderson and Craik, 2017). Cognitive decline is a hallmark even of healthy aging, but it can be exacerbated in the context of pathology, such as Mild Cognitive Impairment (a possible precursor of dementia which does not yet affect daily life activities), or full-blown Alzheimer's disease dementia (Albert et al., 2011; Petersen, 2000). One cognitive area that has repeatedly been shown to be heavily affected by healthy and pathological aging is visual attention capacity (see, for example McAvinue et al., 2012; Habekost et al., 2013; Chapter 1.1). Reduced attention capacity does, of course, also influence everyday situations, for example those in which one has to perform more than one task at the same time (i.e., dual tasking, e.g., Künstler et al., 2018; see Chapter 1.2). However, it is not yet clear which exact mechanism is affected in older adults in these situations.

Theories of cognitive aging often focus on one specific process to explain age-related decline. Prominently, the processing speed hypothesis first mentioned by Birren (e.g., 1974) and furthered by Salthouse (e.g., 1992, 1994, 1996) ascribes decline to a general slowing. When processing is slowed down, some operations cannot be performed successfully due to the limited available time, and different operations can possibly not be performed simultaneously, which would thus affect higher order cognitive functions (Salthouse, 1996). Another possible explanation for cognitive aging was brought forward by Hasher and Zacks (1988; Zacks & Hasher, 1997). They propose that older adults are less able to shield themselves from distracting information compared to younger adults, which then leads to cognitive deficits. Other authors suggest that a combination of factors is responsible for age-related cognitive decline (e.g., Kramer & Willis, 2002; Verhaeghen & Cerella, 2002).

Moreover, age-related changes can be found on the brain level. For example, some brain regions fall prey to cortical thinning, loss of gray matter, or loss of white matter integrity (for a review, see Kennedy & Raz, 2015; Greenwood, 2007). Activation changes during task execution can emerge as over-activation, under-activation, or compensatory activation (see also Reuter-Lorenz & Park, 2010). Importantly, intrinsic functional connectivity (FC) of the brain at rest is vulnerable to aging, which is, for example, often observed in the so-called default mode network that is usually active during rest and suppressed during task execution. Older adults, however, seem to struggle with this suppression (e.g., Persson, Lustig, Nelson, & Reuter-Lorenz, 2007). Further theories were developed to explain observations from neuroimaging. Different activation patterns are often interpreted as compensatory. For example, in older adults, activation during tasks seems to shift from more posterior to more anterior regions (Dennis & Cabeza, 2008; first discovered by Grady et al., 1994), prefrontal activation seems to become less asymmetric (Cabeza, 2002), and cognitive performance comparable to younger adults is often accompanied by an increase in neural activity (Reuter-Lorenz & Cappell, 2008). One model (Park & Reuter-Lorenz, 2009) proposes that older adults respond to neural challenges – such as age-related decline in structure and function – by increasingly recruiting alternative neural regions, or 'scaffolds'. In a revised version of the theory (Reuter-Lorenz & Park, 2014), the authors incorporate the possibility of influencing these scaffolds, for example via cognitive interventions, physical exercise or social engagement. This opens up possibilities to counteract cognitive decline even in older age (see Chapter 1.3). However, effective compensation might not be the only factor in preserved cognitive performance. Those older adults with brain structures or responses similar to those of younger adults also seem to have an advantage – a concept termed 'brain maintenance' (Nyberg, Lövdén, Riklund, Lindenberger, & Bäckman, 2012; see also Lindenberger, 2014). As the name suggests, brain maintenance is mainly about factors involved in preserving brain function or avoiding cognitive decline. It is also believed to be malleable to certain genetic and lifestyle factors. However, it is worth mentioning that not every individual is equally responsive to corresponding interventions (see Section 1.3.2), and it is not clear whether task-independent neural markers could predict training response.

To reach the important goal of counteracting age-related cognitive decline, it is crucial to (1) determine in which situations and in which functions exactly older adults' performance is affected compared to younger adults' performance (and why), (2) evaluate specific targeted interventions, such as visual processing speed training, to counteract cognitive decline, and (3) identify ways to predict individual training gain. In the first chapter of this thesis, I will introduce the topics relevant to the presented projects. These include the theoretical and methodological framework for measuring visual attention capacity, as well as background information on dual tasking situations, cognitive training and resting-state functional resonance imaging. Moreover, the aims of the presented studies will be stated. Chapter 2 includes the first project of this thesis

("Dual task effects on visual attention capacity in normal aging", *published*), while chapter 3 will combine projects 2 and 3 ("Alertness training increases visual processing speed in healthy older adults", *in preparation*). In chapter 4, the main insights of all three projects will be discussed and an outlook for future studies will be given.

1.1 Theoretical and methodological framework: measuring visual attention capacity based on the Theory of Visual Attention (TVA)

In our daily life, we are regularly faced with situations in which we need to select different objects, be it picking out groceries in the supermarket, or looking for our keys. Visual attention is critical for this kind of everyday tasks as it enables us to select and process visual information (Bundesen, 1990). In Claus Bundesen's (1990) mathematical formulation of a Theory of Visual Attention (TVA), the main parameters describing visual attention capacity are the visual processing speed parameter C, and the visual short-term memory (vSTM) storage capacity, parameter K. TVA is a computational theory based on biased competition models (Desimone & Duncan, 1995), i.e., the idea that different stimuli compete to be encoded into vSTM, and that this competition is biased by top-down factors (e.g., task instructions), as well as bottom-up factors (e.g., color). In more detail, the first formulation of the theory centers on two main equations: the rate and the weight equations (Bundesen, 1990; see also Habekost, 2015; Bundesen, Habekost, & Kyllingsbæk, 2005, 2011). More recently, additional factors, such as alertness, were added (Bundesen, Vangkilde, & Habekost, 2015; see Section 1.1.3). According to TVA, recognizing or selecting an object is achieved by making categorizations such as 'object x belongs to category i' or 'object x has feature i'. Making these categorizations equals encoding one or more of this object's features into vSTM. For the purpose of illustration, let us assume that object x is a circle and the category or feature i is the color red.

When different stimuli are presented simultaneously, TVA assumes parallel and independent processing of all stimuli based on two mechanisms (Bundesen, 1990; see also Habekost, 2015; Bundesen et al., 2005, 2011). 'Filtering' refers to the selection of objects, while 'pigeonholing' denotes the selection of categories or features. First, attentional weights for all the stimuli in the visual field are generated; these weights influence processing rates of the stimuli (i.e., how fast they 'race' in the competition) and thus their likelihood for being encoded into vSTM. In a second step, the weighted objects start their race. The processing rate of an object denotes the rate at which this object – in our case the circle – is encoded into vSTM. It is expressed by the rate equation, which describes it as a product of the strength of the sensory evidence that the object belongs to a category (in our case: that the circle is red), and two rather subjective terms – a subjective perceptual bias parameter, and the attentional weight that has been assigned to this object compared to attentional weights assigned to other objects (the circle's relative weight compared to attentional weights of other objects). The sum of the processing rates of all categorizations for all objects in the visual field equals the TVA parameter

C, or total visual processing speed. Objects can enter into vSTM as long as there is still capacity. This capacity is usually assumed to comprise 3-4 objects in young healthy adults (Luck & Vogel, 1997; Shibuya & Bundesen, 1988). As soon as its storage is filled up, no other object can enter into vSTM. However, further categorizations of an object that is already represented in vSTM can still be added. Attentional weights are computed via TVA's weight equation. Here, the pertinence value of our category 'red', i.e., how important it is to focus on red objects, is multiplied with the strength of the sensory evidence that a particular object (e.g., our circle) is red. This product is summed up across all categorizations. Attentional weights are assumed to be stored in a priority map and can then be used to compute processing rates via the rate equation (Bundesen, 1990; see also Habekost, 2015; Bundesen et al., 2005, 2011).

TVA has been shown to account for various attentional phenomena that were experimentally observed in different paradigms, such as cued detection, whole and partial report, visual search or single stimulus recognition (Bundesen, 1990). Additionally, it can account for observations in single-cell processing (Bundesen et al., 2005, 2011). The most common stimulus type are letters, but various other objects have been used, such as circular stimuli, faces (Peers et al., 2005), short words (Habekost, Petersen, Behrmann, & Starrfelt, 2014) or digits (Starrfelt, Habekost, & Leff, 2009). Another version of the paradigm, the CombiTVA, combines both whole and partial report in one task (Vangkilde, Bundesen, & Coull, 2011). TVA-based assessment has also been applied to different patient populations, examining visual attention parameters in simultanagnosia, reading disturbances, neurodegenerative diseases or neurodevelopmental disorders, among others (for a review, see Habekost, 2015).

1.1.1 TVA and its connection to the brain

Bundesen and colleagues (2005; 2011) have proposed a neural interpretation of TVA (NTVA). They link TVA's filtering mechanism to the number of cortical neurons representing, in our case, the categorization 'the circle is red', and the pigeonholing mechanism to the activity level of these neurons. In a first, unselective wave of processing, attentional weights are computed for each object and stored in a priority map. These weights can be used to reallocate attentional capacity via dynamic remapping of the neurons' receptive fields. In the second, selective wave, processing resources have been allocated to different objects according to their attentional weight, and the now weighted objects can start their race for being encoded into vSTM. Each neuron coding for a specific feature only represents one object, but one object can be represented by multiple neurons. TVA assumes that a neuron's receptive field is large enough to cover almost the entire visual field. The rate equation describes the effects of filtering and pigeonholing on the total activation of neurons representing the categorization ‘the circle is red’, while the weight equation represents the likelihood that the neuron represents the circle in its receptive field. NTVA is not assumed to be bound to a definite anatomical location. Bundesen et al. (2005, 2011) do, however, suggest thalamo-cortical pathways. They also propose that objects encoded in vSTM are maintained via a feed-back loop between the lateral geniculate nucleus (LGN) and the thalamic reticular nucleus (TRN).

Several studies have investigated the neural correlates of TVA parameters (e.g., Gillebert et al., 2012; Wiegand et al., 2013, 2014; Chechlacz, Gillebert, Vangkilde, Petersen, & Humphreys, 2015; Menegaux et al., 2017; Ruiz-Rizzo, Neitzel, Müller, Sorg, & Finke, 2018; Ruiz-Rizzo et al., 2019; Haupt, Ruiz-Rizzo, Sorg, & Finke, 2019). For example, by observing event-related potentials (ERPs) with electroencephalography (EEG), Wiegand et al. (2013) found distinct, dissociable neurophysiological markers for visual processing speed *C* and vSTM storage capacity *K*. Young individuals with a higher visual processing speed *C* compared to those with a lower *C* showed a reduced visual N1 response, which was interpreted as greater efficiency in visual processing. Conversely, those with a higher vSTM storage capacity *K* compared to those with a lower *K* showed an enhanced contralateral delay activity over visual areas and a reduced non-lateralized delay activity, supporting NTVA’s suggestion of a visuotopic organization of specific sustained activation responsible for holding items in vSTM. Importantly, Ruiz-Rizzo et al. (2018) observed intrinsic functional connectivity (FC) in 32 young healthy adults and linked it to TVA parameters. Individuals with a higher visual processing speed *C* compared to those with a lower *C* had a lower FC within the cingulo-opercular network (see also Section 1.3.3.2).

1.1.2 Assessment, modeling and parameter estimation

Experimentally, TVA-based parameters are estimated via the performance in two computerized, psychophysical tasks, i.e., whole and partial report of briefly presented stimuli (Duncan et al., 1999). Participants are asked to report as many stimuli as possible (whole report) or all stimuli of one particular feature (e.g., color, partial report) while ignoring distractors. Stimuli are presented for multiple individually adjusted exposure durations, under masked and unmasked conditions, to account for a broad spectrum of attentional capacity. From the resulting data, several parameters can be estimated via a Maximum Likelihood Method, performing an iterative search for the best fitting parameters (see Kyllingsbaek, 2006; Dyrholm, 2011). This method provides us with a function illustrating visual attention capacity, in which the visual threshold *t0* marks the point below which 0 letters are perceived (represented by the point at which the function meets the x-axis). This is the time when visual objects start to race for being encoded into vSTM. Visual processing speed *C* indicates the number of processed stimuli per second (represented as the slope of the function at $t = t0$, or the steepest point), while vSTM storage capacity *K* marks the number of letters that can be consciously and simultaneously maintained in vSTM (represented by the asymptote of the function). The partial report paradigm – which we only ever use as a control in the studies presented in this thesis – can be used to obtain the parameters top-down efficiency α, spatial balance of attentional weights w_{index}, and sensory effectiveness a, in which effects of visual threshold and visual processing speed are not separated.

1.1.3 Visual attention capacity and alertness

Recently, TVA was extended by further breaking down the bias parameter of the rate equation. Bundesen et al. (2015) depict this parameter as a product of the subjective prior probability of being presented with a particular feature (the expectation to see a certain feature, e.g., the color red), the subjective importance ('utility') of identifying this feature, and the alertness level *A*. According to this equation, no categorization will be made in case any of its terms are zero. While alertness is unspecific and speeds up processing for all categorizations and objects, the latter two terms of the product require an 'ideal observer' and are specific to one feature (e.g., the color red). According to the Yerkes-Dodson law (Yerkes and Dodson, 1908), intermediate levels of arousal entail the best performance.

Alertness can be defined as a readiness of the system to perceive or respond to stimuli (Sturm & Wilmes, 2001; Posner, 1978; Thiel, 2004; Haupt, Sorg, Napiórkowski, & Finke, 2018). While tonic alertness describes a general and inherent readiness, phasic alertness denotes the ability to increase this readiness in response to an external cue (Sturm & Willmes, 2001). Visual processing speed seems to be tightly connected to alertness and seems to improve when alertness is improved, be it phasic or tonic alertness. Evidence comes from studies in patients and healthy adults which show that an increased level of tonic alertness or visual or auditory phasic alerting cues often seem to increase visual attention capacity, especially TVA parameter visual processing speed *C* (Finke et al., 2012; Matthias et al., 2010; Petersen, Petersen, Bundesen, Vangkilde, & Habekost, 2017; Wiegand, Petersen, Finke, et al., 2017; Haupt et al., 2018). Alertness decreases with aging, but phasic alerting still seems to affect visual attention capacity in older age (Haupt et al., 2018; but see also Wiegand, Petersen, Bundesen, & Habekost, 2017, for contrary evidence from partial report assessment). Furthermore, drugs designed to enhance alertness also seem to enhance visual processing speed in healthy individuals with a lower baseline speed (Finke et al., 2010) and adult ADHD (Attention Deficit Hyperactivity Disorder;

Low et al., 2018). Thus, there seems to be a theoretically well-grounded and experimentally observed close link between alertness and visual processing speed *C*.

1.1.4 Changes of visual attention capacity during aging

The capacity parameters estimated based on TVA are sensitive to aging (e.g., McAvinue et al., 2012; Habekost et al., 2013; Nielsen & Wilms, 2015). While the results of different studies did not always find the same pattern of age effects on all TVA parameters, they do seem to agree that especially visual processing speed *C* is prone to age decrements, and that it declines rather linearly during the life span. For example, McAvinue et al. (2012) found a linear decline in visual processing speed and vSTM storage capacity after a peak in the teenage years, and a comparably smaller increase in visual threshold. Habekost et al. (2013), who examined older adults between 69 and 87 years, also observed a reduction in parameters *K* and *t0*, but mostly in visual processing speed *C*, which was almost reduced to half of its value between 70 and 85. Nielsen and Wilms (2015) found a decrease in *C* over the lifespan, while no other parameters seemed to be affected.

On a neurophysiological level, Wiegand et al. (2014) found additional ERPs linked to TVA parameters in older compared to younger adults. Those with a lower visual processing speed *C* compared to those with a higher *C* had a reduced anterior N1, while those with higher compared to lower *K* had an enhanced right central positivity. The authors ascribed this to a loss of attentional resources in the case of *C*, and to a compensatory recruitment of neural resources for vSTM storage capacity *K*. Importantly, Ruiz-Rizzo et al. (2019) found a cluster in the cingulo-opercular network to be linked with visual processing speed *C*, and this cluster also mediated the age-related decline in *C*. Specific deficits of visual attention capacity in pathological aging in the case of Mild Cognitive Impairment and Alzheimer's disease have also been reported (Bublak et al., 2011).

1.1.5 Advantages of TVA-based assessment

TVA-based assessment has several advantages compared to other measures of visual attention (cf. Habekost, 2015; Bundesen & Habekost, 2008).

Reliability. TVA-based measurement has proven to be reliable for most of its parameters, shown by bootstrap analyses, which revealed a high internal reliability, low measurement errors and a good retest reliability after a first practice session (Habekost & Bundesen, 2003; Habekost and Rostrup, 2006; Finke et al., 2005; Habekost, Petersen, Behrmann, & Starrfelt, 2014; cf. Habekost, 2015).

Specificity. In various different studies and types of testing, the effects of experimental manipulations or disorders on different aspects of visual attention as well as motor factors are confounded with each other. For example, measures of visual processing speed often involve speeded motor components (e.g., Kreiner & Ryan, 2001). Results based on such measures render it difficult to disentangle pure visual processing speed from motor speed. Other types of measurement that also rely on accuracy, such as the Useful Field of View test (UFOV; Ball & Owsley, 1993) or inspection time paradigms (Deary, 1986), do not distinguish between visual processing speed and visual threshold, i.e., how long a stimulus has to be presented to be perceived. With TVA-based assessment, we are able to specifically and independently measure the effects of different experimental manipulations, disease or aging on several aspects of visual attention. Solely the C and K parameters seem to correlate with each other, which has been suggested to be an indication of a common neural basis (e.g., Finke et al., 2005; Habekost, Petersen, & Vangkilde, 2014; cf. Habekost, 2015; Habekost & Bundesen, 2003).

Validity. It is important for a cognitive test to measure exactly what is intended to be measured. TVA-based assessment is theoretically well-grounded and therefore has an advantage over other types of attention testing. The estimated parameters should represent pure attentional aspects and do not only reflect results from a specific task. Furthermore, the different TVA parameters have been shown to correlate with established clinical tests (see, e.g., Finke et al., 2005; cf. Habekost, 2015; Habekost & Bundesen, 2003).

Sensitivity. TVA based assessment is very sensitive even to small changes in visual attention, and seems to be able to identify subclinical deficits in patients, i.e., deficits that do not show in standard clinical tests (cf. Habekost, 2015; Habekost & Bundesen, 2003).

Overall, the above-mentioned advantages make TVA-based measurement a perfect candidate for assessing changes in visual attention capacity. More specific information about TVA-based assessment in connection to dual tasking (Section 1.2.4), cognitive training (Section 1.3.1) as well as intrinsic FC (Section 1.3.3.2) can be found in the respective chapters.

1.2 Visual attention capacity in dual task situations

In many situations in our daily life, we are faced with having to (or choosing to) perform multiple tasks at the same time. Examples could be rather common, like having a conversation while walking, or more dangerous, like texting while driving. While some think that adverse effects caused by this phenomenon might be on the rise due to 'media multitasking' (Ralph, Thomson, Cheyne, & Smilek, 2014), researchers started to investigate the effects of performing two tasks at the same time, so-called 'dual task' (DT) situations, as early as the nineteenth century (James, 1890). A DT effect can always be seen when the performance of one or both of the concurrently performed tasks deteriorates in the presence of the other compared to single task (ST) conditions (Kahneman, 1973). Interestingly, those who often perform multiple tasks at the same time are not automatically very good at it (Ophir, Nass, & Wagner, 2009; Sanbonmatsu, Strayer, Medeiros-Ward, & Watson, 2013; Ralph et al., 2014).

1.2.1 Experimental designs to measure DT effects

Different experimental paradigms have been used to study DT effects.

Psychological Refractory Period (PRP) Paradigm. In many early studies, one particular experimental design was used to get to the bottom of the mechanisms of DT effects (Telford, 1931; Welford, 1952; for reviews see e.g., Pashler, 1994; Koch et al., 2018). In this setup, two speeded choice reaction tasks – for example the discrimination of a tone and of the orientation of a visual stimulus (e.g., Töllner et al., 2012) – are presented shortly after one another, with varying times between the presentation of the two stimuli (stimulus onset asynchronies or SOAs). It was observed that in case of short SOAs, and thus a higher temporary overlap between component tasks, the reaction time for task 2 suffered. This phenomenon was termed the Psychological Refractory Period (PRP), and the respective paradigm is still often used to test different model predictions (for a review, see Koch, Poljac, Müller, & Kiesel, 2018)

Further DT paradigms. Apart from the PRP paradigm, a variety of possible combinations of tasks to measure DT effects exists. For example, combinations of choice reaction tasks, tracking tasks, memory load tasks and also motor tasks are possible (cf. Pashler, 1994). Investigations are often especially focused on the differences in performance between ST and DT conditions, or DT costs (DTCs; Somberg & Salthouse, 1982). These can be calculated by comparing performance in each task alone to performance in a situation when both tasks are executed at the same time. A special case, important for the first study included in this thesis, is cognitive-motor-interference, or the DTCs caused by the concurrent performance of a cognitive and a motor task (McDowd & Craik, 1988; Woollacott & Shumway-Cook, 2002; Patel, Lamar,

& Bhatt, 2014; Al-Yahya et al., 2011; Schaefer & Schumacher, 2011; Plummer-D'Amato et al., 2012; Guillery, Mouraux, & Thonnard, 2013; Boisgontier et al., 2013). Cognitive-motor interference is often investigated by combining walking or posture tasks with secondary cognitive tasks (for reviews, see Al-Yahya et al., 2011; Boisgontier et al., 2013). Plummer et al. (2013) suggest different types of possible DTCs in these cases, in which the performance on either or both of the tasks can deteriorate, be unaffected or even be facilitated by a concurrent task (e.g., Schmidt-Kassow et al., 2014; Hemond, Brown, & Robertson, 2010). Thus, it is important to always consider the DTCs in both tasks to be able to paint a more accurate picture of how performance is affected, which studies on cognitive-motor interference do not always do (Plummer et al., 2013; Plummer & Eskes, 2015; see also Schaefer, 2014; Al-Yahya et al., 2011). In the area of fine motor skills, research on schizophrenia patients (Fuller & Jahanshahi, 1999) revealed a deteriorated performance in the Purdue Pegboard task (which requires visual selective attention, amongst other functions) when paired with a concurrent finger tapping task. Furthermore, Mioni and colleagues (2016) found that a concurrent finger tapping task in healthy young adults led to elevated thresholds in a visual temporal discrimination task. Thresholds for a comparable auditory task were not affected. The authors concluded that processing of time in the auditory, but not in the visual modality seems to be automatic. Thus, comparably easy motor tasks such as finger tapping can have an effect on the efficiency of visual processing (cf. Künstler et al. 2018). A more recent study by Künstler et al. (2018) that combined TVA-based measurement with a concurrent tapping task will be discussed in more detail in 1.2.4.

1.2.2 Models explaining DT effects

Different models to explain DT interference have been proposed in the literature. While early researchers mostly assumed an attentional bottleneck as the cause for performance decline under DT conditions, other studies rather point to a capacity sharing model.

Bottleneck models. Beginning with Broadbent's (1958) suggestion that only one channel can be processed at a time, structural bottleneck models were proposed (Pashler, 1984; 1994). These models assume that at some stage in task processing, processing is structurally limited and only one task can be processed at a time, i.e., there is only serial, but never parallel processing. This stage is often assumed to be response selection, while stimulus perception and motor reaction can be processed in parallel according to the model (Pashler, 1994; but for opposing views, see e.g., Keele, 1973; Schumacher et al., 1999). Processing of the second task will be stalled until processing of central stages of task 1 are finished, also referred to as queuing (e.g., Pashler, 1984). Evidence for bottleneck models often comes from the PRP paradigm (see Section

1.2.1). While predominantly a structural bottleneck is proposed, there are also ideas for a more strategic bottleneck that can be flexibly applied under certain circumstances (Meyer & Kieras, 1997; Miller, Ulrich, & Rolke, 2009; for a review on parallel vs. serial processing, see Fischer & Plessow, 2015). Additionally, De Jong (1993) suggests multiple bottlenecks at different task stages.

Capacity sharing models. Contrary to bottleneck models, capacity sharing models do not assume one or more structural bottlenecks, but one or more resource pools of attention (e.g., Kahneman, 1973; Navon & Gopher, 1979; Wickens, 1980; Wickens, 2002). According to this idea, attentional resources are finite and two tasks can be performed without interference, as long as capacity limits are not reached. When they are, performance in one or both tasks will suffer (Kahneman, 1973). Processing does not have to be serial, but can be carried out in parallel. A special case is the central capacity sharing model (Tombu & Jolicoeur, 2003) that assumes that capacity is shared at central stages, but not at peripheral stages. The central bottleneck model (Pashler, 1984) can, in turn, also be seen as a special case of the central capacity sharing model, when 100 percent of attentional resources are initially allocated to task 1, while none are given to task 2 until task 1 is completed (Fischer & Plessow, 2015; Navon & Miller, 2002; Tombu & Jolicoeur, 2003; Lehle & Hübner, 2009). Many phenomena that can and cannot be explained by bottleneck theories can be accounted for by a central capacity sharing model (Navon & Miller, 2002; Tombu & Jolicoeur, 2003; Hommel, 1998; Logan & Schulkind, 2000; Miller, 2006). One example that challenges the idea of a structural bottleneck is, the crosstalk effect, i.e., interference between two tasks that are similar, e.g., in response codes (Koch et al., 2018; Koch, 2009; Miller & Alderton, 2006; Janczyk, Pfister, Hommel, & Kunde, 2014). This is especially somewhat contrary to a more serial processing approach when the second task in the PRP paradigm has an effect on the reaction time of task 1, the so-called backward compatibility effect, that has often been reported (Ellenbogen & Meiran, 2008; Janczyk et al., 2014). Similar to the idea of multiple bottlenecks, multiple resource pools for capacity sharing have been proposed (e.g., Navon & Miller, 1987; Wickens, 1980; Wickens, 2002). In these models, two tasks can be carried out concurrently without interfering with each other as long as they do not share the same resources. Logan and Gordon’s (2001) ECTVA model has properties of both capacity sharing and bottleneck models and incorporates the central ideas of TVA. It addresses the aforementioned issues in that it explains how two concurrent tasks can be performed using the preferred and faster serial strategy, although a parallel strategy can be applied in other situations. The model is also able to account for crosstalk effects.

1.2.3 DT and aging

One of the most often reported findings on factors influencing DTCs is a prominent age effect. While studies on DT performance in children exist (e.g., Gautier & Droit-Volet, 2002), in the following, I will focus on differences in DT effects between younger and older adults. Age effects are often (Verhaeghen & Cerella, 2002; Verhaeghen, Steitz, Sliwinski, & Cerella, 2003; Hartley, 2001; Crossley & Hiscock, 1992; Li, Lindenberger, Freund, & Baltes, 2001; Salthouse, Rogan, & Prill, 1984), but not always (Nyberg, Nilsson, Olofsson, & Bäckman, 1997; Somberg & Salthouse, 1982; Tun & Wingfield, 1994; Wickens, Braune, & Stokes, 1987) reported.

Regarding cognitive-motor interactions, both motor and cognitive functions decline over the lifespan (Ketcham & Stelmach, 2001; Park & Reuter-Lorenz, 2009; McAvinue et al., 2012; Habekost et al., 2013), but there is also an additional age-sensitive DT factor (e.g., Verhaeghen & Cerella, 2002; Verhaeghen et al., 2003), even for tasks that seem to be comparably easy (e.g., Künstler et al., 2018). In general, it seems that cognitive and motor functions show higher correlations in older adults (Li & Lindenberger, 2002), so that for example walking is more cognitive for older compared to younger adults (Lindenberger, Marsiske, & Baltes, 2000). DT performance even seems to be connected to the risk of falls in older adults (Faulkner et al., 2007; Verghese et al., 2002). An influential study on cognitive-motor interference during walking is Lundin-Olsson, Nyberg and Gustafson (1997) who found that those older adults who stopped talking when they were walking had a higher risk of falling. In another study by Lindenberger et al. (2000), younger, middle-aged and older adults walked on two narrow tracks with two complexity levels while memorizing word lists. Overall, older adults showed higher DTCs than younger adults. In the younger participants, under DT conditions on the easy track, motor performance declined more than memory performance, while older participants showed higher decrements in the cognitive task than in the walking task compared to the ST condition. This result was interpreted as older adults prioritizing walking, which is reasonable considering their high risk and the detrimental consequences of falling (Schaefer, 2014; see also the results of a follow-up study to Lindenberger et al., 2000, by Li et al., 2001).

Proposed underlying causes for aging effects in DT situations include a general slowing, a process-specific slowing, more cautious task coordination strategies (Glass et al., 2000), and complexity (McDowd & Craik, 1988). Regarding the last point, enhancing the difficulty or complexity of a task often increases DTCs. While older adults often already show impaired performance when concurrently executing two relatively simple tasks, younger adults' performance seems to be impaired only with higher task load (Woollacott & Shumway-Cook, 2002; Fraser, Li, & Penhune, 2010). In the aforementioned study by Lindenberger et al. (2000), all three age groups showed higher DTCs in the cognitive task with higher complexity of the walking task. For younger adults, the complex condition was even the only one that produced DTCs.

To summarize, DT performance seems to be sensitive to age decrements, and one of the reasons could be that even relatively simple tasks seem to pose a higher complexity for older adults. However, we don't know yet how performing a concurrent task affects the performance in TVA-based assessment.

1.2.4 Effects of DT on visual attention capacity as measured based on TVA

TVA-based estimation of model parameters (see Section 1.1) seems to be an excellent method to investigate DT effects on visual attention (cf. Poth, Petersen, Bundesen, & Schneider, 2014; Künstler et al., 2018). First, we can independently measure effects of a concurrent task on different aspects of visual attention, such as vSTM storage capacity, visual processing speed or visual threshold. Additionally, Goodness-of-fit (GOF) measures make it possible to compare model fits in ST and DT conditions, enabling us to get a qualitative insight into DT effects. We also do not introduce a manual motor confound because participants are not required to press a single button in the whole report task and also do not have to give speeded responses, making it a perfect candidate for assessing the effects of a concurrent manual motor task.

Poth and colleagues (2014) investigated the effects of a secondary cognitive task on the performance in TVA-based assessment. They combined whole and partial report measurements with a monitoring task in which participants had to react to luminance changes of a fixation cross as fast as possible. Additionally, they manipulated the salience of this luminance change. Their results show a negative influence of the secondary cognitive task on visual processing speed. The authors interpret this finding as more attentional weights that are given to the monitoring task, resulting in less attentional weights, and thus visual processing speed, being allocated to the whole report task. In high salience conditions, in which participants could bank more on the external salience of the luminance increase, visual processing speed decline was less pronounced.

More recently, Künstler et al. (2018) investigated the effects of a concurrent motor task, i.e., alternating finger tapping with the index and middle fingers of the right hand, on TVA-based whole report measurement in healthy middle to older aged adults. The motor task was performed with an accuracy of more than 96% across conditions, suggesting the finger tapping task to be relatively simple. While no detrimental effects on finger tapping were found under DT conditions, visual processing speed as well as vSTM storage capacity were negatively affected by the introduction of a secondary task. These findings point to a capacity sharing account in cognitive-motor DT situations, in which attention is shared between the visual and the motor domain. However, it is not yet clear whether and how exactly younger and older adults differ in their whole report performance during a secondary fine-motor task. Additionally – in case we find age decrements in DT performance – it would be interesting to investigate whether increased complexity of the concurrent task can shift younger participants' performance to the older adults' level.

1.3 Enhancement of visual attention capacity: cognitive training of visual processing speed

Faced with impending cognitive decline, individuals of all ages search for means to enhance their cognitive performance, and are overwhelmed with an abundance of commercial advertising claims. Especially cognitive training is often marketed as an easily accessible magic bullet (Simons et al., 2016). Despite its recent popularity (see also Harvey, McGurk, Mahncke, & Wykes, 2018), reports of systematic cognitive training emerged as early as the late 19th, early 20th century (for a historical review, see Katz, Shah, & Meyer, 2018).

1.3.1 Foundations of cognitive training

In their definition of cognitive training, Gates and Valenzuela (2010) propose that it has to involve repeated practice on standardized tasks targeting specific cognitive domains (for other definitions and distinctions from other forms of cognitive training, see, e.g., Clare & Woods, 2004; Choi & Twamley, 2013; Mowszowski, Batchelor, & Naismith, 2010). One reason why such training might have positive effects on cognition is given by the concept of cognitive reserve (e.g., Stern, 2002). This concept was originally developed to account for the puzzling finding that some older adults show age-appropriate, normal cognitive performance, while, at the same time, presenting with comparably grave signs of aging pathology (such as amyloid plaques or neurofibrillary tangles, Katzman et al., 1988). While brain reserve describes a more passive form of reserve in which anatomical features such as a comparably larger brain size help stave off cognitive decline for longer, cognitive reserve is considered more 'active' and can be influenced during the life course (Barulli & Stern, 2013). In several studies, Stern and colleagues found that those with higher compared to lower education (Stern, Alexander, Prohovnik, & Mayeux, 1992), occupational attainment (Stern et al., 1995) or amount of leisure activities (Scarmeas et al., 2003) were able to cope with present pathology markedly longer than their less cognitively active peers. However, these patients would show a more rapid cognitive decline as soon as symptoms were apparent (Stern, Albert, Tang, & Tsai, 1999). Luckily, it seems like physical and cognitive activity can still enhance cognitive reserve even in older age (e.g., Lenehan et al., 2016; Stern, 2012; Marioni, van den Hout, Valenzuela, Brayne, & Matthews, 2012; Summers et al., 2017; Wilson et al., 2005). The concept of 'brain maintenance' is seen as complementary to that of reserve (Nyberg et al., 2012). It centers on cases in which brain structures or functions do not show any or only delayed decline in older age. Brain maintenance seems to depend on genes as well as on lifestyle factors such as cognitive training. Finally, the

Scaffolding Theory of Aging Cognition (Park & Reuter-Lorenz, 2009) describes the recruitment of alternative neural circuits in older adults to compensate for functional decline, stating that these ‘scaffolds’ can be influenced by interventions such as cognitive training. That is, cognitive and neuronal plasticity seem to exist even in older age (cf. Greenwood & Parasuraman, 2010). Cognitive plasticity means that cognitive functions can be influenced, for example, by age or interventions, while neuronal plasticity denotes the fact that changes on the brain level, such as neurogenesis or synaptogenesis, can occur. Novelty of experiences seems to be an especially important factor for plasticity to transpire (cf. Greenwood & Parasuraman, 2010; see also Straube, Korz, & Frey, 2003; Kempermann & Gage, 1999), as well as an initial mismatch between environmental demands and individual functions (Lövdén, Bäckman, Lindenberger, Schaefer, & Schmiedek, 2010). In one example of plasticity, Maguire, Woollett and Spiers (2006; see also Maguire et al., 2000) examined the brains of taxi drivers in London. To be able to acquire an official license, these drivers have to memorize the entirety of the London street system. Compared to bus drivers who only drove fixed routes, the taxi drivers in the study had a larger posterior hippocampus volume, and a reduced anterior hippocampus volume. With more years of navigation experience, these changes increased. These results suggest that the repeated practice in navigating led to long-lasting changes in the brain, and hint at the possibility of influencing brain structures via systematic cognitive training.

Several cognitive functions have been targeted by cognitive training interventions, among these working memory (e.g., Jaeggi, Buschkuehl, Jonides, & Perrig, 2008), long-term memory, reasoning, or processing speed (e.g., Ball et al., 2002). However, controversy exists among researchers as to whether cognitive training actually ‘works’ (cf. Simons et al., 2016). Due to hyperbolic claims of companies marketing commercial ‘brain training’ games, 75 researchers (Stanford Center on Longevity and Berlin Max Planck Institute for Human Development, 2014) even felt it was necessary to sign an open letter urging caution considering the interpretation of results of cognitive training studies (which was followed shortly after by a letter of an opposing camp of 127 researchers, detailing that there is proof for some positive effects caused by cognitive training; Cognitive Training Data, 2014). However, as Katz and colleagues (2018) put it in their PNAS paper, asking whether cognitive training works is comparable to asking whether medicine works – it is an unspecific question that cannot be answered conclusively. Meta-analyses often compare different training programs, training durations or outcome measures, so it is not surprising that results vary (cf. Edwards, Fausto, Tetlow, Corona, & Valdes, 2018; Zokaei, MacKellar, Čepukaitytė, Patai, & Nobre et al., 2017; Katz et al., 2018). Thus, it is crucial to evaluate the success of cognitive training programs in targeting specific functions, as well as to find ways to predict individual training gain in order to be able to tailor interventions to individual needs (cf. Zokaei et al., 2017).

A broad distinction can be made between strategy-based and process-based training (cf. Lustig, Shah, Seidler, & Reuter-Lorenz, 2009). Strategy-based training could, for example, teach methods such as the method of loci and is mostly applied to the memory domain. Process-based training involves a more implicit repeated practice of some kind of basic task and seems to be the more effective form of training (cf. Edwards et al., 2018). A range of well-known process-based training studies on different cognitive functions exists. Among these is for example a heatedly discussed paper proposing working memory training can improve fluid intelligence (Jaeggi et al., 2008). In this study, young adults performed dual *n*-back training, in which two adaptive working memory tasks are concurrently presented in the visual and auditory domain. Compared to a passive control group, training participants not only significantly improved their performance in the trained task, but also showed transfer to a nonverbal reasoning task supposed to represent fluid intelligence. Moreover, the amount of this transfer increased with a higher number of training sessions. However, the replication of this effect was not always successful (e.g., Chooi & Thompson, 2012; Redick et al., 2013; Thompson et al., 2013)

A second rather famous study is that of Anguera and colleagues (2013) who specifically developed the video game ‘NeuroRacer’ to assess and improve cognitive functions. The training of interest was a multitasking setting, in which participants had to simultaneously perform a driving task and a symbol discrimination task. By examining 174 participants, the authors found that performance declined linearly from the age of 20 to the age of 79. Moreover, when participants over 60 were trained on the multitasking game for 12 hours, they achieved the same level of performance as those at the age of 20 who played the game for the first time. An active control group performed both of the tasks subsequently instead of simultaneously, while a passive control group did not receive any training. Only the multitasking training group improved in working memory and sustained attention, and these changes lasted at least six months after completion of the training. Additionally, electroencephalography (EEG) measures revealed that two neural correlates of cognitive control (midline theta and long-range theta coherence between frontal and posterior brain regions) improved from pre- to post-test only in this group, and reached an activity pattern similar to that in younger adults.

Training studies designed to enhance processing speed. As already mentioned above, cognitive functions decline over the lifespan, and one of the most gravely affected candidates is visual processing speed. Visual processing speed is essential for many daily life activities (e.g., Ball, Edwards, & Ross, 2007; Ross et al., 2015) as well as performance in cognitive tasks (e.g., Salthouse, 1996). It seems to be associated with a higher risk of falls in older adults (e.g., Davis et al., 2017). Nishita et al. (2017) even suggest that processing speed training might help individuals live longer. Furthermore, a processing speed deficit is a key symptom of various diseases such as Multiple Sclerosis (Rao, Aubin-Faubert, & Leo, 1989), Parkinson's disease (Grossman et al., 2002), Depression (Gögler et al., 2017), or Schizophrenia (Brébion, Amador, Smith, & Gorman, 1998).

Processing speed training often shows comparably high effect sizes (e.g., Papp, Walsh, & Snyder, 2009; Kueider, Parisi, Gross, & Rebok, 2012; Kelly et al., 2014; Lampit, Hallock, & Valenzuela, 2014). But even if training programs are set out to improve visual processing speed, they can assume various forms, such as simple paper and pencil tasks (Takeuchi et al., 2011), computerized rapid recognition tasks (Takeuchi et al., 2011), reaction time tasks (Lawlor-Savage, Clark, & Goghari, 2019), or, prominently, the so-called Useful Field of View (UFOV) task (Ball et al., 2002; for a review of processing speed training, see Takeuchi & Kawashima, 2012). The latter, used both for training and as an outcome measure, consists of several tasks which involve briefly presented stimuli and are designed to measure visual processing speed, divided attention, and selective attention. Among different kinds of visual processing speed training programs, it seems to be the best-researched (more than forty published studies to date; for a review, see Edwards et al., 2018). Probably one of the most famous and influential training studies in general, and specifically also in the area of visual processing speed, is the ACTIVE (Advanced Cognitive Training for Independent and Vital Elderly, Ball et al., 2002) study, a multicenter, randomized controlled trial, in which 2832 healthy older adults were divided into one of four groups: a memory training, a reasoning training, a visual processing speed (UFOV) training and a passive control group. Results showed that in each of the groups the proximal outcome was improved compared to the passive control group, while, as expected, no transfer to any of the other tasks occurred. Thus, for example, memory training did improve memory, but not processing speed and the opposite was true for processing speed training. However, effect sizes for the processing speed group were three to five times the size of the effects of the memory or reasoning training groups (Edwards et al., 2018). The special role of processing speed training was particularly evident in follow-up measures that revealed advantages of predominantly this training group compared to the passive control group in several daily life outcomes. For example, positive outcomes could be found for health-related quality of life (Wolinsky et al., 2006), the onset of suspected clinical depression (Wolinsky et al., 2009), self-rated health (Wolinsky et al., 2010), driving mobility (Edwards, Delahunt, & Mahncke, 2009), and even the risk of developing dementia (Edwards et al., 2017). Effects – on the proximal outcome and on outcomes such as the important measure of instrumental activities of daily living – could be observed up to 10 years after training (Rebok et al., 2014; for the five-year-follow-up, see Willis et al., 2006). Those participants who had received four sessions of booster training at eleven and 35 months after the initial training showed even better results (Ball et al., 2002). One massive point of criticism considering the ACTIVE trial is, however, that the training groups were not compared to an active control group. This point was addressed in subsequent studies, which led to comparable results (e.g., Vance et al., 2007; Wolinksy, Vander Weg, Howren, Jones, & Dotson, 2013; Edwards et al., 2005).

In the area of alertness training, Van Vleet et al. (2016) evaluated the effects of twelve sessions of an alertness training program (TAPAT, Tonic and Phasic Alertness Training) in twelve healthy older adults. The training consisted of a monitoring task, in which participants had to react to distractor stimuli, but needed to withhold key presses in response to targets. Results showed that this training, compared to an active control training (n = 12) that was matched in stimuli but not in the active ingredient 'alertness', enhanced the rate of skill acquisition in a processing speed task (UFOV) that was performed before each training session. Differences between the groups were only found in the second half of training, in which the active control group seemed to plateau, while members of the alertness training group still seemed to improve. Higher processing speed for the alertness training compared to the active control group was still found six weeks after training, suggesting a long-lasting effect. However, the authors did not report effects on processing speed caused by just the alertness training program itself (without the additional UFOV training). Nevertheless, these results are further evidence for the link between alertness and processing speed.

While, strictly speaking, video game training is not necessarily included in the definition of cognitive training, it is still worth noting that it seems to be able to enhance visual processing speed or reaction times (e.g., Clark, Lanphear, & Riddick, 1987; Dustman, Emmerson, Steinhaus, Shearer, & Dustman, 1992; Goldstein et al., 1997; for a meta-analysis on the effects of video game training on healthy older adults, see Toril, Reales, & Ballesteros, 2014). Action video games seem to improve factors such as visual processing speed in healthy young adults (Dye, Green, & Bavelier, 2009). However, this kind of games might not be suitable for or accepted by older adults (e.g., McKay & Maki, 2010). Thus, games are specifically designed to increase cognitive functions. For example, Nouchi, Saito, Nouchi and Kawashima (2016) trained 36 healthy older adults on processing speed games and compared them to an active control group (n = 36) who trained on knowledge quiz training game. Both groups performed their training at home, for 15 minutes at least five times a week, for four weeks. Participants of the processing speed group improved their processing speed and inhibition of executive function in untrained tasks; moreover, their scores of depressive mood decreased.

The sometimes long-lasting and far-reaching effects of visual processing speed training, especially in the form of UFOV training, seem promising. It is, however, not clear whether these effects really result from an increase in pure visual processing speed. The UFOV task does not only train or measure speed, but also various other functions such as visual threshold, and these individual functions are not clearly disentangled from each other (cf. Woutersen et al., 2017; see also Protzko, 2017; Ball et al., 2007). Therefore, we first have to ensure that specific training interventions achieve their goal of improving the targeted construct to be able to draw meaningful conclusions. In our case that means that the intervention we applied should improve the latent parameter of visual processing speed. Such "near" transfer to a construct is important to prove, and should be theoretically well-grounded (cf. Noack, Lövdén, Schmiedek, & Lindenberger, 2009; Noack, Lövdén, & Schmiedek, 2014). Thus, a highly sensitive, theory-based measure is needed to determine whether we really achieve the desired outcome when we set out to enhance visual processing speed (cf. Zokaei et al., 2017). TVA-based assessment provides such a sensitive measure.

Training-induced enhancement of TVA-based visual attention capacity. As detailed in Section 1.1.5, TVA-based assessment offers a variety of advantages compared to other types of measurements. As it is very sensitive even to small alterations in attentional functioning (Habekost & Bundesen, 2003), it should enable us to detect any training-related changes in visual attention, making it perfectly suited for evaluating the usability of a training program. To date, only a few studies have investigated the effects of cognitive training on parameters derived from TVA, and, to my knowledge, none of these studies was carried out in healthy older adults. Thus, for the purpose of a short review, I will focus on the effects of different forms of cognitive training in the broadest sense on visual attention capacity in healthy young adults and patients. Jensen, Vangkilde, Frokjaer and Hasselbalch (2012) trained 16 healthy young participants on mindfulness-based stress reduction and compared them to both an active control group practicing non-mindfulness stress reduction (n = 15), and to an inactive control group (n = 16). Apart from reduced stress and increased mindfulness, they found a significant improvement in vSTM storage capacity K and visual threshold $t0$ only in the mindfulness training group. Peers et al. (2018) compared the effects of selective attention training, working memory training and a waitlist condition on a variety of different tasks, among these also TVA-based whole report, in stroke survivors. They found that selective attention training enhanced vSTM storage capacity K. Furthermore, working memory training reduced the variability in TVA performance, which was interpreted as a marker for sustained attention. Effects on visual processing speed were not reported. Probably most relevant for our purposes is the evidence from video game training. Wilms, Petersen and Vangkilde (2013) compared different TVA parameters (among other tasks) in 42 young male adults categorized as expert video game players, casual video game players or non-video game players. They found that the video game experts had, on average, a higher visual processing speed *C*. Schubert et al. (2015) also compared expert video gamers to non-experts and replicated the results on visual processing speed *C*, although advantages for experts were restricted to the lower positions of the display. This effect seems to attenuate a disadvantage for letters presented at the lower half of the screen (see also Bublak et al., 2011). Additionally, experts had lower visual thresholds compared to non-experts. These differences are, of course, only observational. That is why, in a second experiment, Schubert et al. (2015) trained 21 video-game naïve participants on the action video game Medal of Honor for 15 sessions of one hour each, and compared them both to an active control group playing the puzzle game Tetris (n = 20), and to a passive control group (n = 21). Medal of Honor, set in a World War II scenario, is an action video game requiring fast motor responses. After compared to before training, participants showed a very specific increase in visual processing speed *C* at the lower right positions of the display, the locations for which experts had an advantage from the start. No effects on any further TVA parameters were found. The authors explain these results with the special characteristics of this type of action video game, in which participants have to pay a significant amount of attention to rapid changes in the lower right corner. Additionally, they note that longer practice might lead to more pronounced effects in more parameters.

To sum up, TVA parameters seem to be malleable to cognitive interventions in patients and healthy young adults. However, we do not know yet whether cognitive training can also affect TVA parameters, and specifically visual processing speed, in healthy older adults.

1.3.2 Factors influencing training response

A growing number of studies find that training outcomes are not identical for every participant, but individual differences in response to training exist. To create personalized interventions with maximum benefits, it is crucial to get to the bottom of these differences. For example, some studies found that baseline performance was related to the amount of training gain. Sometimes, those who already have a higher ability seem to profit more from training (Guye, De Simoni, & von Bastian, 2017; Strobach & Huestegge, 2017; Wiemers, Redick, & Morrison, 2018). This could be interpreted as a form of magnification effect, i.e., that those who already have better resources will be able to profit more from cognitive training. Conversely, other studies suggest that those with a lower baseline performance profit more from cognitive training (e.g., Karbach, Könen, & Spengler, 2017; Zinke et al., 2014; Whitlock, McLaughlin, & Allaire, 2012), pointing to a more compensatory effect, or more ‘room for improvement’.

Furthermore, differences in age have been found to affect training response. Again, different results contradict each other in that some studies find that younger adults profit more from training than older adults (e.g., Zinke et al., 2014; Wass, Scerif, & Johnson, 2012; Dorbath, Hasselhorn, & Titz, 2011), while other studies find a higher training gain for older adults (Bherer et al., 2008; Karbach & Kray, 2009). Hering, Meuleman, Bürki, Borella and Kliegel (2017) even found a difference between younger-old and older-old participants in a sample of adults aged 60-82 years. In this case, the older-old participants profited more from working memory training (but see also Borella et al., 2014). However, in their meta-analysis, Karbach and Verhaeghen (2014) did not find any differences in training response between younger and older adults.

In a secondary analysis of the ACTIVE-study, Clark, Xu, Unverzagt and Hendrie (2016) found that those participants who had received fewer than 12 years of education showed a 50% greater effect on the UFOV outcome measure induced by processing speed training than those with 16 and more years of education. These differences were still seen three years after completion of the initial training. For the reasoning and memory training groups, there was no education-related difference in training success. Thus, it seems education can play a role in training response, depending on the applied type of training.

Additional factors possibly related to individual training gain are beliefs about whether cognitive functions can be influenced by training (e.g., Jaeggi, Buschkuehl, Shah, & Jonides, 2014; Foroughi, Monfort, Paczynski, McKnight, & Greenwood, 2016; but see also Tsai et al., 2018), crystallized intelligence (Hering et al., 2017; Wiemers et al., 2018), the variant of the APOE genotype (Feng et al., 2015), or personality traits like conscientiousness or neuroticism (Studer-Luethi, Jaeggi, Buschkuehl, & Perrig, 2012; Urbánek & Marček, 2016). Furthermore, certain general factors seem to make it more likely for training to be rated as successful. For example, training programs that constantly adapt the difficulty of the task to the individual ability level seem to elicit greater benefits than non-adaptive training (e.g., Edwards et al., 2018; Lövdén et al., 2010; Kelly et al., 2014; Flegal, Ragland, & Ranganath, 2019). Furthermore, it is important to control for general motivational, practice or placebo effects by using active and passive control groups (e.g., Klingberg, 2010; Shipstead, Redick, & Engle, 2012).

Summing up, not every training intervention seems to be equally effective for everyone, and several studies hint at possible causes for inter-individual differences in training success. However, studies differ in their observations. It would be helpful to find reliable neural markers indicative of specific possible future training gain, so individuals will only spend their time on the kind of training that is most likely beneficial for them.

1.3.3 Cognitive training and resting state fMRI assessment

Cognitive training effects are not only evaluated on the behavioral level. Multiple studies are centered on exploring the neural underpinnings of possible training-related improvements (for reviews, see Lustig et al., 2009; Belleville & Bherer, 2012). In general, changes after different types of cognitive training include gains in cortical thickness (e.g., Engvig et al., 2010), changes in white matter architecture (e.g., Engvig et al., 2012), and increases or decreases in brain activation (e.g., Dahlin, Neely, Larsson, Bäckman, & Nyberg, 2008; Erickson et al, 2007), amongst others. More recently, researchers started to evaluate training effects on functional connectivity (FC) at rest.

1.3.3.1 Foundations of resting state fMRI measurement

In assessing the effects of a cognitive intervention, it can be insightful to relate behavioral outcomes to the brain level. Functional magnetic resonance imaging (fMRI) allows us to peek into the brain non-invasively by observing the blood-oxygen level dependent (BOLD) signal that indirectly reflects neuronal activity (Ogawa, Lee, Kay, & Tank, 1990). Traditionally, BOLD signals were observed in relation to the execution of a task; a slightly newer method is the measurement of spontaneous coherent low frequency fluctuations in the range of 0.01-0.1 Hz, correlating in time among spatially distant brain regions, or intrinsic FC, during rest (for a review, see Van den Heuvel & Pol, 2010). The measurement is typically carried out when participants are lying awake in the scanner, often with their eyes closed, not performing any task and not attending to a particular stimulus. From the activity during rest, the BOLD signal is observed, and so-called intrinsic connectivity networks (ICNs) can be estimated, that overlap with brain systems involved in certain functions like attention, vision or executive functions (e. g. Sorg et al., 2007). These spontaneous coherent low-level fluctuations were discovered rather accidentally by researchers trying to eliminate noise from their data (Biswal, 2012). Although it was first criticized (Biswal, 2012), the phenomenon was subsequently observed in more and more brain networks (Hampson, Peterson, Skudlarski, Gatenby, & Gore, 2002; Greicius, Krasnow, Reiss, & Menon, 2003; Raichle et al., 2001).

The observed spontaneous coherent low-level fluctuations may be in part a result of spontaneous cognitive processes (Rosazza & Minati, 2011), but can also be observed during sleep (Horovitz et al., 2008) or anesthesia (Vincent et al., 2007), and even similarly in rodents

(Lu et al., 2012) and monkeys (Hutchison et al., 2012). On the one hand, ICNs seem to be reliable and consistent over a multitude of studies and participants (Damoiseaux et al., 2006; Smith et al., 2009; Biswal et al., 2010) and also within participants (Shehzad et al., 2009; Thomason et al., 2011). On the other hand, they are also rather individual and can be influenced by factors like personality (Kunisato et al., 2011), genes (Glahn et al., 2010), or even mood (Harrison et al., 2008), and sleep deprivation (De Havas, Parimal, Soon, & Chee, 2012).

1.3.3.2 The cingulo-opercular network

Several ICNs have been described, among these, for example, a default mode network (Raichle et al., 2001), a frontoparietal network (Dosenbach et al., 2007), and a dorsal attention network (Fox, Corbetta, Snyder, Vincent, & Raichle, 2006). Especially important for one of the studies presented in this thesis is the cingulo-opercular network (Dosenbach et al., 2007), which is also referred to as the ‘ventral attention’ (Yeo et al., 2011) or the ‘salience’ network (Seeley et al., 2007). It includes regions such as the insula, the anterior cingulate cortex and the thalamus (Seeley et al., 2007; Dosenbach et al., 2007), and has been linked to tonic alertness (Sadaghiani et al., 2010; Coste & Kleinschmidt, 2016; Schneider et al., 2016). Sadaghiani and D’Esposito (2014) found that a higher demand on tonic alertness goes along with a higher FC in the cingulo-opercular network. Critically, this network has been found to be connected to visual processing speed parameter *C* measured based on TVA in healthy young (Ruiz-Rizzo et al., 2018) and healthy older adults (Ruiz-Rizzo et al., 2019; see also Section 1.1.1). Additionally, Haupt et al. (2019) recently linked the degree to which healthy young adults could benefit from phasic alerting cues in the form of an improvement in visual processing speed *C* to the FC in the cingulo-opercular network. This association was negative, i.e., a higher *C* caused by alerting cues was linked to a lower FC in the cingulo-opercular network. Thus, for the evaluation of an effect of alertness training on visual processing speed measured as TVA parameter *C*, we were specifically interested in this particular network.

Healthy older adults compared to younger adults generally show decreased FC within and between networks (Damoiseaux et al., 2007; Andrews-Hanna et al., 2007; Tomasi & Volkow, 2012), and this is also true for the cingulo-opercular network (Onoda, Ishihara, & Yamaguchi, 2012; Geerligs, Renken, Saliasi, Maurits, & Lorist, 2014; Ferreira & Busatto, 2013; Ruiz-Rizzo et al., 2019). Furthermore, decreased FC in the cingulo-opercular network was reported to be linked to cognitive impairment (Onoda et al., 2012). Zhang and Raichle (2010) even propose decreased FC within networks as a sensitive early biomarker for disease.

In conclusion, FC in the cingulo-opercular network seems to be linked to alertness and visual processing speed as measured based on TVA. Furthermore, it seems to be affected by aging. Therefore, FC in the cingulo-opercular network seems to be a suitable starting point in the search of a neural marker to possibly predict change in visual processing speed induced by alertness training in healthy older adults.

1.3.3.3 Training studies involving FC at rest

As FC seems to depend on prior experience (Lewis, Baldassarre, Committeri, Romani, & Corbetta, 2009; Tambini, Ketz, & Davachi, 2010) and to be related to cognitive reserve (Arenaza-Urquijo et al., 2013), it is reasonable to expect a connection to cognitive training. In addition to various training studies in younger participants (e.g., Mackey, Singley, & Bunge, 2013; Martínez et al., 2013; Jolles, van Buchem, Crone, & Rombouts, 2013), training-induced FC changes can also be found in healthy older adults. For example, twelve weeks of gist reasoning training led to an increase in FC in the default mode network and the central attention network in healthy older adults compared to a waitlist control group (Chapman et al., 2013). Similarly, after a multi-domain training intervention aimed at improving memory, reasoning and problem solving, applied in 24 sessions over 3 months, healthy older adults showed an increase in, or maintenance of, FC in the default mode network, the central executive network and the cingulo-opercular network compared to a waitlist control group (Cao et al., 2016). Importantly, a pilot study on 14 healthy older adults who completed 10 hours of adaptive Useful Field of View (UFOV) training (a kind of visual processing speed training; see also Section 1.3.1) reported increased FC in different regions relevant for task performance, such as executive function and visual attention, compared to both an active control group – involved in challenging, cognitively stimulating activities aimed at improving executive functions, reasoning and recall – and a passive control group (Ross et al., 2018). The authors speculate that such a change of FC in a cognitive control network might be a sign for a more efficient use of neural resources. Moreover, they suspect it to be a neural mechanism for the transfer to daily life activities that studies on UFOV training have reported before (see also Section 1.3.1). Training-induced changes in intrinsic FC can also be found in patients affected by mild cognitive impairment (e.g., Lin et al., 2016).

The aforementioned studies show that cognitive training can influence FC under certain conditions. However, as we saw in Section 1.3.2, not everyone profits from every training intervention. Now that we know that FC is malleable by training interventions, it is possible to explore the potential predictive power of baseline FC for training-induced behavioral change.

This might enable us to eventually predict whether an individual will or will not profit from a certain training routine.

The attempt to use imaging data to predict the success of different interventions has been made in several other areas. For example, Erickson et al. (2010) found that the amount of improvement in the complex video game Space Fortress was predicted by the volume of the dorsal striatum before training in healthy young adults. Heinzel, Lorenz et al. (2014) investigated differences between younger and older adults in BOLD responses during a working memory task. Those older adults who had a more 'youth-like' activation pattern in the form of decreased activation in the frontoparietal network at baseline improved more during a subsequent 12-week working memory training intervention. In the area of FC at rest, Gallen and colleagues (2016) found that a certain pattern in the organization of the ICNs of older adults predicts how much they can improve due to different forms of cognitive training. This link was greater in networks related to associative functions than sensory-motor areas. Based on these results, the authors make rather broad assumptions about the general susceptibility of an individual to training interventions. These results are intriguing; however, they do not answer the question whether we can use FC to predict the specific training-induced change after a targeted training intervention. Patient studies teach us that not everyone has the same needs when it comes to cognitive enhancement (e.g., Bublak et al., 2005; for a review, see Habekost, 2015). Moreover, not every healthy individual profits from cognitive training programs in the same way (see Section 1.3.2). Therefore, it is possible that certain individuals profit more from one training intervention (e.g., training of visual processing speed), while others profit more from a different training intervention (e.g., working memory training). A specific neural marker for training success on a specific function might be a first step to stratifying individuals according to their individual training needs.

1.4 Aims of this thesis

The main goal of this thesis was to investigate how visual attention capacity is affected by aging in certain situations, and how an age-related functional decline can be counteracted.

In study 1 (see Section 2.1), we examined the influence of a concurrently presented secondary finger tapping task on visual attention capacity, measured based on TVA in healthy older and younger adults. Moreover, a subset of the younger adults performed the same secondary task in a more complex version to investigate whether complexity was one of the drivers of possible age-related differences in dual task performance.

In study 2.1 (see Section 2.2), we trained healthy older adults on an adaptive alertness task and examined whether we could find a specific enhancement in latent visual processing speed measured based on TVA. The results of this training group were compared to those of an active control group – who trained on a working memory update task (visual *n*-back) –, and to those of a passive control group who did not receive any training.

In study 2.2 (see Section 2.2), we wanted to examine whether baseline FC in the cingulo-opercular network, that had been previously linked to alertness as well as TVA-based visual processing speed, could serve as a neural marker for the susceptibility to a specific form of training, i.e., indicate how much a healthy older adult could profit from subsequent alertness training in the form of specifically enhanced visual processing speed.

To sum up, the specific aims were to investigate…

A) … how the introduction of a secondary, motor task influences the execution of a primary visual attention task (TVA whole report) in healthy older adults, and to see how this performance compares to that of younger adults under comparable or more difficult conditions (study 1).
B) … the impact of an alertness training program specifically on a latent parameter of visual processing speed in healthy older adults (study 2.1).
C) … whether we could find a neural marker (in the form of FC of the cingulo-opercular network assessed before training) for subsequent alertness training-induced gain in visual processing speed in healthy older adults (study 2.2).

2. Dual Task Effects on Visual Attention Capacity in Normal Aging

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Dual Task Effects on Visual Attention Capacity in Normal Aging

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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

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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 $\times$ a $\times$ b blue = (17.95; 45.15; —67.08)] or red [CIE L $\times$ a $\times$ 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.

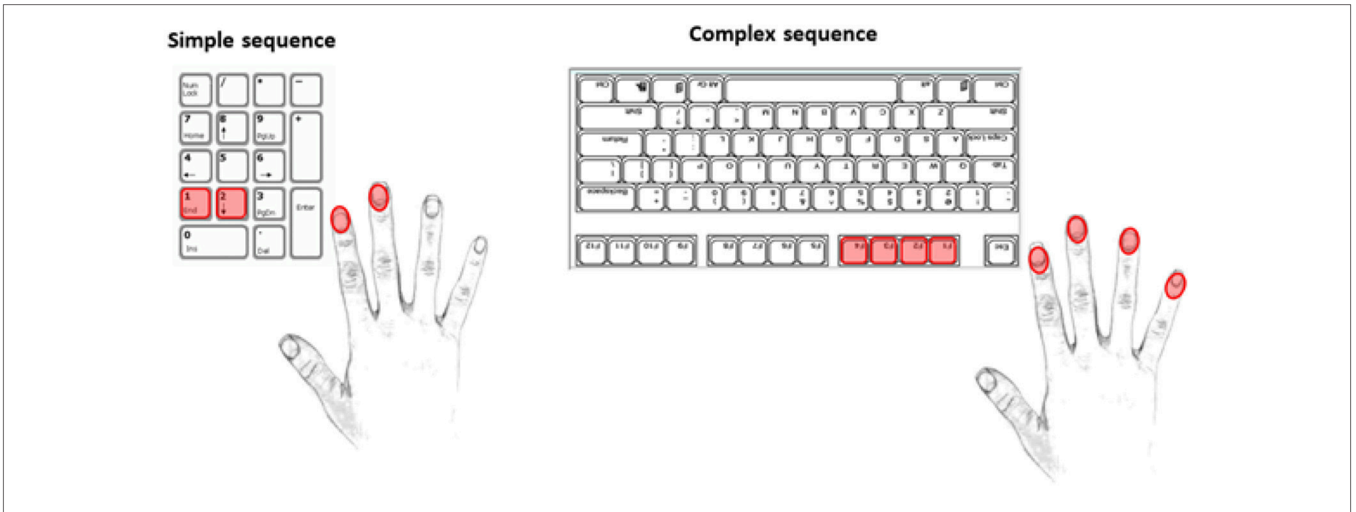

FIGURE 1 | Simple and complex tapping sequences. Used keys and fingers are marked in red.

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.

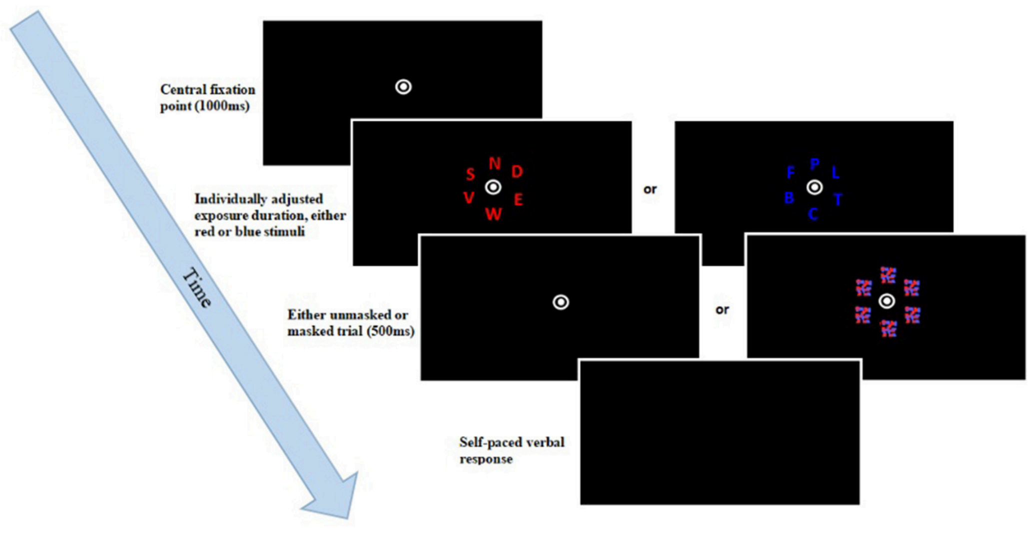

FIGURE 2 | TVA whole report trial sequence. After the presentation of a fixation point, six either red or blue letters were briefly displayed, followed by a mask in some of the trials. Participants had to name all letters they had recognized.

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

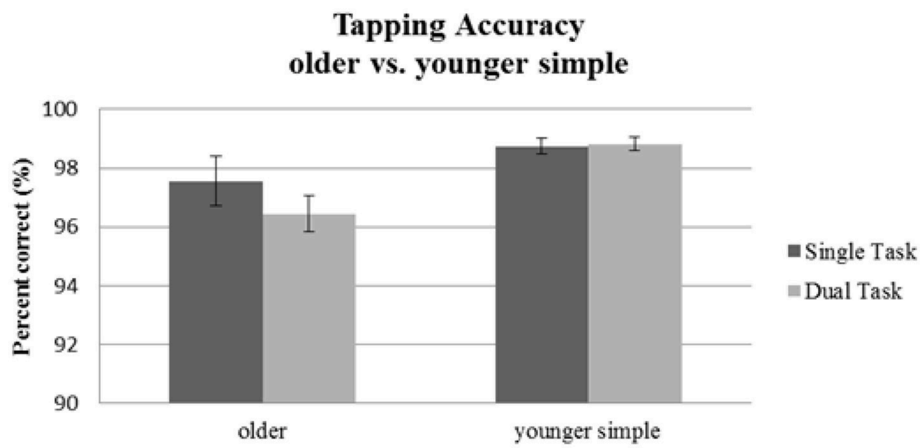

FIGURE 3 | Tapping accuracy as indicated by percentage of correct taps for the older group performing the simple tapping sequence vs. the younger group performing the simple tapping sequence. Error bars indicate standard errors of the mean.

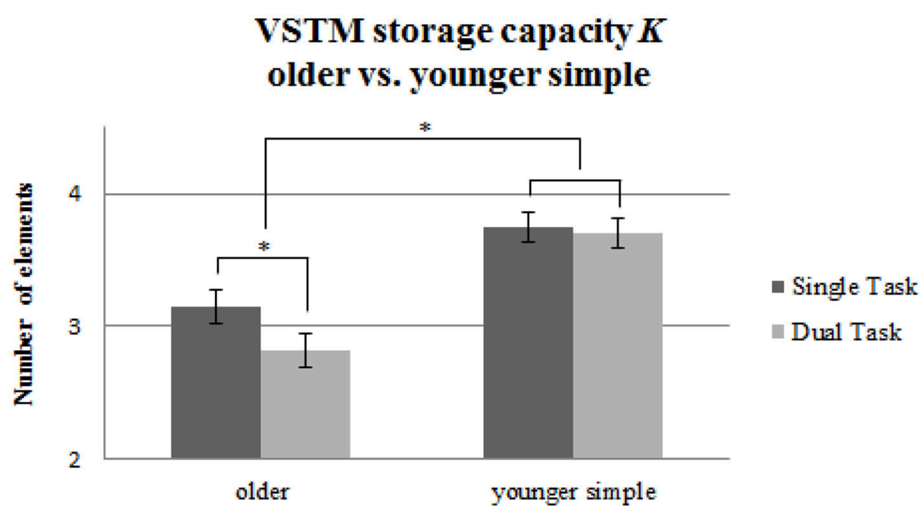

FIGURE 4 | VSTM capacity *K* measured in maximum number of recognized letters for the older group performing the simple tapping sequence vs. the younger group performing the simple tapping sequence. Error bars indicate standard errors of the mean. Significant differences are denoted by an asterisk (*).

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.

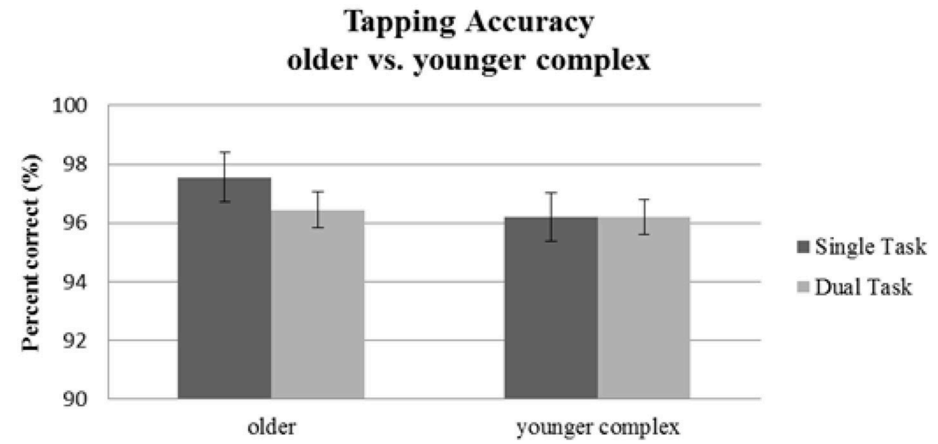

FIGURE 5 | Tapping accuracy as indicated by percentage of correct taps for the older group performing the simple tapping sequence vs. the younger group performing the complex tapping sequence. Error bars indicate standard errors of the mean.

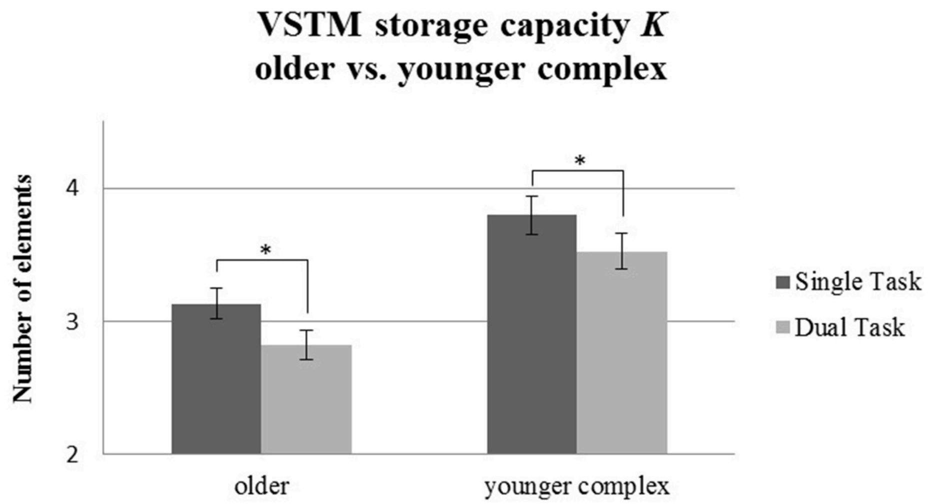

FIGURE 6 | VSTM capacity *K* measured in maximum number of recognized letters for the older group performing the simple tapping sequence vs. the younger group performing the complex tapping sequence. Error bars indicate standard errors of the mean. Significant differences are denoted by an asterisk (*).

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.

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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

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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.

Supplementary Materials

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

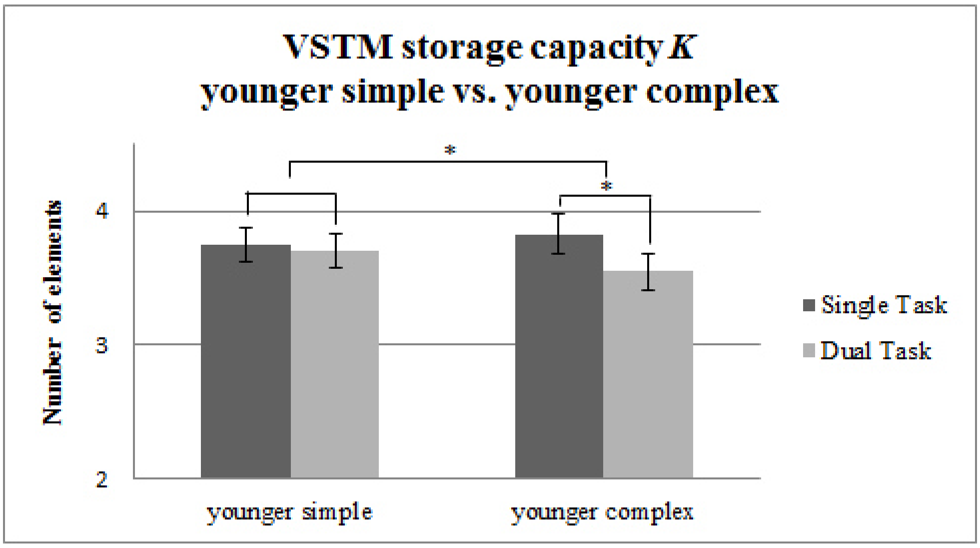
To explore the differences between a simple versus a more complex tapping sequence in younger participants – which should increase the difficulty of the task – a comparison was run between the two younger groups.

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 $t_0 = 0$).

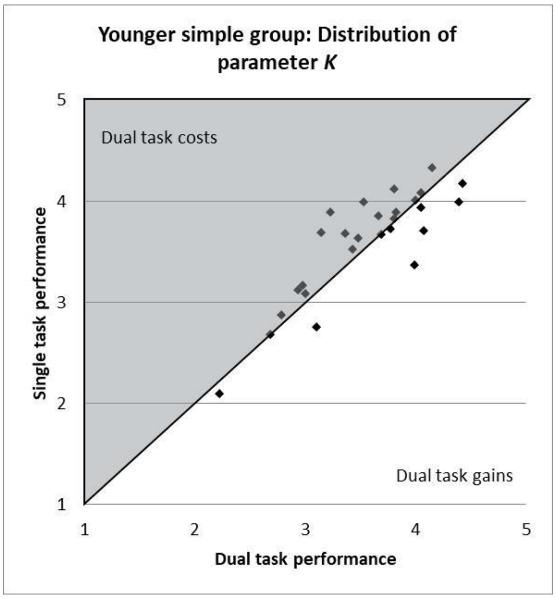
	Wilcoxon-Test		
	Older simple	**Younger simple**	**Younger complex**
Z	-.024	-1.415	-.362
***p*-value**	.98	.16	.72
r²	< .001	.07	.004

	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

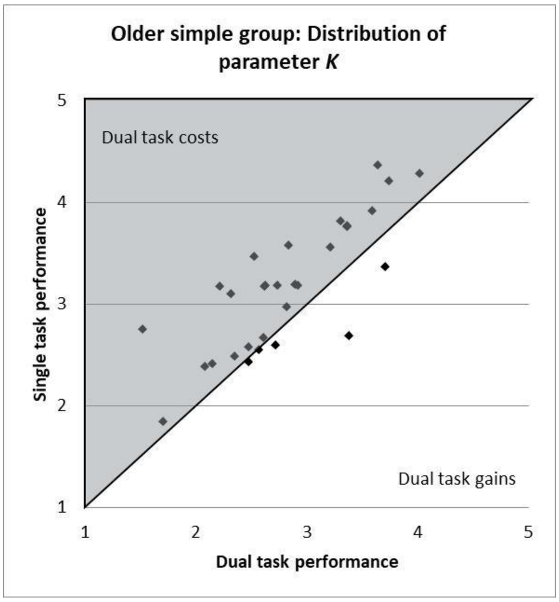
Note. Md = Median; os = older simple group; ys = younger simple group; yc = younger complex group; ** $p < .001$

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

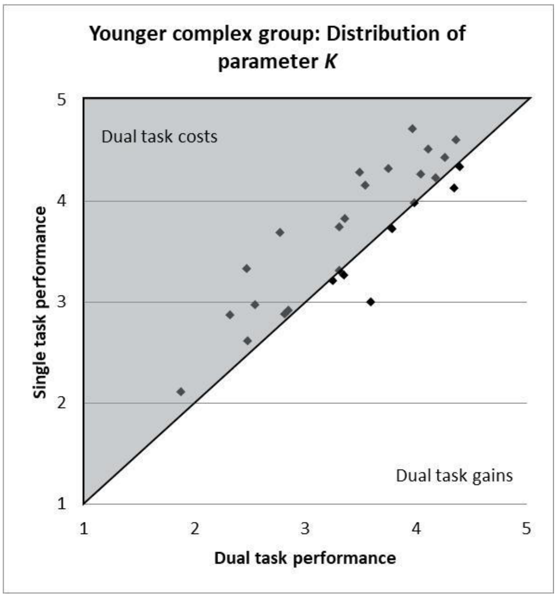
S2.



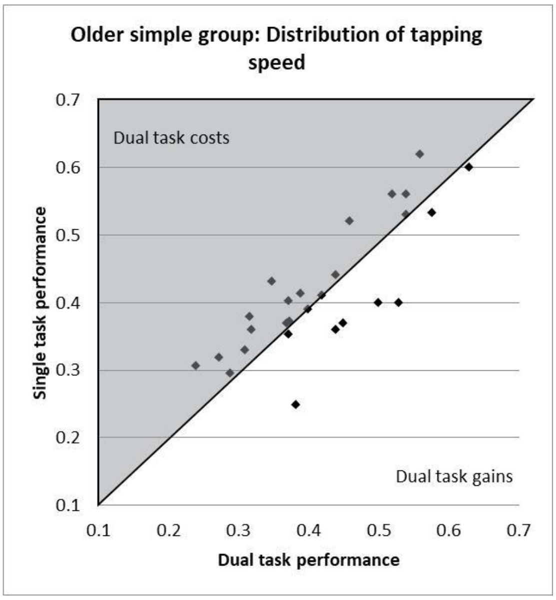
S3.



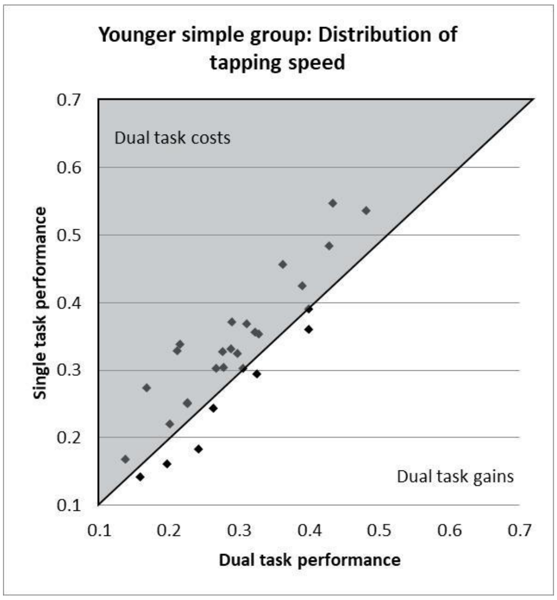
S4.



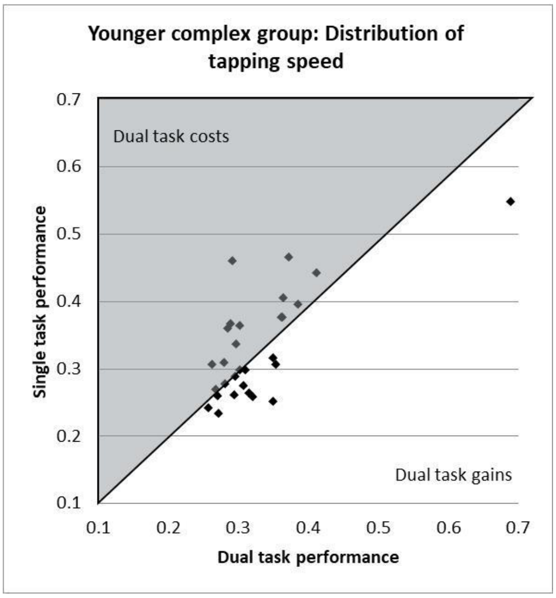
S5.



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

Supplementary Table 4. Individual values of Goodness-of-Fit (single, dual, with and without the exclusion of tapping errors) and of TVA parameters visual processing speed *C*, VSTM storage capacity *K* and visual threshold t_0 (single and dual task conditions) for each of the three groups.

ID	**Goodness-of-fit**			**Parameter *C***		**Parameter *K***		**Parameter *t0***		**Tapping Accuracy**		**Tapping Speed**	
	Single	Dual uncorr.	Dual corr.	Single	Dual	Single	Dual	Single	Dual	Single	Dual	Single	Dual
YS01	0.989	0.992	0.952	23.35	35.16	4.08	4.06	5.04	10.00	98.97	99.42	0.30	0.28
YS02	0.927	0.944	0.944	22.90	43.32	3.67	3.37	-46.28	-15.50	99.82	99.91	0.33	0.28
YS03	0.992	0.974	0.974	90.19	70.87	3.89	3.83	14.31	8.80	100.00	99.87	0.24	0.26
YS04	0.995	0.98	0.984	22.91	27.70	4.32	4.15	3.32	10.00	97.12	99.01	0.33	0.21
YS05	0.996	0.984	0.987	33.74	19.09	3.99	3.54	18.12	8.61	97.37	98.14	0.17	0.14
YS06	0.995	0.984	0.985	34.69	38.69	3.94	4.05	.51	-1.52	98.97	98.52	0.30	0.27
YS07	0.988	0.965	0.967	29.09	17.20	3.69	3.15	-4.15	-22.17	100.00	99.01	0.33	0.29
YS08	0.958	0.983	0.983	45.05	23.55	3.99	4.40	-.04	-5.77	99.38	99.60	0.22	0.20
YS09	0.979	0.972	0.972	32.69	34.11	3.82	3.81	4.62	-1.25	99.90	99.74	0.18	0.24
YS10	0.991	0.996	0.996	27.18	33.86	3.63	3.49	2.76	.35	100.00	99.47	0.55	0.43
YS11	0.988	0.97	0.97	56.22	60.58	3.72	3.78	8.99	9.20	-[1]	99.43	-[1]	0.40
YS12	0.923	0.998	0.998	36.93	22.16	2.75	3.11	10.00	4.31	97.34	95.78	0.35	0.33
YS13	0.977	0.984	0.986	18.12	20.61	3.52	3.43	-36.29	-19.04	98.33	98.88	0.29	0.33
YS14	0.98	0.994	0.995	25.85	36.54	3.89	3.23	-3.50	7.67	100.00	97.31	0.37	0.29
YS15	0.983	0.99	0.989	19.23	24.78	4.17	4.43	-21.80	-11.64	99.46	99.26	0.48	0.43
YS16	0.984	0.994	0.994	17.00	15.52	2.68	2.69	14.48	8.13	99.82	99.82	0.32	0.30
YS17	0.978	0.951	0.956	19.63	15.16	3.11	2.94	-3.44	-38.72	99.49	98.00	0.46	0.36
YS18	0.991	0.958	0.954	17.69	16.59	2.09	2.23	-1.01	-11.09	97.08	97.92	0.34	0.22
YS19	0.981	0.985	0.985	36.73	28.21	3.67	3.69	-9.02	-14.55	100.00	99.48	0.42	0.39
YS20	0.992	0.976	0.977	37.08	38.21	5.24	4.97	-1.78	-1.04	98.79	99.05	0.36	0.32
YS21	0.971	0.983	0.984	50.07	37.62	4.00	4.00	8.19	6.46	97.36	97.75	0.16	0.20
YS22	0.985	0.982	0.982	13.93	10.15	2.87	2.79	-22.35	-26.16	100.00	100.00	0.27	0.17
YS23	0.991	0.995	0.996	15.80	21.77	3.08	3.01	.38	-1.24	95.28	94.51	0.37	0.31
YS24	0.938	0.991	0.991	35.46	40.26	4.86	5.10	-24.23	-3.46	95.14	99.05	0.30	0.31
YS25	0.992	0.984	0.985	39.43	62.35	5.40	5.22	-5.66	1.11	99.58	99.84	0.25	0.23
YS26	0.983	0.977	0.968	27.78	25.98	3.16	2.98	10.00	8.89	98.00	98.95	0.25	0.23
YS27	0.907	0.987	0.987	57.36	38.12	3.37	4.00	10.00	4.06	100.00	99.59	0.54	0.48
YS28	0.989	0.978	0.975	42.21	27.00	3.70	4.08	-7.26	-23.92	97.40	99.72	0.14	0.16
YS29	0.969	0.982	0.982	61.48	31.25	4.11	3.81	8.76	9.10	99.56	99.16	0.39	0.40
YS30	0.981	0.957	0.956	40.36	25.43	3.85	3.67	12.40	10.00	99.46	99.12	0.14	0.16
OS01	0.979	0.984	0.984	38.08	45.30	4.28	4.02	10.77	8.77	99.44	99.44	0.25	0.38

ID	Goodness-of-fit			Parameter *C*		Parameter *K*		Parameter *t0*		Tapping Accuracy		Tapping Speed	
	Single	Dual uncorr.	Dual corr.	Single	Dual	Single	Dual	Single	Dual	Single	Dual	Single	Dual
OS02	0.949	0.921	0.921	48.37	33.47	2.68	3.38	4.89	-9.97	99.41	100.00	0.53	0.58
OS03	0.991	0.969	0.957	40.28	19.38	2.47	2.35	10.00	-4.38	82.14	89.63	0.40	0.37
OS04	0.952	0.979	0.979	42.77	43.31	3.90	3.59	2.51	5.16	98.97	99.07	0.31	0.24
OS05	0.978	0.981	0.987	31.14	22.22	2.57	2.48	29.24	16.11	99.51	97.41	0.30	0.29
OS06	0.991	0.968	0.967	11.04	20.37	2.74	1.53	.48	4.80	97.11	94.49	0.44	0.44
OS07	0.956	0.967	0.962	38.10	36.93	3.80	3.31	14.64	17.42	100.00	94.40	0.41	0.39
OS08	0.98	0.98	0.975	17.23	13.91	1.83	1.71	33.93	55.02	97.37	92.48	0.35	0.37
OS09	0.896	0.93	0.93	25.27	64.11	3.46	2.53	-41.12	-1.10	97.61	98.62	0.32	0.27
OS10	0.985	0.959	0.959	20.85	21.20	2.96	2.82	10.00	-6.73	99.71	98.82	0.53	0.70
OS11	0.969	0.955	0.96	34.53	40.76	2.42	2.48	8.00	10.00	99.06	99.55	0.40	0.75
OS12	0.993	0.974	0.964	42.32	42.75	2.59	2.72	6.67	7.22	96.62	93.00	0.40	0.50
OS13	0.997	0.957	0.962	21.86	17.69	3.36	3.71	17.58	15.19	95.61	98.26	0.41	0.42
OS14	0.976	0.953	0.959	13.68	15.37	2.37	2.09	7.84	13.31	98.49	89.28	0.36	0.44
OS15	0.968	0.901	0.901	43.52	37.05	2.54	2.57	10.00	7.02	97.46	99.88	0.36	0.32
OS16	0.981	0.981	0.981	32.24	22.60	3.75	3.37	15.03	15.94	95.47	-[1]	0.39	-[1]
OS17	0.982	0.954	0.95	30.16	26.74	3.17	2.22	8.77	26.52	99.33	98.73	0.60	0.63
OS18	0.993	0.977	0.977	35.77	25.07	3.17	2.74	18.28	18.21	98.92	98.42	0.74	0.55
OS19	0.962	0.981	0.982	35.58	25.04	3.17	2.92	35.22	33.35	96.61	91.03	0.37	0.45
OS20	0.966	0.994	0.997	29.13	26.17	3.09	2.32	20.00	20.00	99.41	96.82	0.62	0.56
OS21	0.932	0.934	0.911	40.46	9.19	4.35	3.64	10.00	10.10	99.40	97.07	0.33	0.31
OS22	0.944	0.983	0.985	31.97	17.55	2.66	2.62	20.00	20.00	98.13	91.07	0.53	0.54
OS23	0.976	0.976	0.975	34.52	51.85	3.57	2.84	8.49	16.43	100.00	98.34	0.37	0.37
OS24	0.997	0.982	0.998	21.44	16.94	3.16	2.62	31.14	37.11	99.74	95.00	0.52	0.46
OS25	0.99	0.996	0.994	23.48	25.18	2.40	2.16	14.12	8.44	80.83	94.16	0.40	0.53
OS26	0.989	0.949	0.949	28.33	23.02	3.18	2.90	16.17	7.55	100.00	99.78	0.56	0.54
OS27	0.958	0.918	0.918	33.14	12.93	4.20	3.74	5.66	-15.40	98.64	97.54	0.56	0.52
OS28	0.974	0.98	0.974	40.70	31.53	3.75	3.37	5.40	8.40	99.76	95.42	0.43	0.35
OS29	0.99	0.989	0.99	36.12	28.98	3.17	2.63	18.52	12.60	100.00	99.61	0.38	0.32
OS30	0.955	0.976	0.965	29.52	42.79	3.54	3.22	5.28	13.55	100.00	99.66	0.37	0.37
YC01	0.965	0.956	0.951	24.60	25.53	3.73	3.31	-28.66	-9.03	99.79	95.58	0.37	0.29
YC02	0.98	0.994	0.993	32.82	42.63	4.22	4.18	7.08	4.18	98.93	97.42	0.37	0.36
YC03	0.991	0.993	0.992	27.37	23.13	3.19	3.25	5.21	5.36	99.83	98.63	0.30	0.26
YC04	0.998	0.983	0.986	32.68	24.02	3.30	3.31	3.76	2.99	92.56	91.61	0.26	0.32
YC05	0.997	0.987	0.985	22.90	26.28	4.50	4.11	-1.05	2.58	90.59	95.56	0.40	0.36
YC06	0.986	1,000	1,000	18.06	18.96	3.71	3.79	10.00	12.16	97.51	99.29	0.55	0.69
YC07	0.967	0.963	0.964	20.53	23.48	2.86	2.32	1.79	10.00	100.00	99.23	0.46	0.29

ID	Goodness-of-fit			Parameter *C*		Parameter *K*		Parameter *t0*		Tapping Accuracy		Tapping Speed	
	Single	Dual uncorr.	Dual corr.	Single	Dual	Single	Dual	Single	Dual	Single	Dual	Single	Dual
YC08	0.994	0.982	0.988	58.49	44.37	4.59	4.37	8.07	-5.70	97.28	95.82	0.33	0.30
YC09	0.962	0.98	0.985	20.32	25.08	2.60	2.48	2.08	1.43	92.71	87.68	0.31	0.35
YC10	0.976	0.996	0.995	48.43	26.00	4.14	3.54	4.52	-4.42	97.02	94.81	0.26	0.27
YC11	0.954	0.988	0.989	24.92	29.41	4.32	4.39	4.99	.89	99.58	98.68	0.38	0.36
YC12	0.988	0.98	0.978	17.66	19.93	2.87	2.81	-8.38	-16.84	98.58	95.90	0.28	0.28
YC13	0.98	0.981	0.982	36.79	42.07	3.81	3.36	-5.14	7.90	-[1]	97.18	-[1]	0.30
YC14	0.984	0.994	0.991	22.26	30.56	5.21	3.97	-2.89	-9.40	98.67	98.74	0.30	0.31
YC15	0.964	0.981	0.98	22.99	21.54	3.67	2.77	7.46	7.12	98.24	99.43	0.44	0.41
YC16	0.966	0.973	0.967	45.20	65.48	5.04	4.65	-4.24	6.06	99.33	97.13	0.24	0.26
YC17	0.985	0.993	0.993	23.66	24.29	4.71	3.97	-11.65	-.63	98.79	99.49	0.36	0.29
YC18	0.952	0.974	0.974	38.36	43.32	3.97	3.99	-6.15	-8.59	99.17	98.12	0.30	0.30
YC19	0.967	0.947	0.939	35.00	20.27	3.26	3.35	-14.41	-39.56	98.94	98.53	0.27	0.27
YC20	0.997	0.999	0.999	25.50	24.57	4.11	4.35	15.01	8.17	89.54	96.17	0.26	0.29
YC21	0.996	0.986	0.984	31.16	23.87	4.27	3.49	-1.83	-20.72	81.97	94.22	0.26	0.32
YC22	0.922	0.905	0.906	15.44	16.68	4.31	3.75	-62.34	-49.99	100.00	99.60	0.46	0.37
YC23	0.99	0.987	0.991	19.23	17.88	2.91	2.85	16.79	-4.39	98.89	88.57	0.39	0.39
YC24	0.977	0.977	0.976	46.77	53.24	4.25	4.05	2.94	1.57	97.20	97.07	0.29	0.30
YC25	0.972	0.965	0.908	10.48	23.15	2.10	1.88	1.38	30.00	87.42	92.18	0.32	0.35
YC26	0.955	0.979	0.977	19.52	19.21	2.99	3.60	-10.25	-25.08	99.18	98.36	0.36	0.30
YC27	0.976	0.977	0.974	87.54	75.86	5.46	5.18	-4.91	-9.75	100.00	96.42	0.31	0.28
YC28	0.991	0.985	0.983	33.91	21.15	2.96	2.55	-1.99	-8.77	93.10	98.79	0.23	0.27
YC29	0.992	0.988	0.988	44.08	21.60	3.32	2.47	20.00	.73	90.40	90.80	0.27	0.31
YC30	0.988	0.974	0.973	28.90	30.94	4.41	4.26	10.89	17.35	94.64	96.53	0.25	0.35

Note. uncorr. = without the exclusion of tapping errors; corr. = tapping errors excluded; YS = younger simple group; OS = older simple group; YC = younger complex group; [1] missing value due to technical problems

Supplementary Table 5. Individual values of Goodness-of-Fit (single, dual, with and without the exclusion of tapping errors) and of TVA parameters visual processing speed *C*, VSTM storage capacity *K* and visual threshold t_0 (single and dual task conditions) for each of the three groups with the minimum value of t_0 fixed to 0.

ID	Goodness-of-fit			Parameter *C*		Parameter *K*		Parameter t_0	
	Single	Dual uncorr.	Dual corr.	Single	Dual	Single	Dual	Single	Dual
YS01	0.989	0.992	0.952	23.35	35.16	4.08	4.06	5.04	10.00
YS02	0.852	0.919	0.919	66.92	73.04	3.31	3.26	.00	.00
YS03	0.992	0.974	0.974	90.19	70.87	3.89	3.83	14.31	8.80
YS04	0.995	0.98	0.984	22.91	27.70	4.33	4.16	3.32	10.00
YS05	0.996	0.984	0.987	33.74	19.09	3.99	3.54	18.12	8.61
YS06	0.995	0.984	0.984	34.69	40.55	3.94	4.01	.51	.00
YS07	0.986	0.915	0.967	31.97	25.93	3.65	3.02	.00	.00
YS08	0.958	0.984	0.982	45.10	26.27	3.99	4.29	.00	.00
YS09	0.979	0.971	0.972	32.69	35.19	3.82	3.82	4.62	.00
YS10	0.991	0.996	0.996	27.18	33.86	3.63	3.49	2.76	.35
YS11	0.988	0.97	0.97	56.22	60.58	3.72	3.78	8.99	9.20
YS12	0.923	0.998	0.998	36.93	22.16	2.75	3.11	10.00	4.31
YS13	0.917	0.956	0.955	34.70	30.27	3.32	3.31	.00	.00
YS14	0.977	0.994	0.995	27.50	36.54	3.88	3.23	.00	7.67
YS15	0.971	0.98	0.979	26.07	30.18	4.12	4.38	.00	.00
YS16	0.984	0.994	0.994	17.00	15.52	2.68	2.69	14.48	8.13
YS17	0.978	0.913	0.913	20.91	28.36	3.11	2.83	.00	.00
YS18	0.99	0.94	0.936	18.14	21.76	2.09	2.18	.00	.00
YS19	0.975	0.981	0.981	45.54	41.75	3.63	3.53	.00	.00
YS20	0.992	0.975	0.977	38.36	38.96	5.23	4.97	.00	.00
YS21	0.971	0.983	0.984	50.07	37.62	4.00	4.00	8.19	6.46
YS22	0.962	0.957	0.957	19.57	15.22	2.84	2.65	.00	.00
YS23	0.991	0.995	0.996	15.80	22.37	3.08	3.01	.38	.00
YS24	0.917	0.99	0.991	62.37	43.46	4.59	5.04	.00	.00
YS25	0.991	0.984	0.985	43.72	62.35	5.35	5.22	.00	1.11
YS26	0.983	0.977	0.968	27.78	25.98	3.16	2.98	10.00	8.89
YS27	0.907	0.987	0.987	57.36	38.12	3.35	4.00	10.00	4.06
YS28	0.982	0.934	0.935	51.78	45.04	3.66	3.79	.00	.00
YS29	0.969	0.982	0.982	61.48	31.25	4.11	3.81	8.76	9.10
YS30	0.981	0.957	0.956	40.36	25.43	3.85	3.67	12.40	10.00
OS01	0.979	0.984	0.984	38.08	45.30	4.28	4.02	10.77	8.77
OS02	0.949	0.917	0.917	48.37	47.33	2.68	3.27	4.89	.00
OS03	0.991	0.968	0.959	40.28	22.03	2.47	2.33	10.00	.00
OS04	0.952	0.979	0.979	42.77	43.31	3.90	3.59	2.51	5.16
OS05	0.978	0.981	0.987	31.14	22.22	2.57	2.48	29.24	16.11

ID	Goodness-of-fit			Parameter *C*		Parameter *K*		Parameter t_0	
	Single	Dual uncorr.	Dual corr.	Single	Dual	Single	Dual	Single	Dual
OS06	0.991	0.968	0.967	11.04	20.37	2.74	1.53	.48	4.80
OS07	0.956	0.967	0.962	38.10	36.93	3.80	3.31	14.64	17.42
OS08	0.98	0.98	0.975	17.23	13.91	1.83	1.71	33.93	55.02
OS09	0.831	0.923	0.927	70.64	67.41	3.19	2.53	.00	.00
OS10	0.985	0.956	0.959	20.85	25.07	2.96	2.78	10.00	.00
OS11	0.969	0.955	0.96	34.53	40.76	2.42	2.48	8.00	10.00
OS12	0.993	0.974	0.964	42.32	42.75	2.59	2.72	6.67	7.22
OS13	0.997	0.957	0.962	21.86	17.69	3.36	3.71	17.58	15.19
OS14	0.976	0.953	0.959	13.68	15.37	2.37	2.09	7.84	13.31
OS15	0.968	0.901	0.901	43.52	37.05	2.54	2.57	10.00	7.02
OS16	0.981	0.981	0.981	32.24	22.60	3.75	3.37	15.03	15.94
OS17	0.982	0.954	0.95	30.16	26.74	3.17	2.22	8.77	26.52
OS18	0.993	0.977	0.977	35.77	25.07	3.17	2.74	18.28	18.21
OS19	0.962	0.981	0.982	35.58	25.04	3.17	2.92	35.22	33.35
OS20	0.966	0.994	0.997	29.13	26.17	3.09	2.32	20.00	20.00
OS21	0.932	0.934	0.911	40.46	9.19	4.35	3.64	10.00	10.10
OS22	0.944	0.983	0.985	31.97	17.55	2.66	2.62	20.00	20.00
OS23	0.976	0.976	0.975	34.52	51.85	3.57	2.84	8.49	16.43
OS24	0.997	0.982	0.998	21.44	16.94	3.16	2.62	31.14	37.11
OS25	0.99	0.996	0.994	23.48	25.18	2.40	2.16	14.12	8.44
OS26	0.989	0.949	0.949	28.33	23.02	3.18	2.90	16.17	7.55
OS27	0.958	0.918	0.893	33.14	12.88	4.20	3.97	5.66	.00
OS28	0.974	0.98	0.974	40.70	31.53	3.75	3.37	5.40	8.40
OS29	0.99	0.989	0.99	36.12	28.98	3.17	2.63	18.52	12.60
OS30	0.955	0.976	0.965	29.52	42.79	3.54	3.22	5.28	13.55
YC01	0.925	0.955	0.947	46.17	31.59	3.52	3.26	.00	.00
YC02	0.98	0.994	0.993	32.82	42.63	4.22	4.18	7.08	4.18
YC03	0.991	0.993	0.992	27.37	23.13	3.19	3.25	5.21	5.36
YC04	0.998	0.983	0.986	32.68	24.02	3.30	3.31	3.76	2.99
YC05	0.996	0.987	0.985	23.29	26.28	4.51	4.11	.00	2.58
YC06	0.986	1,000	1,000	18.06	18.96	3.71	3.79	10.00	12.16
YC07	0.967	0.963	0.964	20.53	23.48	2.86	2.32	1.79	10.00
YC08	0.994	0.977	0.984	58.49	52.32	4.59	4.31	8.07	.00
YC09	0.962	0.98	0.985	20.32	25.08	2.60	2.48	2.08	1.43
YC10	0.976	0.995	0.993	48.43	28.13	4.14	3.54	4.52	.00
YC11	0.954	0.988	0.989	24.92	29.41	4.32	4.39	4.99	.89
YC12	0.981	0.975	0.972	20.87	27.71	2.82	2.78	.00	.00
YC13	0.977	0.981	0.982	41.90	42.07	3.79	3.36	.00	7.90
YC14	0.981	0.988	0.984	23.33	37.49	5.18	3.90	.00	.00
YC15	0.964	0.981	0.98	22.99	21.54	3.67	2.77	7.46	7.12

ID	Goodness-of-fit			Parameter *C*		Parameter *K*		Parameter t_0	
	Single	Dual uncorr.	Dual corr.	Single	Dual	Single	Dual	Single	Dual
YC16	0.964	0.973	0.967	51.38	65.48	4.89	4.65	.00	6.06
YC17	0.978	0.993	0.993	28.53	24.56	4.61	3.97	.00	.00
YC18	0.947	0.966	0.967	44.93	56.20	3.90	3.91	.00	.00
YC19	0.941	0.842	0.848	51.79	54.19	3.19	2.92	.00	.00
YC20	0.997	0.999	0.999	25.50	24.57	4.11	4.35	15.01	8.17
YC21	0.995	0.956	0.961	32.28	36.13	4.26	3.39	.00	.00
YC22	0.818	0.833	0.833	47.70	44.50	3.73	3.32	.00	.00
YC23	0.99	0.988	0.991	19.23	19.49	2.91	2.83	16.79	.00
YC24	0.977	0.977	0.976	46.77	53.24	4.25	4.05	2.94	1.57
YC25	0.972	0.965	0.908	10.48	23.15	2.10	1.88	1.38	30.00
YC26	0.939	0.953	0.977	24.28	30.55	2.92	3.38	.00	.00
YC27	0.977	0.971	0.974	103.34	101.33	5.41	5.11	.00	.00
YC28	0.988	0.977	0.974	36.42	25.69	2.92	2.53	.00	.00
YC29	0.992	0.988	0.988	44.08	21.60	3.32	2.47	20.00	.73
YC30	0.988	0.974	0.973	28.90	30.94	4.41	4.26	10.89	17.35

Note. uncorr. = without the exclusion of tapping errors; corr. = tapping errors excluded; YS = younger simple group; OS = older simple group; YC = younger complex group

3. Alertness training increases visual processing speed in healthy older adults

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MP and AR contributed equally as first authors. **MP**, AR, PR, HM, CS, and KF contributed to the design of the studies. **MP**, PR, TS1, and SM collected the behavioral data. **MP** and AR collected the imaging data. **MP** analyzed the behavioral data, and AR analyzed the imaging data. **MP** and AR wrote the manuscript. PR, HM, TS1, TS2, SM, TS3, CS, and KF contributed to the data discussion and to a first version of the manuscript. KF further commented on and reviewed the current version of the manuscript.

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Abstract

Visual processing speed decreases with aging. As it is an essential cognitive function for the performance of most cognitive tasks and daily living activities, it is crucial to evaluate effective means to counteract this decrease. Here, we investigated whether alertness training increases visual processing speed in healthy older adults and whether functional connectivity (FC) in the cingulo-opercular network measured before training is associated with the individual increase in visual processing speed after training. We used the computational framework of Bundesen's theory of visual attention (TVA) to quantitatively model and estimate visual processing speed. In study 1, 75 healthy older adults participated in one of three age-, sex- and education-matched groups for alertness training, active control training (visual *n*-back), or no training. In study 2, we assessed, in another sample of 30 healthy older adults, whether the individual FC in the cingulo-opercular network before training is related to the individual training-induced increase in visual processing speed. In study 1, a significant Group×Session interaction indicated an increase in visual processing speed only in the alertness training, but not in the control groups. Visual processing speed did not differ between the groups before training but increased in the alertness training group only after training. In study 2, the individual level of FC in the cingulo-opercular network was associated with the individual training-induced change in visual processing speed. These results indicate that alertness training could help to counteract a slowed visual processing in older adults and that FC in the cingulo-opercular network could be used as a neural marker for prediction of individual change and stratification of individuals who profit from training.

Keywords: Alertness training; brain maintenance; cingulo-opercular network; functional connectivity; theory of visual attention; visual processing speed

Introduction

Demographic change is a major challenge for societies and particularly their health care systems. With increasing age comes an elevated risk for cognitive decline and dementia (e.g., Park & Reuter-Lorenz, 2009). Especially visual processing speed is an essential cognitive function for the performance of most cognitive tasks and daily living activities (Bugaiska & Thibaut, 2015; Deary, Johnson & Starr, 2010; Hertzog & Bleckley, 2001; Park & Reuter-Lorenz, 2009; Salthouse, 1996; 2000; 2004). Visual processing speed decreases with aging (Habekost et al., 2013; McAvinue et al., 2012; Park & Reuter-Lorenz, 2009; Ruiz-Rizzo et al., 2019), and more so in individuals at risk for dementia (Ruiz-Rizzo et al., 2017). The age-related slowing of visual processing has been linked to an increased risk of falls (e.g., Davis et al., 2017*)*, and even to mortality (Lavery, Dodge, Snitz, & Ganguli, 2009; Nishita et al., 2017). Thus, it is crucial to evaluate means to counteract this decrease, in order to ultimately prolong the functional independence of older adults. An exact quantification of visual processing speed, and thus, evaluation of the effectiveness of treatments is possible using the theory of visual attention (TVA; Bundesen, 1990). Based on the report accuracy of briefly presented letter arrays, several visual attention parameters affected by aging – such as visual processing speed, visual short-term memory (vSTM) capacity, visual perceptual threshold, and top-down control – can be estimated independently from each other in a process-pure manner, i.e., functionally specific changes in processing speed can be dissociated from those in other attentional parameters (see Habekost, 2015, for review). Furthermore, responses in the TVA-based paradigms are given verbally, without speed stress, ensuring that perceptual, rather than motor, capabilities determine the outcome. TVA proposes a direct influence of the level of alertness, i.e., the arousal or "readiness" state of the brain (Posner, 2008), on visual processing speed (Bundesen, Vangkilde, & Habekost, 2015). Accordingly, visual processing speed has been shown to increase after phasic alerting cues in healthy younger (Matthias et al., 2010; Petersen, Petersen, Bundesen, Vangkilde, & Habekost, 2017) and older (Haupt, Sorg, Napiórkowski, & Finke, 2018) adults. Moreover, psychostimulants have been shown to enhance visual processing speed in healthy individuals with lower baseline performance (Finke et al., 2010) and in patients with attention deficit hyperactivity disorder (ADHD; Low et al., 2018). The first TVA-based training intervention showed enhancements in visual processing speed in younger adults after video-gaming (Schubert et al., 2015). Based on those results, we hypothesized that a targeted intervention involving tonic alertness training could also increase visual processing speed in healthy older adults.

Significant gains from the computerized training of cognitive functions have been repeatedly reported also in older adults (Ball, Edwards, & Ross, 2007; Kelly et al., 2014; Kueider, Parisi, Gross, & Rebok, 2012; Wolinsky et al., 2010; Wolinsky et al., 2006; Van Vleet et al., 2016; Milewski-Lopez et al., 2014). However, there is considerable interindividual variability in the training response (e.g., Guye, De Simoni, & von Bastian, 2017; Clark, Xu, Unverzagt, & Hendrie, 2016). Arguably, training procedures can only be effective when applied to the "right" individuals, meaning that interindividual differences in responsiveness have to be considered. Identification of a neural marker that is related to the degree of change in visual processing speed could be useful to validly predict the individual training benefit (e.g., Zokaei, MacKellar, Čepukaitytė, Patai, & Nobre, 2017). Resting-state functional magnetic resonance imaging (rs-fMRI) studies have previously linked tonic alertness to the 'cingulo-opercular network' (e.g., Sadaghiani et al., 2010; Schneider et al., 2016). The cingulo-opercular network is a set of brain regions, including the anterior cingulate cortex, the insula, the frontal operculum, and the thalamus (Seeley et al., 2007; Dosenbach et al., 2006), whose rs-fMRI activity indicates functional connectivity (FC) among them. FC refers to the temporal correlation of spontaneous blood-oxygenation-level-dependent (BOLD)-fMRI fluctuations, given at a frequency < 0.1 Hz, among sets of brain regions (Fox & Raichle, 2007). Notably, recent TVA-based studies have documented that visual processing speed *C* is also related to the FC in the cingulo-opercular network (Haupt, Ruiz-Rizzo, Sorg, & Finke, 2019; Ruiz-Rizzo, Neitzel, Müller, Sorg, & Finke, 2018) and that age-related differences in visual processing speed among individuals go along with differences in FC in this network (Ruiz-Rizzo et al., 2019). Furthermore, the degree to which healthy younger adults can benefit from phasic alerting cues was found to be negatively associated with the FC in the cingulo-opercular network (Haupt et al., 2019). Thus, based on the prior evidence relating FC in the cingulo-opercular network, alertness, and visual processing speed *C*, we hypothesized that individual FC in this network measured before alertness training might be related to the individual change in visual processing speed *C* after training in healthy older adults.

In study 1, using a process-based, adaptive, tonic alertness training program (CogniPlus, Version 2.04; Sturm, 2007) and modeling based on TVA, we determined whether alertness training increases visual processing speed in a group of 25 healthy older adults. The CogniPlus program has already shown to be feasible and effective in patients with acquired brain damage (e.g., Thimm, Fink, Küst, Karbe, & Sturm, 2006; Hauke, Fimm & Sturm, 2011). Thus, we reasoned that it would also be appropriate for alertness training in healthy older adults. To test the specificity of the alertness training benefit for visual processing speed, we conducted several control analyses for (i) the measurement of visual processing speed and (ii) the alertness training. First, we examined whether alertness training also improves other visual attention parameters that determine the individual attentional performance but that do not seem directly influenced by alertness, i.e., visual threshold and vSTM storage capacity (TVA-based whole report) and top-down control (TVA-based partial report). Second, regarding alertness training, we controlled for retest and unspecific non-cognitive factors related to the training setting, such as placebo or practice effects, hours of computer use, and regular group trainings. Specifically, to control for retest effects, we included in our study a passive control group of healthy older adults (n = 25), who did not take part in any training but who were assessed twice in a time frame similar to the alertness training group. To control for unspecific non-cognitive factors associated with training, we included an active control group of healthy older adults (n = 25), who participated in a visual working memory training (i.e., n-back task; Buschkuehl, Jaeggi, Kobel, & Perrig, 2007). Based on the direct relationship between alertness and visual processing speed (Bundesen et al., 2015), we predicted increased visual processing speed after alertness training only, i.e., not present or to a lower extent in the control groups or the other visual attention functions.

In study 2, we determined whether individual variability in the FC in the cingulo-opercular network before training is associated with individual variability in the change in visual processing speed following alertness training. To do so, we used rs-fMRI, and modeling based on TVA in an additional, independent sample of 30 healthy older adults. We obtained FC using a data-driven approach (i.e., independent component analysis and dual regression) and tested the association between FC and visual processing speed change in a voxelwise regression model. Based on previous evidence (e.g., Ruiz-Rizzo et al., 2018; Haupt et al., 2019), we predicted that FC in the cingulo-opercular network would be associated with visual processing speed change. To confirm the specificity of this association, we conducted two additional control analyses. First, we examined the association between visual processing speed change and FC in other brain networks relevant for visual attention (Ruiz-Rizzo et al., 2018) or aging (Andrews-Hanna et al., 2007; Ferreira & Busatto, 2013), such as visual, dorsal attention, right frontoparietal, and default mode networks. Second, we examined the association between FC in the cingulo-opercular network and the change in the other three visual attention parameters used as control parameters in study 1 (i.e., visual threshold, vSTM storage capacity, and top-down control). We expected a significant effect only for FC in the cingulo-opercular network and only for visual processing speed.

Materials and Method

Participants

We recruited healthy older participants through flyers at the Ludwig-Maximilians-Universität München (studies 1 and 2) and Humboldt-Universität zu Berlin (study 1). Sample size was based on a power analysis following a study measuring the effect of psychostimulants on visual processing speed (Finke et al., 2010), which revealed a minimum of 19 participants to find significant effects (based on a power of 80%). For the sample size calculation of study 2, we used the results of Ruiz-Rizzo et al. (2018) on the relationship of FC in the cingulo-opercular network to visual processing speed in younger adults, which resulted in a necessary sample of at least 22 participants. We initially tested more participants due to expected drop-out in a study including training and brain measures in older adults. Seventy-five participants in study 1 were evenly assigned to alertness training (n = 25; mean age: 69.1 ± 6.6 years old), active control training (visual n-back; n = 25; mean age 68.0 ± 6.1 years), or no training (passive control group; n = 25; mean age 68.8 ± 5.4 years; see also Table 1). Initially, we tested 82 participants in study 1 and 40 participants in study 2. In each study, some of the participants had to be excluded due to health or technical issues during testing or training (study 1: 2 in the alertness training group, 1 in the active control group, and 4 in the passive control group; study 2: 9 participants; for detailed information on exclusion reasons, see Supplementary Materials), and 2 participants dropped out of study 2. The resulting samples were then 75 participants in study 1 and 29 participants in study 2 (mean age study 2: 69.8 ± 4.4 years). Participants in the specific alertness training and in the active control group were blinded to their group belongingness, i.e., as to whether they were participants of the specific training of interest or the active control group.

All participants in both studies had normal or corrected-to-normal vision, were not colorblind, did not suffer from any neurological, psychiatric, or systemic disease (e.g., depression, stroke, diabetes mellitus), and did not show signs of beginning dementia in the Mini Mental Status Examination (MMSE; Folstein, Folstein & McHugh, 1975; criterion: value ≥ 27). No participant in study 2 had contraindications to undergo MRI and none showed clinically relevant vascular or white-matter lesions, as judged by a radiologist. All participants were paid for their participation at the end of the studies. Handedness was tested with the Edinburgh Handedness Inventory (Oldfield, 1971), and crystallized verbal intelligence with the "Mehrfachwahl-Wortschatz-Test" (MWT-B; Lehrl, 1999). Handedness and MMSE scores were missing for two participants in study 1. IQ-scores were missing for four participants in study 1 and for one in study 2. The groups in study 1 did not differ in gender, handedness, age, IQ, MMSE, or years of education (Table 1). All participants in both studies gave written consent according to the declaration of Helsinki II prior to taking part in the respective study. The studies were approved by the Ethics Committees of the respective study sites.

General Procedure

Participants from both studies completed a short practice session in which they were familiarized with the TVA-based whole- and partial-report paradigms, and then performed a complete whole- and partial-report pre-test session on another day (Figure 1A). In the subsequent 5 to 6 weeks, the alertness training (both studies) and active control (study 1) groups participated in 16 training sessions lasting 45 minutes each. The training of interest consisted of an alertness task, whereas the active control training consisted of a visual *n*-back task. All participants who started training completed all sessions. The passive control group participants did not participate in any training or testing between pre- and post-test (i.e., 5 to 6 weeks). After this period, all participants completed a whole- and partial-report post-training testing session. In study 2, participants underwent a 12-minute rs-fMRI session at the beginning of the study, before behavioral testing and alertness training.

Alertness Training and Active Control Tasks

The tasks for the alertness training and active control groups were run on PCs with 19-inch monitors (screen resolution 1280 × 1024 pixels; 60-Hz refresh rate) in a well-lit room. Within a given group (i.e., either the alertness training group or the active control group), several participants could simultaneously perform the respective task, though ensuring at least two seats or a non-transparent screen between two participants. The two types of tasks were never mixed in the same, parallel testing session. In each session, tasks started at the easiest level; thereafter, the level was gradually adjusted to participants' performance. Sessions were terminated after 45 minutes, when the current block was finished.

Alertness Training Group Task. We used the CogniPlus ALERT S2 Training of Intrinsic Alertness (Version 2.04, Sturm, 2007; Figure 1B) as specific training of interest. In every session, the training started after a general instruction. The adaptive training task with 18 levels of difficulty consisted of a video-game-like environment in which participants viewed and monitored a motorcycle ride from the perspective of the driver in rural and urban colored scenes during night and fog conditions. At various, and changing, locations along the road, objects were presented, including deer and horses, trees, stones, cars and trucks parked beside the road, green traffic lights, and open railway crossings. Approximately 10 times per block, one of these objects unpredictably turned into an obstacle, such as animals running into the road, trees falling or cars turning into the road from the side, traffic lights turning red, or railway crossing gates closing. Participants' task was to press the <enter> key on the keyboard as fast as possible when they encountered an obstacle.

If the <enter> key was pressed 'in time' (see below), the motorcycle stopped, the obstacle disappeared, and the ride was continued from the same location on the street (i.e., 'hit'). If not, an emergency-brake action was initiated automatically, accompanied by a loud noise and a yellow exclamation mark (i.e., 'miss'). After a short break, the motorcycle continued the ride again at the same location. Key presses in the absence of an obstacle were counted as 'false-alarm' responses. Participants wore headphones during the entire session to isolate them from outside noises and to present them with driving and braking noises. Skipping of intermediate levels was possible. For every level, there were specific maximum times for timely reactions: the maximum was 1.8 seconds for the lowest level and 0.3 seconds for the highest. The program recorded ten successive reactions to obstacles ('hits', 'misses', or 'false alarms') and subsequently adjusted itself to the highest level for which the necessary reaction times were reached in 80% of the cases. If the participant responded so slowly that the emergency braking occurred in ≥ 50% of cases, the program was set back to the next lower level. All transitions were indicated to the participants on the screen during a short break. The current level was continuously presented on the tachometer. At the beginning of the session, the program adjusted the level after only five reactions. In the first session, there was a short practice phase in which participants received feedback for missed or false-alarm reactions, and the task was explained to them again. After three consecutive correct reactions, the actual training session started.

Active Control Group Task. We used a visual *n*-back-task (Figure 1B; Buschkuehl et al., 2007) as active control training because it is cognitively demanding and is not designed to enhance alertness or visual processing speed. We used it to control for general factors associated with the training situation, such as placebo effects, social interaction, active attendance to the university, and computer use. After oral and written instructions, participants saw a series of trials consisting of randomly presented blue squares on a black background in 1 out of 8 possible locations, each presentation lasting 3 seconds (Figure 1B). During an entire block, a white fixation cross was presented in the center of the screen. Each time the current location was a match for one that was presented n trials back, the <A> key had to be pressed on the keyboard. The task was adaptive, with different levels that varied in the (n-back) value of n.

If 75–85% of the reactions were given correctly, the level was maintained within one block. If the number of correct reactions dropped below this range, n was reduced by 1; if it rose above, *n* was then increased by 1. Misses and false alarms were counted as errors. At the beginning of each block, the current *n*-back level and a visual instruction were shown. Each block consisted of 20+*n* trials and lasted about one minute, depending on the *n*-back level; it contained 6 targets and 14+*n* distractors. After each block, visual feedback was provided and a new block could be started by pressing the spacebar.

Assessment of Visual Attention Parameters with TVA-based Whole- and Partial-report Paradigms

All participants completed first the whole-report and then the partial-report paradigm in about one hour. On the first day, there was a short whole- and partial-report practice session to familiarize participants with the procedure and reduce simple retest effects (Schubert et al., 2015). This practice session consisted of a configuration phase and 2 blocks of the whole and the partial report each. The individual exposure durations were determined separately for the practice and the pre- and post-test sessions.

Study 1

The TVA-based assessment was conducted on a PC with a 17-inch monitor (screen resolution 1024 × 768 pixels; 75-Hz refresh rate) in a dimly lit test room (different from the training room). The viewing distance of 60 cm was controlled by the use of a chin rest. Every participant was tested separately.

In both tasks, participants received written instructions to fixate a central white cross (0.3°) that was presented for 300 ms and to maintain this fixation until the stimulus array appeared. The background of the display was black for the whole experiment. After a further 100 ms, red and/or green letters (0.58° high × 0.48° wide; taken from the set {ABEFHJKLMNPRSTWXYZ}) were presented; the same letter could appear only once per trial. Participants did not know in advance at which specific position the letters would appear. Stimuli were masked (by grey squares sized 0.5° with an ‘x’ and a ‘+’ inside presented for 500 ms after stimulus presentation at the position) or unmasked. After the presentation, participants were asked to verbally, and in any order without time pressure, report the stimuli that they were fairly sure they had recognized. Subsequently, the experimenter entered the reported letters and started the next trial. All participants were presented with displays in the same, pre-randomized order.

Whole Report. On every trial, five equidistant red or green letters were presented in a vertical column positioned 2.5° to the left or the right of the fixation cross (Figure 2A), with three different exposure durations. The task was to report as many letters as possible. Half of the trials were masked. Due to a visual persistence/iconic buffering effect on unmasked trials (Sperling, 1960), this procedure resulted in six different '*effective*' exposure durations.

The three presentation times were determined individually in a pre-testphase. To this end, the individual exposure duration was identified by determining the presentation time at which a participant could correctly report on average 1 letter per trial (i.e., 20% report accuracy) in a block of 24 masked trials. The resulting presentation time was taken as the 'medium exposure duration' in the actual experiment, together with a short (about half the medium time) and a long (double the medium time) exposure duration. The test phase consisted of 4 blocks of 48 trials each, resulting in 192 trials. The 12 different conditions (2 hemi-fields × 2 masking conditions × 3 exposure durations) appeared in randomized order and equally often. Performance accuracy (i.e., the number of letters reported correctly) was measured as a function of (effective) exposure duration.

Partial Report. In each trial, either a single target letter, a target letter plus a distractor letter, or two (dual) target letters appeared in the corners of a virtual (5° × 5°) square positioned in the center of the screen. Target letters were always red and distractors were always green. All of the stimuli were masked. In dual trials, stimuli appeared in vertical or horizontal but never in diagonal arrangement. Only target letters were to be reported, while distractors were to be ignored.

In the 32-trial pre-test phase, an individual exposure duration was identified by determining the presentation time at which about 80% of the single targets and at least 60% of the dual targets could be reported correctly. The identified presentation time was then used in the test phase, which consisted of 6 blocks of 48 trials each, totaling 288 trials. The 16 different conditions (4 × single target, 8 × target and distractor, 4 × dual target) were presented in randomized order and equally often within each block.

For study 2, we used a newer version of the paradigm as the studies were not conducted simultaneously. This different version still enabled the estimation of the same parameters (Figure 3A; Supplementary Materials).

TVA Parameter Estimates

The different TVA parameters were estimated by modeling participants' performance in the whole- and partial-report paradigms. Details of this TVA-based fitting procedure can be found in Kyllingsbæk (2006; see also Shibuya & Bundesen, 1988).

Whole Report. In whole report, the probability of identifying a stimulus in relation to its effective exposure duration is modeled by an exponential growth function. Increasing exposure durations lead to an exponentially increasing selection probability for a given stimulus. The function's slope at its origin gives the number of elements that can be processed per second (visual processing speed or *C* parameter). The function's asymptote indicates the maximum number of stimuli that can be stored in vSTM (vSTM storage capacity or *K* parameter). The effective exposure duration in masked trials is defined by the difference of the presentation time *t* minus the estimated minimal effective exposure duration t_0 (visual threshold, measured in milliseconds, below which the probability of report is assumed to be zero). t_0 serves as the functions' coordinate. In the unmasked condition, parameter μ (iconic memory buffer) reflects the possibility to use visual persistence and iconic buffering of the letter array, expressed in milliseconds.[1] t_0 and μ are assumed to be constant for a given subject (e.g., Bundesen, 1990). Goodness-of-Fit values, which quantify how well the parameters estimated by the model fit the observed data, did not significantly differ between pre- and posttest in any of the groups in study 1 or study 2 (see Supplementary Table 1), suggesting a qualitatively comparable performance of the model at both times of TVA assessment.

Partial Report. From performance in the partial-report, the ability to top-down prioritize the processing of target over distractor stimuli, top-down control α, can be estimated. Top-down control is the ratio of the attentional weight for distractors w_D to the weight of target stimuli $w_{T,}$ averaged across hemifields. Lower α-values are indicative of a higher efficiency of top-down control; values close to 1 would indicate equal weighting of targets and distractors; and values higher than 1 would reflect prioritization of the distractors.

Statistical analyses of behavioral data

To check that both cognitive training programs effectively enhanced the performance in the respective trained tasks, we calculated paired-sample *t*-tests with reaction times (in ms) in the first vs. the last session in the alertness training group, and with the *n*-back level in the active control group, respectively (Figure 1B).

To examine whether only alertness training increases visual processing speed, we compared the alertness training group to the active and passive control groups using mixed-design analysis of variance (ANOVA) with the between-participants factor Group (alertness

[1] Parameter μ is of no particular interest in this study but is mainly estimated to provide fitting of the remaining parameters of interest. Analyses revealed that μ did not differ between pre- and posttest.

training vs. active control vs. passive control) and the within-participants factor Session (pretest vs. posttest) on visual processing speed.

We additionally tested for the specificity of the effect of alertness training on the visual processing speed parameter by means of a mixed design ANOVA for study 1 and paired-sample *t*-tests for study 2 on the other three TVA-estimated visual attention parameters. Results are accompanied by 95% confidence intervals (CI) of the differences between the means. Statistical analyses were performed using IBM SPSS 24. Results were deemed significant at a *p*-value of < 0.05 (two-tailed).

Neuroimaging data

Resting-state fMRI data acquisition

MRI data were acquired in the *Klinikum rechts der Isar* of the Technical University Munich, on a Philips Ingenia 3T system (Netherlands), using a 32-channel SENSE head coil. Foam padding was used to constrain participants' head motion during the scanning, and earplugs and headphones were provided to reduce adverse effects of scanner noise. Functional MRI T2*-weighted data were collected for 12.5 min during resting state with eyes closed. We asked participants to try not to fall asleep and confirmed this at the end of the sequence. For each participant, 600 volumes of BOLD-fMRI signal were acquired using a multiband (Feinberg and Setsompop, 2013) echo-planar imaging (EPI) sequence, with a 2-fold in-plane SENSE acceleration (SENSE factor, S = 2) and an M-factor of 2 (Preibisch, Bührer, & Riedl, 2015); repetition time, TR = 1,250 ms; time to echo, TE = 30 ms; phase encoding, PE direction: anterior-posterior; flip angle = 70º; field of view, FOV = 192 x 192 mm^2; matrix size = 64 x 64, 40 slices; slice thickness = 3.0 mm; interslice gap 0.3 mm; reconstructed voxel size = 3 x 3 x 3.29 mm^3. Additionally, a high-resolution T1-weighted anatomical volume was acquired using a 3D magnetization prepared rapid acquisition gradient echo (MPRAGE) sequence with TR = 9 ms; TE = 4 ms; inversion time, TI = 0 ms; flip angle = 8º; 170 sagittal slices; FOV = 240 x 240 mm^2; reconstructed voxel size = 1 mm isotropic. No physiologic monitoring (cardiac or respiratory) was performed during the scanning.

Resting-state fMRI Data Analysis

Data preprocessing

For each participant, 600 resting-state fMRI volumes were preprocessed using the Data Processing Assistant for Resting-State fMRI (DPARSF; Chao-Gan & Yu-Feng, 2010), a toolbox for data analysis of resting-state fMRI based on SPM12 (https://www.fil.ion.ucl.ac.uk/spm/software/spm12/) and REST (Song et al, 2011), running on

MATLAB (R2016b; The MathWorks, Inc., Natick, MA, United States). To start with, the first five volumes were discarded from each dataset to compensate for the time before longitudinal steady-state magnetizations. Next, the remaining volumes were slice-timing-corrected, realigned, and co-registered to the individual anatomical volume. Data were segmented in tissue types (i.e., gray matter, white matter, and cerebrospinal fluid) and normalized to MNI (Montreal Neurological Institute) space using DARTEL (Diffeomorphic Anatomical Registration Through Exponentiated Lie Algebra; Ashburner, 2007) with a 2-mm isotropic voxel size, and smoothed using a 4-mm full-width-at-half-maximum (FWHM) Gaussian kernel (Chao-Gan & Yu-Feng, 2010). Normalized data were then band-pass filtered to allow frequencies between 0.01 and 0.1 Hz. Finally, a nuisance covariates regression was performed on the resting-state fMRI data and included six head motion parameters and their corresponding first temporal derivatives; the signal averaged over the white matter, the lateral ventricles, and the whole brain; and “bad” time points or those with a framewise displacement value > 0.5 mm as well as 1 back and 2 forward neighboring time points (Power, Barnes, Snyder, Schlaggar, & Petersen, 2012).

Independent component and dual regression analyses

We analyzed the 595 preprocessed resting-state fMRI volumes by employing group independent-component analysis (ICA) with 20 dimensions in FSL 5.0.9 MELODIC version 3.14 (Beckmann & Smith, 2004; Smith et al., 2004). We chose 20-dimension ICA following previous ICA-based studies (e.g., Ruiz-Rizzo et al., 2018; Smith et al., 2009). The preprocessed data were first normalized for voxelwise mean and variance and then reduced to a 20-dimensional subspace by probabilistic principal component analysis. Next, data were decomposed into time courses and spatial maps by optimizing for non-Gaussian spatial distributions using a fixed-point iteration technique (Hyvarinen, 1999). The 20 resulting independent components were then used as input for a dual regression (Beckmann et al., 2009; Filippini et al., 2009), a multivariate approach that consists in a spatial and a temporal regression. In the spatial regression, each of the 20 group independent component maps is regressed onto each participant’s preprocessed dataset, thus yielding 20 time courses (i.e., one per independent component) normalized by their standard deviation (Nickerson, Smith, Öngür, & Beckmann, 2017). In the temporal regression, the 20 time courses are regressed onto each participant’s preprocessed dataset, thus yielding 20 spatial maps for each participant. The time courses and spatial maps obtained from the dual regression can be used for the group statistical analysis because they include information on the amplitude (time course) and shape (spatial map) of a particular network (see, e.g., Nickerson et al., 2017). Next, we selected the components (see below) that represented the cingulo-opercular network, the focus of our study, and those that represented the default-mode, dorsal attention, right frontoparietal, and visual networks, to control for the specificity of our hypothesis.

Network selection

We performed a spatial cross-correlation between all 20 group spatial maps resulting from ICA and dual regression and the templates of resting state networks reported by Yeo et al. (2011), using the *fslcc* command in FSL. Based on these cross-correlations, we selected the spatial maps with the highest coefficients with the networks of interest (the main one and three for control) as resting-state networks for further group statistical analyses. We identified one cingulo-opercular network ($r = .39$ with Yeo_8), our network of interest. To control for the specificity of our results, we also identified three networks relevant for visual attention (following Ruiz-Rizzo et al., 2018) and one network relevant for aging (following Andrews-Hanna et al., 2007; Ferreira & Busatto, 2013). These networks were the visual ($r = .61$ with Yeo_1), dorsal attention ($r = .42$ with Yeo_6), and default mode ($r = .36$ with Yeo_17) networks. We used an additional set of resting-state network templates based on ICA (i.e., Allen et al., 2011) to identify the third network relevant for visual attention, the right frontoparietal network ($r = .60$ with IC60 of Allen et al.). This latter ICA-based templates further confirmed the spatial maps selected before [cingulo-opercular network: $r = .44$ with IC55 of Allen et al.; visual network: $r = .50$ with IC46; dorsal attention network: $r = .34$ with IC72; and default mode network: $r = .25$ with IC25].

Statistical analyses of rs-fMRI data

Multiple regression of change in visual processing speed on FC in the cingulo-opercular network

To investigate whether the level of FC in the cingulo-opercular network measured before training is associated with the degree of increase in the visual processing speed parameter *C* after training, we conducted a voxelwise regression using SPM12. Based on the general linear model, we predicted the voxelwise level of FC in the voxels belonging to the cingulo-opercular network from the standardized individual values of *C* change after alertness training (i.e., $(C_{post} - C_{pre}) / (C_{post} + C_{pre})$). We additionally included in the model regressors of no interest, such as participants' age, education, sex, and an individual framewise displacement metric of the rs-fMRI volumes (based on Jenkinson, Bannister, Brady, & Smith, 2002 as recommended by Yan et al., 2013). We used the same model to predict the FC in the other four 'control' networks (i.e., visual, dorsal attention, right frontoparietal, and default mode networks) to assess the specificity of the hypothesized association between FC in the cingulo-opercular network and the standardized value of parameter C change. Clusters were considered significant at a $p < 0.05$ family-wise error (FWE) corrected for multiple comparisons at the cluster level (height whole-brain threshold $p < 0.001$ uncorrected). Similarly, we repeated this analysis for the FC in the cingulo-opercular network, but using, separately, the standardized change after alertness training in the other visual attention parameters (K, α, and $t0$), instead of standardized C change, as predictors, to control for the specificity of the association with visual processing speed.

Results

Behavioral data: Training and "transfer" effects

Training effects

In study 1, there was a significant training-induced change in the respectively trained task from the first to the last session in both the alertness training and active control groups [alertness training: $t(24) = 17.52$, $p < .001$, 95% confidence interval (CI) of the difference between means in ms (100.6, 127.5), Cohen's $d = 3.48$; n-back active control training: $t(24) = -5.78$, $p < .001$, 95% CI (-2.2, -1.0), Cohen's $d = -1.28$). We replicated the result for the alertness training program in our second, non-controlled experiment in the independent sample of 29 healthy older adults [$t(28) = 12.14$, $p < .001$, 95% CI of the difference between means in ms (99.1, 139.4), Cohen's $d = 1.96$]. Thus, both cognitive training programs improved performance in the respective trained task (see also Table 2).

Effect of alertness training on visual processing speed

In study 1, the ANOVA did not reveal significant main effects for Session [$F(1, 72) = 1.50$, $p = .225$; $\eta_p^2 = .02$] or Group [$F(2, 72) = 1.42$, $p = .249$; $\eta_p^2 = .04$], indicating no overall improvement from pre- to post-test or general differences between groups in the visual processing speed parameter. Most importantly, as hypothesized, the Group × Session interaction was significant [$F(2, 72) = 3.82$, $p = .026$; $\eta_p^2 = .10$], which indicates a specific, alertness training related improvement in the visual processing speed parameter (Figure 2B). At pre-test, the three groups did not differ (ANOVA with between-subject-factor Group: $F(2, 72) = .65$, $p = .526$; $\eta_p^2 = .02$), while they did at post-test [$F(2, 72) = 3.13$, $p = .050$; $\eta_p^2 = .08$]. Post-hoc pairwise t-tests revealed that only in the alertness training group was the participants' visual processing speed parameter significantly higher post- compared to pre-training [$t(24) = -2.84$, $p = .009$, 95% CI (-5.2, -.8), Cohen's $d = .25$], whereas no such effect was evident in the active or passive control groups (both p-values > .547; Figure 2B). This effect was replicated, as the visual processing speed parameter also significantly increased after alertness training in the second, independent sample of older adults of study 2 [$t(28) = -2.22$, $p = .035$, 95% CI (-9.3, -.4), Cohen's $d = .30$; Figure 3B]. Thus, overall, these results indicate, first, that alertness training can robustly boost the visual processing speed parameter and, second, that this effect is neither found after another type of cognitive training nor due to retesting (see also Table 2).

Control analyses: Effects of alertness training on other TVA parameters

We performed control analyses to confirm that the effect of alertness training was specific for visual processing speed and not due to a general improvement of attentional performance, indicated by effects on other TVA parameters. For vSTM storage capacity *K*, we found no significant main effects of Session or Group in study 1 (both *p*-values > .134). There was a non-significant trend for an interaction [$F(2, 72) = 2.88$, $p = .062$; $\eta_p^2 = .07$] which was caused by a somewhat higher *K* value in the passive control group compared to the other groups only in the post-test. VSTM was also not increased after alertness training in study 2 [$t(28) = -.95$, $p = .352$, 95% CI (-.17, .06), Cohen's $d = .09$; see also Table 2].

For visual perceptual threshold t_0, we found a non-significant trend in study 1 for Session [$F(1, 72) = 3.94$, $p = .051$; $\eta_p^2 = .05$], indicating a slight improvement from pre- to post test across groups. The main effect of Group and the interaction were non-significant (*p* values > .471). In study 2, *t0* significantly decreased from pre- to post-test [$t(28) = 2.10$, $p = .045$, 95% CI (.04, 3.9), Cohen's $d = .29$]. To examine whether this effect was specific to alertness training, we compared the standardized changes in parameter t_0 (the subtraction of pre- from post-training t_0, relative to the total value of both) of the participants in study 2 to those of the active control group in study 1, using an independent sample *t*-test. This standardized change was not significantly different between groups [$t(52) = -.43$, $p = .669$, 95% CI [-.36, .23], Cohen's d = .12], suggesting that, across groups and studies, there was a slight but unspecific test repetition effect on visual perceptual threshold. Finally, no significant main or interaction effects were observed for top-down control α (all *p*-values > .268). In summary, these results indicate that the effect of alertness training on visual processing speed is robust and specific (see also Table 2).

Imaging data: Intrinsic FC before alertness training

FC in the cingulo-opercular network and training-induced visual processing speed change

We investigated whether the individual level of FC in the cingulo-opercular network before alertness training is associated with the degree of increase in visual processing speed after training. We tested this association in an additional, independent sample of 29 healthy older adults (study 2). All participants underwent rs-fMRI and then completed the same tonic alertness training program with pre- and post-training TVA-based assessment as the sample of study 1. Based on a voxelwise multiple regression, we found one cluster in the cingulo-opercular network that positively correlates with visual processing speed change (Figure 3D). Specifically, higher FC in the medial superior frontal gyrus (x, y, z MNI peak coordinates: 0, 30, 60, $k = 51$ voxels; Z = 4.57; FWE-corrected *p*-value at the cluster level = .010) within this network was associated with a stronger increase in visual processing speed after alertness training across participants (to aid visualization of this effect at the individual level, we present this result in a scatter plot next to the brain-overlaid result in Figure 3D).

Control analyses: Specificity of FC in the cingulo-opercular network and visual processing speed

To confirm the specificity of the association between FC in the cingulo-opercular network and visual processing speed change, we conducted two additional control analyses: the association between visual processing speed change and FC in other brain networks relevant for visual attention or aging, and the association between FC in the cingulo-opercular network and the change in the other three visual attention parameters used as control parameters in study 1. First, as expected, voxelwise regression analyses in which standardized change in visual processing speed *C* was used to predict FC in other networks (visual, dorsal attention, right frontoparietal, and default mode networks) yielded no significant results. Second, and also as expected, no significant clusters were found in the cingulo-opercular network when the standardized change in vSTM storage capacity *K*, visual perceptual threshold *t0*, or top-down control *a* were used as predictors in voxelwise regression analyses.

Discussion

In two studies in healthy older adults, we asked (a) whether alertness training leads to an increase in visual processing speed that is not found in control groups, and (b) whether the individual FC in the cingulo-opercular network before alertness training is associated with the individual increase in visual processing speed following training. In the first study, a significant interaction between group and session showed that 10.5 hours of computerized, specific, tonic alertness training enhances the TVA parameter visual processing speed. Furthermore, in accordance with the assumptions of a close link between alertness and visual processing speed and of independence between the distinct TVA parameters (Bundesen et al., 2015; see also, e.g., Haupt et al., 2018; Matthias et al., 2010; Petersen et al., 2017; Finke et al., 2010), the improvement in visual processing speed was not accompanied by a more unspecific, general improvement of all TVA parameters, such as visual threshold, visual short-term memory (vSTM), or top-down control. In the second study, as expected, we found that FC in the cingulo-opercular network was closely related to individual training benefit. This relation was, as expected, not found with FC in the control networks nor was it observed between the FC in the cingulo-opercular network and the control visual attention functions. Taken together, our results suggest that a targeted cognitive training can modify visual processing speed as a basic parameter underlying multiple visual tasks and that individual FC in the cingulo-opercular network could be used as a marker for predicting benefits in visual processing speed derived from alertness training in older adults.

Alertness training increases visual processing speed in healthy older adults

As predicted based on the TVA assumption of a close relationship between alertness and visual processing speed (e.g., Bundesen et al., 2015), it is possible to increase visual processing speed based on intrinsic alertness training in seniors. In accordance with Zokaei et al. (2017) who suggested that a main aim of training studies should be to evaluate specific and targeted interventions, we used a controlled design in order to evaluate the alertness training. As the improvement in visual processing speed was found neither in the passive nor in the active control group, who also underwent an adaptive training program not designed to enhance visual processing speed (Buschkuehl et al., 2007), and as the specifically trained group outperformed the control groups following the training, the enhancement was not due to retest or placebo effects – such as the knowledge that one is taking part in a cognitive training program –, repeated computer use, or regular group gatherings. We can therefore conclude that it was the specific alertness training that caused the effect on visual processing speed.

Assessing training outcomes in healthy samples requires sensitive measures as the effects to be expected are small (cf. Zokaei et al., 2017). TVA parameters have been found to be sensitive even to such minor changes in diverse neurocognitive enhancement studies in healthy adults (e.g., Finke et al., 2010; Jensen, Vangkilde, Frokjaer, & Hasselbalch, 2012; Haupt et al., 2018; Schubert et al., 2015). Importantly, the parameters are independent, thus providing a unique measure of visual processing speed that is controlled for the influence of visual threshold, vSTM capacity, and top-down control (see Habekost, 2015, for review). Finally, the parameter visual processing speed is not influenced by motor speed (Kreiner & Ryan, 2001). The use of a "pure" perceptual measure is crucial, as the training used here requires fast motor responses ("breaks") in increasingly narrower time windows. The demonstration that this latent parameter can be enhanced, thus, provides clear, direct support to the assumption, put forward in previous studies, that targeted training can increase the speed of information processing (e.g., Ball et al., 2002; Vance et al., 2007; Edwards et al., 2005; for reviews, see Edwards, Fausto, Tetlow, Corona, & Valdes, 2018; Takeuchi & Kawashima, 2012). Based on the parameter-specific measurement, it is possible to exactly define the underlying mechanism of increased performance following alertness training. For example, it was previously shown that alertness training leads to an improvement in the useful field of view task (UFOV; Ball & Owsley, 1993; Van Vleet et al., 2016). The use of latent modeling, grounded in a theory that mathematically links alertness and visual processing speed (Bundesen et al., 2015) allows a mechanistic interpretation of the observed effects (Noack, Lövdén, & Schmiedek, 2014). Namely, based on the control analyses on other attentional parameters, we can conclude that, as hypothesized, the alertness training leads to a benefit in visual processing speed and not in the further TVA parameters theoretically not assumed to rely on alertness, such as vSTM capacity, visual threshold, and top-down control. Notably, and important for typically aspired transfer effects, such result does *not* imply that the training can induce potential benefits only in a narrow pool of tasks that are equal to the whole report. In contrast, the demonstration that such a basic parameter as visual processing speed is indeed enhanced via the training implies that multiple tasks using visual stimulus material – be it a lab or a daily living task – can profit from such training and be improved. However, the TVA-based measurement shows that the improved performance in the whole report task following alertness training does not result from changes in other attention parameters, such as visual threshold, visual short-term storage, or the ability to filter out irrelevant information, and also not from an increased motor speed. Note that the effect found on visual threshold in study 2 seems to be a retest effect, as it does not differ significantly from that of the active control group in study 1. Thus, in accordance with the clear-cut assumptions in TVA, we can conclude that increased cortical arousal due to enhanced intrinsic alertness following a relatively low amount of training leads to an increased rate of uptake of visual information in healthy seniors.

Finally, the successful replication of the alertness training effect on visual processing speed in a second, independent sample, demonstrates the robustness of the benefits on visual processing speed in older adults induced by alertness training. This replication also supports the assumption that the fine-grained TVA measurement is sensitive and highly reliable, and thus adequate, for the assessment of neurocognitive enhancement following training.

FC in the cingulo-opercular network is closely related to individual training benefit

Higher FC in the cingulo-opercular network before alertness training was closely associated with higher training-induced visual processing speed gain. This association remained significant when controlling for individual differences in visual processing speed before training, age, education, sex, or head-motion during MRI scanning. These results confirm our assumption of a specific visual processing speed link with FC in the cingulo-opercular network (and not with FC in the control networks), which was based on the results of previous studies (Haupt et al., 2019; Ruiz-Rizzo et al., 2018). In particular, we previously found that, in older ages, visual processing speed can be preserved to a level comparable to that of younger adults if FC in the cingulo-opercular network is also relatively comparable (Ruiz-Rizzo et al., 2019). According to the model of brain maintenance in aging, high FC might reflect a "youth-like" type of brain functioning (e.g., Heinzel et al., 2014; Lindenberger, 2014; Meinzer, Lindenberg, Antonenko, Flaisch, & Flöel, 2013; Nagel et al., 2011; Nyberg, Lövdén, Riklund, Lindenberger, & Bäckman, 2012). In this context, the current results indicate that such youth-like FC in the cingulo-opercular network reflects higher plasticity, i.e., the potential to improve following a targeted visual processing speed intervention. Moreover, the control analyses showed that FC in the cingulo-opercular network was specifically related to visual processing speed change. Such specificity and robustness of findings indicate that FC in the cingulo-opercular network might be a useful marker of alertness function in old age and of the individual potential to profit from alertness training interventions.

Within the cingulo-opercular network, the significant cluster peak was located on the medial superior frontal gyrus, close to the supplementary motor area, a region previously associated with the speed or timing aspect of task performance. In patients, lesions of the right superior medial frontal lobe have been shown to impair inhibitory control in the stop signal task (Floden & Stuss, 2006), and, in healthy individuals, greater activation in the superior frontal cortex correlates with more efficient response inhibition (Li, Huang, Constable, & Sinha, 2006).

Additionally, a role in the temporal prediction and explicit timing has been proposed for the supplementary motor area (Coull, Cheng, & Meck, 2011). Thus, our anatomical result of the medial superior frontal gyrus based on the association with an unspeeded parameter fits also well in the context of its role in speeded responses.

The association between FC in the cingulo-opercular network and the training-induced change in visual processing speed is a first relevant step for the identification of a neural marker of training gains. Particularly, this association might, in future studies, help to identify a priori those individuals with the greatest probability for benefit and could thus open a path in the direction of personalized training interventions (cf. Zokaei et al., 2017). Now that such potential marker is identified, which also reflects the previous documentation of the FC in the cingulo-opercular network for alertness functions, particularly in old age (Ruiz-Rizzo et al., 2019), it could also be tested whether the same marker predicts intervention response in clinical groups. This would be especially relevant in patients with mild cognitive impairment at risk for Alzheimer’s disease, who have been found to show specific decreases in TVA parameter visual processing speed, compared to age-matched healthy participants (Bublak, Redel, & Finke, 2006; Bublak et al., 2011; Ruiz-Rizzo et al., 2017). As TVA-based studies documented significantly lower visual processing speed in various neurodevelopmental disorders, such as ADHD and dyslexia (Stenneken et al., 2011; Low et al., 2018), and in psychiatric diseases, such as depression and schizophrenia (Gögler, Willacker et al., 2017; Gögler, Papazova et et al., 2017), the potential usefulness of such predictive marker could be tested in a range of different populations suffering from low alertness functions.

Outlook

The enhancement of visual processing speed as assessed by the UFOV-task has been linked to improvements in instrumental activities of daily living (Tennstedt & Unverzagt, 2013), better driving mobility (Edwards, Delahunt, & Mahncke, 2009; Edwards, Lunsman, Perkins, Rebok, & Roth, 2009; Roenker, Cissell, Ball, Wadley, & Edwards, 2003), better health-related quality of life (Wolinsky et al., 2006), better self-rated health (Wolinksy et al., 2010), and even to a reduced risk of developing dementia (Edwards et al., 2017). Future studies should verify these links using also the latent, sensitive TVA outcome measure. Follow-up measurements would, additionally, make it possible to assess potential long-term effects of alertness training on visual processing speed, as has been shown before by training interventions targeting processing speed (see, e.g., Rebok et al., 2014; Willis et al., 2006).

A combination of alertness training with other methods for cognitive enhancement such as physical exercise (see Bullock & Giesbrecht, 2014, for a proposed connection between physical exercise and the neural mechanisms described by NTVA) or transcranial direct current stimulation (tDCS; see Gögler, Willacker et al., 2017, for a recent demonstration of enhancement of visual processing speed in major depression patients) might reveal even bigger training effects. In the long run, this might help to make better predictions about who will and who will not benefit from a certain training intervention and might play a significant role in prevention strategies against cognitive decline (see also Edwards et al., 2017).

Conclusion

Based on a solid theoretical model and extending previous evidence, the current results indicate that 10.5 hours of alertness training can reliably increase the latent parameter visual processing speed in healthy older adults. Moreover, they suggest that higher FC in the cingulo-opercular network is related to higher individual training response and, thus, could be used as a neural marker for predicting individual training gain.

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Tables

Table 1. Demographic data and questionnaire scores for all participants

Demographic variable	Alertness Training	Active control	Passive control	Replication Alertness Training
Gender (N): m/f	11/14	9/16	9/16	12/17
Handedness: r/l/b	24/-/1	20/1/2[a]	24/-/1	28/1/-
Age [years]: M ± SD(range)	69.1 ± 6.6 (60-86)	68.0 ± 6.1 (54-85)	68.8 ± 5.4 (59-80)	69.8 ± 4.4 (61-77)
Education [years]: M ± SD (range)	11.6 ± 1.9 (8-14)	11.5 ± 1.5 (10-14)	11.5 ± 1.3 (9-13)	11.1 ± 1.4 (8-13)
Verbal IQ: M ± SD	125.7 ± 11.3	123.8 ± 11.9[a]	120.7 ± 8.6	124.1 ± 12.4[a]
MMSE: M ± SD	29.2 ± .9	29.2 ± .8 [a]	29.0 ± 1.1	28.6 ± 1.2

Note. M: male; f: female; r: right; l: left; b: bilateral; M: Mean; SD: standard deviation; MWT-B: Mehrfachwahl-Wortschatz-Intelligenztest, Version B; MMSE: Mini-Mental State Examination; IQ: Intelligence Quotient,derived from the MWT-B score.

[a] missing values

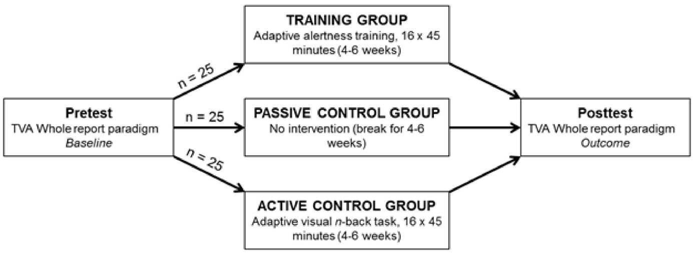
Table 2. Trained measures and TVA-based parameters.

	Study 1						**Study 2**	
	Alertness training (active training)		**Visual *n*-back (active control)**		**No training (passive control)**		**Alertness training (active training)**	
	Pre	**Post**	**Pre**	**Post**	**Pre**	**Post**	**Pre**	**Post**
Trained task	401.4 ± 37.7 ms	287.3 ± 17.4 ms	2.6 ± .8 elements	4.1 ± 1.5 elements	-	-	415.0 ± 67.0 ms	296.7 ± 34.5 ms
TVA - *C* (letters / s)	16.5 ± 4.7	19.5 ± 6.4	16.2 ± 5.8	15.5 ± 4.9	17.9 ± 6.1	17.7 ± 5.6	34.1 ± 15.2	38.6± 17.4
TVA - *K* (max. number of letters)	2.6 ± .4	2.5 ± .4	2.5 ± .4	2.6 ± .3	2.4 ± .4	2.5 ± .4	2.8 ± .6	2.8 ± .6
TVA - t_0 (ms)	16.2 ± 25.9	14.8 ± 39.4	24.2 ± 22.8	19.0 ± 21.0	28.2 ± 28.1	21.1 ± 29.5	6.9 ± 7.3	4.9 ± 5.6
TVA - α (distractor / targets)	.44 ± .2	.46 ± .2	.37 ± .2	.38 ± .2	.36 ± .2	.39 ± .2	.46 ± .2	.44 ± .1

Mean ± standard deviation (SD) are shown.

Figures

A Study Design



B Alertness Training and Active Control Tasks and Performance

Alertness Training

Active Control (visual **n***-back)*

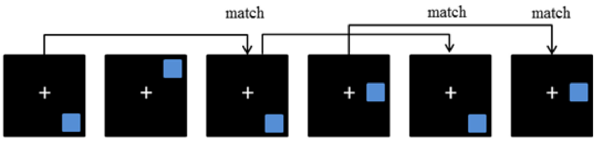


Figure 1. A Study Design. Design for the study sequence for each group in study 1. **B Alertness Training and Active Control Tasks and Performance.** *Left top panel:* Display example for the alertness training task taken with friendly permission from Schuhfried (retrieved November 2nd, 2015 from http://www.schuhfried.at/typo3temp/pics/C_0f3032a3e2.jpg). The participants had to react to the obstacle (crossing car) by pressing the enter key as fast as possible. In the actual displays the scene was darker and foggier (studies 1 and 2). *Left bottom panel:* Example for the 2-back task in the visual *n*-back control training. The participants had to press "A" when the current square position matched the square position that was presented two displays back (study 1). *Right panel:* Participants' performance in the alertness training (*right top panel*; Reaction times in ms) and the active control training (*right bottom panel*; mean *n*-back level) tasks at the first and the last training session (study 1). Error bars indicate standard errors of the mean.

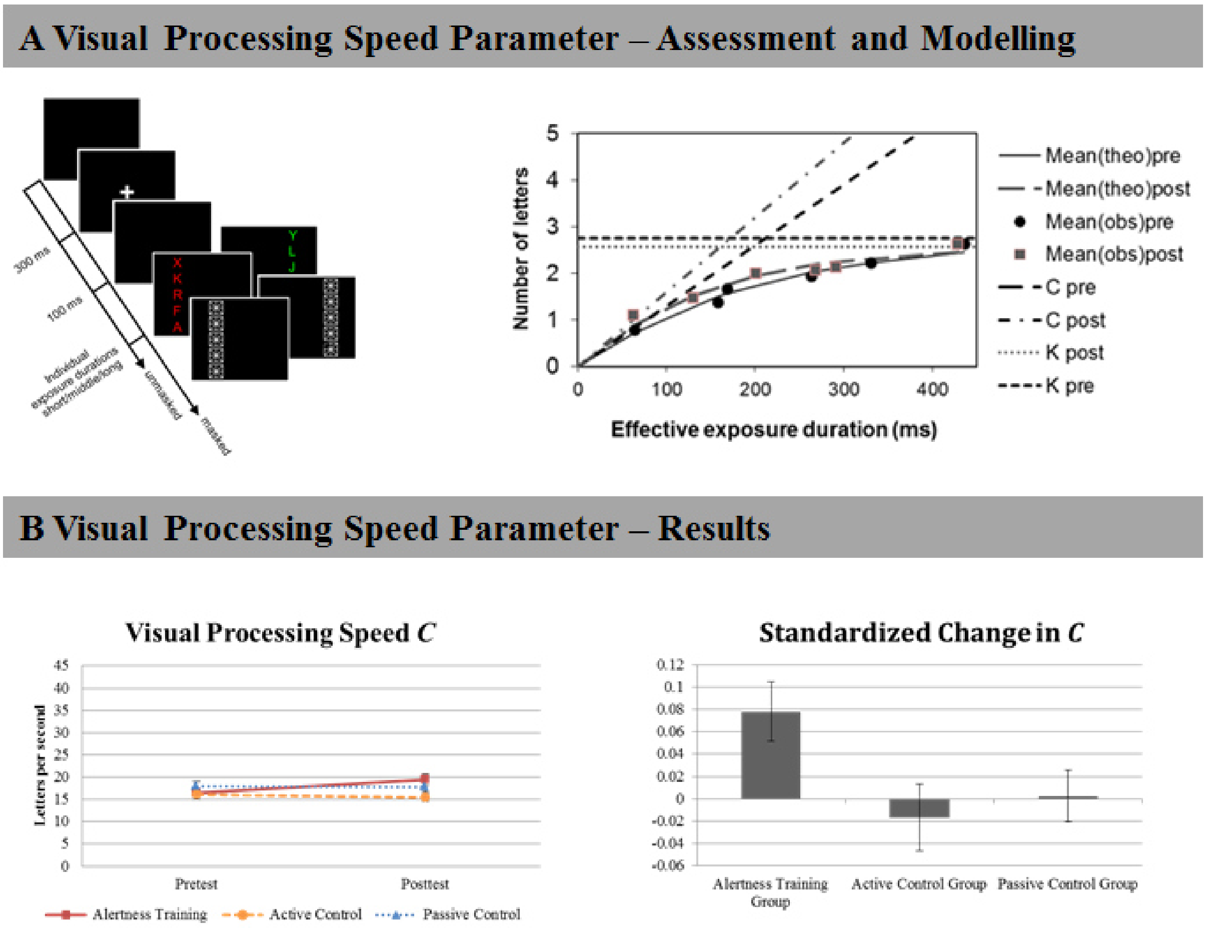


Figure 2. A Visual Processing Speed Parameter - Assessment and Modelling. *Left panel:* Exemplary display types and trial sequence in the whole report paradigm of the Theory of Visual Attention (study 1). The participants had to report as many letters as possible. The letters were either all red or all green and the background was always black. *Right panel:* Whole-report performance for a representative participant of the experimental training group at pre- and posttest (study 1). Mean number of correctly identified letters as a function of effective exposure duration. The best fits from the TVA to the observations are shown by curves in which the slopes correspond to perceptual processing speed (C). The asymptotes as representatives for the estimated vSTM storage capacities (K) are shown as dotted lines. **B Visual Processing Speed Parameter- Result.** *Left panel:* Values of Visual processing speed *C* measured in processed letters per second in the alertness training group, the visual *n*-back group and the passive control group at pre- and posttest (study 1). Error bars indicate standard errors of the mean. *Right panel:* Standardized Change in Visual Processing Speed *C* [(Cpost - Cpre)/(Cpost + Cpre)] in all three participant groups (study 1).

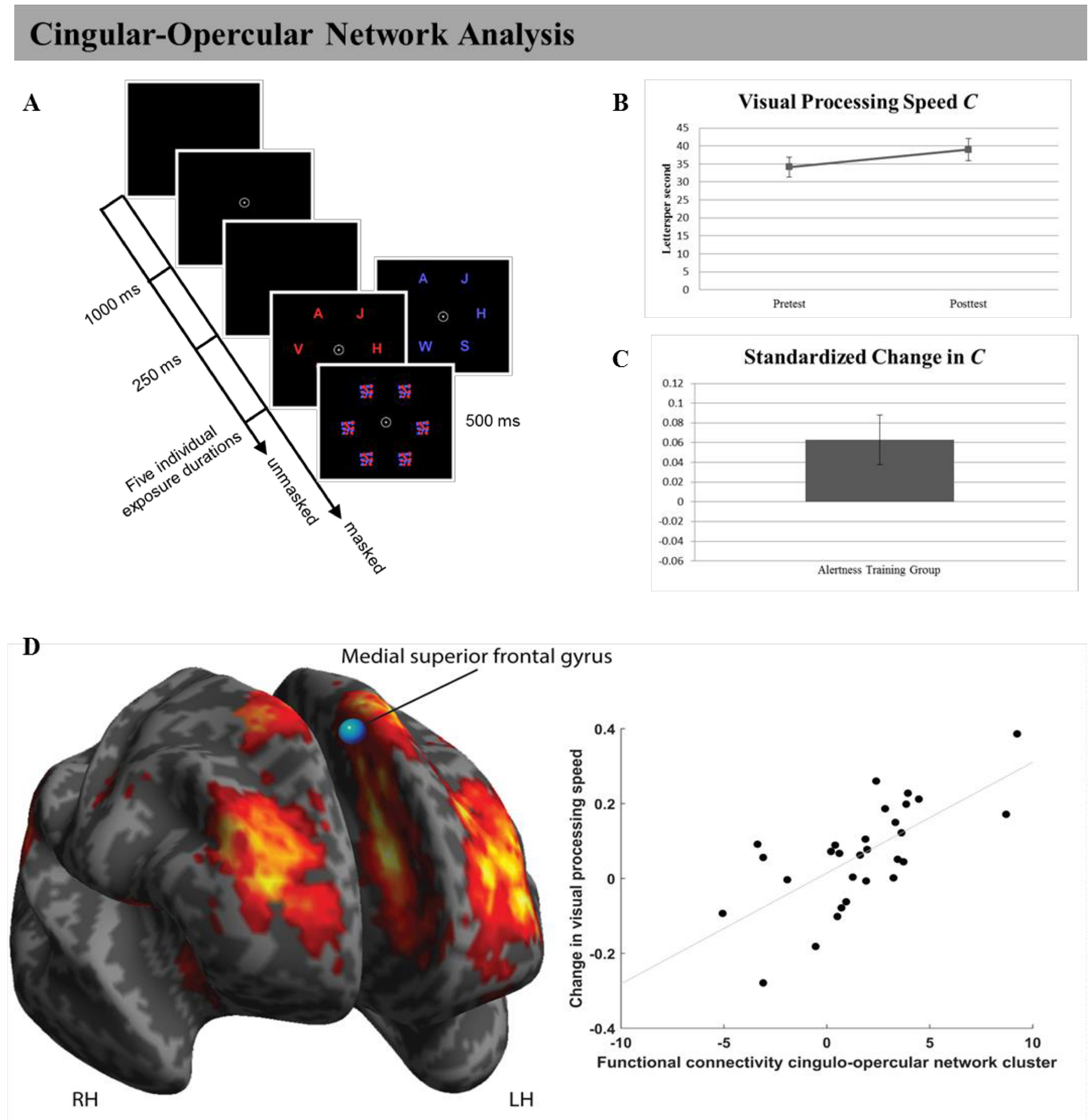


Figure 3. A Exemplary display types and trial sequence in the whole report paradigm of the Theory of Visual Attention in study 2. The participants had to report as many letters as possible. The letters were either all red or all blue and the background was always black. **B** Values of Visual processing speed *C* measured in processed letters per second in the alertness training group at pre- and posttest (study 2). Error bars indicate standard errors of the mean. **C** Standardized Change in Visual Processing Speed *C* [(*Cpost* - *Cpre*)/(*Cpost* + *Cpre*)] in the alertness training group (study 2). **D** Significant correlation between FC and change in visual processing speed *C*. The FC in the medial superior frontal gyrus cluster of the cingulo-opercular network before alertness training is positively correlated with the degree of change in visual processing speed after the training. The scatter plot on the right is the visualization of the individual values of the cluster obtained from the voxelwise linear regression (plotted on the left).

Supplementary Materials

Reasons for the exclusion of participants

Study 1

Alertness training group: two participants had to be excluded due to health reasons (*n* = 1, a longer sickness during the training phase) and technical issues (*n* = 1, technical issues at post-test).

Active control group: *n* = 1 participant had to be excluded due to personal issues

Passive control group: *n* = 4 participants had to be excluded due to personal issues

Study 2

Nine participants had to be excluded due to personal (*n* = 2 could not adequately participate in post-test due to personal distress), health (*n* = 1 exhibited signs of neurodegeneration in the brain scan suggesting frontotemporal dementia; *n* = 1 suffered from cerebral hemorrhage; *n* = 1 exhibited signs of psychiatric disorder), or testing issues (for *n* = 2 there were technical problems with the TVA assessment; *n* = 2 were excluded due to excessive head motion in the scanner). Additionally, two participants dropped out.

Supplementary Table 1. Goodness-of-Fit (GOF) values for all groups in studies 1 and 2.

	GOF *pre*	**GOF *post***	***t*-test *pre* vs. *post***
Study 1			
Alertness Training	0.936 ± 0.029	0.874 ± 0.214	$t(24) = 1.40$, $p = .17$
Active Control	0.932 ± 0.027	0.942 ± 0.022	$t(24) = -1.78$, $p = .09$
Passive Control	0.934 ± 0.082	0.946 ± 0.043	$t(24) = -.86$, $p = .40$
Study 2			
Alertness Training	0.971 ± 0.032	0.965 ± 0.027	$t(28) = 1.08$, $p = .29$

Mean ± standard deviation (SD), are shown.

Study 2: Whole and partial report assessment

For study 2, slightly different versions of the TVA paradigms were run using Matlab [2009; The MathWorks, Inc., Natick, MA, United States], and Psychtoolbox (Brainard, 1997). The TVA-based assessment was conducted on a PC with a 24-inch monitor (screen resolution 1024 × 768 pixels; 100-Hz refresh rate) in a dimly lit test room (different from the training room). The viewing distance of 60 cm was controlled by the use of a chin rest. Every participant was tested separately.

At the beginning of each trial, participants had to fixate a point (0.9 x 0.9 centimeters) that was presented in the center of the screen for 1000 milliseconds. After a delay of 250 milliseconds, red and/ or blue isoluminant letters (taken from the alphabet excluding the letters I, Q, and Y) were presented equidistantly around this fixation point. The same letter could not be presented more than once in a trial. The background was, again, black during the whole experiment. Stimuli could either be masked for 500 milliseconds by jumbled red and blue specks (1.5° visual angle) to avoid visual persistence effects (Sperling, 1960), or unmasked. After the presentation of the letters and/ or masks, participants had to verbally report as many letters as possible, of which they were fairly sure they had recognized, in any order and without emphasis on speed. The experimenter typed in the reported letters and the next trial was started. After each block, participants got accuracy feedback in the form of a colored bar, which indicated the percentage of correctly reported letters out of all reported letters, aiming for an optimum of 70-90%. A higher percentage lead the experimenter to encourage the participant to try to report more letters, while a lower percentage lead to the instruction to be more conservative. Each condition was randomly presented equally often in every block.

Whole report

Each trial consisted of the presentation of six isoluminant and equidistant letters around the fixation point in an invisible circle (5.73° visual angle), either all of them blue or red. After an initial presentation of the instructions on the screen including two examples, the experiment started with a pretest comprised of four blocks with 12 triples of trials in total, to determine exposure durations individually and automatically employing a Bayesian adaptive staircase model and to accustom the participants to the task. In each triple of trials, only one trial was decisive for the adjustment of exposure durations; the other two trials (one unmasked and presented for 200 milliseconds, and one masked and presented for 250 milliseconds) were only used for the familiarization with the task. The critical trial was a masked trial in which letters were first presented for 100 milliseconds. Subsequently, the exposure duration for the next trial was decreased by 10 milliseconds, if at least one letter in the critical trial was reported correctly. This procedure was reiterated until one final exposure duration was identified for which the participant could report no letter correctly. This ‘lowest’ exposure duration was combined with four additional pre-set exposure durations which depended on the individually adjusted ‘lowest’ exposure duration for the main experiment, resulting in five masked exposure durations. Moreover, the second shortest and the longest exposure durations were unmasked in some of the cases, resulting in 7 effective exposure durations. Twenty trials were included for each of these seven conditions, adding up to four blocks of 140 trials (5 trials per condition; 35 trials per block).

The resulting data was then analyzed using the LibTVA script (Dyrholm, 2012) in Matlab (2015b; The MathWorks, Inc., Natick, MA, United States), calculating a maximum likelihood fit for the data.

Partial Report

In each trial, either a single target letter (= red letter), a target letter plus a distractor letter (= blue letter), or two (dual) target letters appeared in the corners of a virtual square positioned 7.5 cm around the fixation point. All of the stimuli were masked (500 ms). When 2 letters were presented, they always appeared in vertical or horizontal, but never in diagonal arrangement. Only target letters were to be reported, while distractors were to be ignored. The 16 different conditions (4 × single target, 8 × target and distractor, 4 × dual target) were presented in randomized order and equally often within each block. Again, there was a pretest of the paradigm to determine individual exposure durations. Initially, participants had to report letters from 40 trials presented for 80 milliseconds each. This exposure duration was lowered in steps of 10 milliseconds when participants could report two letters correctly in the dual target condition. When participants could only report one letter, the exposure duration of 80 milliseconds was maintained. When they could not name any of the two letters in the dual task condition, the exposure duration was raised 10 milliseconds at a time. The exposure duration was kept when participants could report one of two targets per trial on average. After that, 40 trials were presented for the resulting exposure duration. If 70-90% of the single targets and at least 50% of the dual targets were reported correctly, the exposure duration was maintained for the main experiment. If these criteria could not be met, the experimenter could manually increase or decrease exposure durations and reassess them in 40 more trials. The main experiment consisted of six blocks of 48 trials each (3 repetitions of 16 conditions), resulting in 288 trials in total.

4. General Discussion

A growing life expectancy creates new challenges in the form of age-related cognitive decline and disease. To ensure cognitive fitness and independence up until old age, we have to evaluate the specific age-related changes older adults experience in daily life and explore ways to specifically counteract such decline. In the studies of this dissertation, we used the sensitive assessment of visual attention capacity based on the Theory of Visual Attention (TVA; Bundesen, 1990) in healthy older adults to (1) evaluate specific age-related deficits in TVA parameters in a motor-cognitive dual task (DT) situation, (2) investigate the specific effects of an alertness training program on the parameter visual processing speed and, (3) in combination with the assessment of resting-state functional magnetic resonance imaging (fMRI), identify a specific neural marker indicating subsequent alertness-training-induced change in visual processing speed.

4.1 Brief summary of the presented studies

In the first study, we investigated the specific effects of a concurrent continuous motor task on the parametric assessment of visual attention capacity in older compared to younger adults. To this end, healthy younger and older participants performed an alternating tapping task with the index and middle fingers of their dominant hand simultaneously to the TVA-based whole report paradigm. We ensured qualitatively similar assessment in single vs. dual task by comparing model fits between both conditions. We found that only older adults showed DT-related deteriorations in their performance in the attention task, and these deteriorations were specific to visual short-term memory (vSTM) capacity *K*. Younger participants' attentional performance was not significantly affected by the concurrent motor task, and tapping accuracy did not deteriorate in the DT condition in any of the groups. A second sample of healthy younger adults performed a more complex version of the motor task – i.e., sequential tapping with the index, middle, ring and little fingers of the dominant hand – simultaneously to TVA whole report. This complex tapping sequence led to comparable DT decrements in vSTM capacity *K* in the younger participants as the simple tapping task did in the older participants.

In the second manuscript included in this thesis, we went beyond the assessment of specific age-related changes in visual attention capacity, by asking how to counteract age-related attentional decline. In study 2.1, based on previous evidence of a link between alertness and TVA parameter visual processing speed *C* (Bundesen et al., 2015; Matthias et al., 2010; Petersen et al., 2017; Haupt et al., 2018; Finke et al., 2010; Low et al., 2018), we investigated whether alertness training had a specific effect on latent visual processing speed. We trained a group of 25 healthy older adults on an adaptive, computerized, game-like tonic alertness task (CogniPlus, Version 2.04; Sturm, 2007), and compared them to an active (visual *n*-back training) and to a passive control group. Furthermore, to test whether our assumption of a specific link between increased alertness and visual processing speed is valid, we performed control analyses on further TVA parameters. We found that 10.5 hours of alertness training specifically increased latent visual processing speed. As expected, none of the control groups showed any significant changes, and no other parameters were affected.

In study 2.2, our goal was to identify a possible neural marker for subsequent change in visual processing speed caused by alertness training. The degree to which individuals profit from cognitive training seems to vary (see also Section 1.3.2; e.g., Guye et al., 2017; Clark et al., 2016), and in order to deliver the appropriate intervention to every individual, it would be helpful to unveil possible indicators for training response. We focused on the intrinsic functional connectivity (FC) of the cingulo-opercular network that had been previously shown to have links to alertness as well as to visual processing speed *C* (Ruiz-Rizzo et al., 2018; 2019; Haupt et al., 2019; Sadaghiani et al., 2010; Schneider et al., 2016). In a second sample of 29 healthy older adults, we tested whether the change in visual processing speed from pre- to post-test caused by alertness training was linked to the FC within the cingulo-opercular network assessed before training. We replicated the specific enhancing effect of alertness training on visual processing speed. Furthermore, we found that higher (i.e., more ‘youth-like’) FC, especially expressed in a cluster in the superior middle frontal gyrus close to the supplementary motor area, was linked to a higher training-related gain in visual processing speed.

4.2 Main Insights

The main insights of the presented studies will be addressed in the following paragraphs.

4.2.1 VSTM capacity as limiting factor in DT situations

Study 1 showed that, with a sufficiently complex concurrently presented finger tapping task, both older and younger participants exhibited a specific deficit in vSTM capacity *K* when performing TVA-based whole report. Künstler et al. (2018) already reasoned that the brief exposure durations in TVA whole report and the qualitatively similar TVA model fits under ST and DT conditions – a result that we replicated – speak to the continuous performance of both tasks instead of a possible switching of attention. Furthermore, we excluded those trials of TVA-based assessment in which tapping errors occurred during stimulus presentation to ensure participants did not stop tapping when letters were presented (i.e., that they did not only perform one task at a time). Thus, in terms of explanatory models for DT effects, our results are more indicative of a capacity sharing model (e.g. Navon & Gopher, 1979; see also Künstler et al., 2018) – which proposes that capacity is shared between the tasks in a DT situation and both tasks can be processed in parallel – compared to a bottleneck model (Pashler, 1984, 1994) – which blames some form of bottleneck for DT task decrements and claims that tasks can only be processed sequentially. It seems like both the briefly presented letters in TVA whole report and finger sequences in the tapping task tapped into the same limited capacity, i.e., TVA parameter *K*, or vSTM capacity – which can be considered similar to the concept of visual working memory as defined by Luck and Vogel (2013). *K* seems to be relevant for the processing stage of response selection (Logan & Gordon, 2001; Klapp, 1976; Künstler et al., 2018) and is suggested to be vulnerable to interference (Jonides et al., 2008), which could explain the observed DT decrements. Our motor task did not require visual monitoring; in fact, we ensured that participants did not watch their fingers while tapping. Thus, it seems more likely that a central capacity was shared between the visual and the motor task (see also Künstler et al., 2018). However, we cannot entirely rule out that both tasks tapped into a common specific resource, such as visuospatial working memory (e.g., Baddeley, 2012; but see also Logie, 1995; Katus & Eimer, 2018 for a separation of visual and spatial/tactile modalities in working memory). Previous studies have demonstrated the effects on visual attention capacity caused by a secondary visual task in healthy younger adults (Poth et al., 2014) and by a secondary motor task in healthy middle-aged to older adults (Künstler et al., 2018). Our results expand this evidence by demonstrating the specific motor-cognitive DT decrements in younger and older adults.

4.2.2 Complexity-dependent aging effects on motor-cognitive dual tasking

In study 1, older adults showed DT decrements in vSTM capacity earlier than younger adults, i.e., older adults were already affected by a concurrent alternating tapping task with only two fingers. These results are in line with numerous other studies that found age effects on motor-cognitive DT performance (Woollacott & Shumway-Cook, 2002; Boisgontier et al., 2013; Schaefer, 2014). Due to age-related decline (see also McAvinue et al., 2013; Habekost et al., 2013), a shared capacity, i.e., vSTM storage capacity *K*, might have been reduced in older adults to the point that it was exhausted even by the addition of a relatively simple motor task to the TVA-based visual attention task. For younger adults, however, this capacity seems to have only been depleted when the concurrent tapping task was more complex, and thus more capacity-demanding. This suggests a role of complexity in age-related differences in DT performance and is in agreement with other authors who suggest that complex motor tasks are more cognitive and place more demand on attention in older than in younger adults (e.g., Lindenberger et al., 2000; Albinet, Tomporowski, & Beasman, 2006; Woollacott & Shumway-Cook, 2002). Our results add to previous evidence demonstrating that even relatively simple concurrent motor tasks – in our case, performed at a level of 96 % accuracy, on average, in healthy older participants – can have a detrimental effect on the performance of a visual attention task in older adults (Künstler et al., 2018, Mioni et al., 2016; Fuller & Jahanshahi, 1999).

4.2.3 Alertness training specifically increases latent visual processing speed

As hypothesized, in study 2.1, we found that alertness training specifically increased latent visual processing speed as measured based on TVA. TVA specifies a theoretical link between alertness and visual processing speed by including alertness as part of the bias factor in its rate equation (Bundesen et al., 2015). Furthermore, experimental evidence has shown effects of phasic alerting (Matthias et al., 2010; Haupt et al., 2018) and stimulant medication (Finke et al., 2010; Low et al., 2018) on parameter *C*. Importantly, the alertness training and our TVA-based outcome task had entirely different task and reaction demands. While the alertness training program required fast motor responses in the form of key presses, no stress was put on speed in TVA's verbal report. Thus, it is unlikely that the change in visual processing speed was merely a result of similarity between training and outcome tasks. Rather, the results speak for an enhancement of 'pure' visual processing speed, independent of motor factors. This kind of theoretically well-grounded 'near' transfer to a latent construct is a highly desirable outcome for training studies (cf. Noack et al., 2009; 2014). The fact that we replicated the training-induced effect on visual processing speed, or parameter *C*, in study 2.2 further fosters the link between this parameter and alertness, and corroborates the robustness of the results of study 2.1.

To control for simple practice or re-test effects, in study 2.1, we compared the results of the training group to those of a passive control group that only attended pre- and post-test measurements, but did not receive any form of training. Furthermore, because a training intervention lasting several weeks might come with certain motivational effects and expectations (i.e., placebo effects might cause possible parameter changes; e.g., Foroughi et al., 2016), and because possible effects after training could also be a consequence of unspecific factors such as regular computer practice or regular social contact, we additionally compared the results of the training group to those of an active control group. This active control group was trained on an adaptive visual-*n*-back task (Buschkuehl, Jaeggi, Kobel, & Perrig, 2007) – a task that has often been successfully used in working memory training studies in varying forms (e.g., Jaeggi et al., 2010; Heinzel, Schulte, et al., 2014). As this task was not merely created as non-effective control training, but was instead targeted at a different cognitive construct, expectation or motivation effects in the active control group should be comparable to those in the alertness training group. Importantly, members of the alertness training and the active control groups were blinded to each other's existence, and the participants of the active control group did not know that they were not taking part in the training of interest. As participants of the control groups did not show any improvement, we can conclude that the higher processing speed values in the training group at post-test were indeed specifically caused by the alertness training program.

Furthermore, to control for unspecific training-related effects on visual attention capacity, we evaluated changes in further TVA parameters, such as vSTM capacity, visual threshold or top-down control in studies 2.1.and 2.2. We did not find an enhancement in any other visual attention parameters caused by alertness training, thus corroborating our hypothesis of a specific influence on visual processing speed. That is, alertness training can be used to specifically target visual processing speed.

TVA-based assessment enables us to specifically evaluate training effects on separable aspects of attention independent of motor speed. This is important, as outcome measures in visual processing speed training studies often do not separate pure perceptual speed from other aspects like visual threshold or motor speed (e.g., Ball et al., 2002; Kreiner & Ryan, 2001). Especially results from studies that train participants in and assess results with the Useful Field of View (UFOV) task often seem to be promising and far-reaching. However, it is not clear whether these results really stem from an enhanced visual processing speed or are maybe the consequence of the enhancement of a different aspect of cognition (Woutersen et al., 2017; see also Protzko, 2017; Ball et al., 2007). It would be insightful to replicate these results with more sensitive measures, such as TVA-based assessment.

Training effects on parameter *C* have been previously demonstrated after a video game intervention in healthy young adults (Schubert et al., 2015). However, speed improvements were limited to the lower half of the screen. To our knowledge, studies 2.1 and 2.2 are the first to demonstrate cognitive training effects on a TVA parameter in healthy older adults.

4.2.4 'Youth-like' FC in the cingulo-opercular network is a neural marker for subsequent training gain in visual processing speed

Not everyone profits the same from a given training intervention (see Section 1.3.2; e.g., Guye et al., 2017; Clark et al., 2016). Thus, it is crucial to uncover indicators that could possibly predict a positive training response. The cingulo-opercular network has been associated with alertness (Sadaghiani et al., 2010; Schneider et al., 2016) as well as visual processing speed

(Ruiz-Rizzo et al., 2018, 2019). Importantly, a recent study by Haupt and colleagues (2019) found that the degree to which healthy young adults could profit from phasic alerting cues in the form of an enhanced visual processing speed was mediated by the cingulo-opercular network. Thus, it is reasonable to assume that a more long-term enhancement of alertness, and thus a benefit for visual processing speed, could be similarly linked to this network. As expected, we found a specific relationship between the FC of the cingulo-opercular network before training and the training-induced change in visual processing speed. We performed control analyses with networks such as the default mode network and the frontoparietal network to confirm this suspected unique link and to rule out an unspecific association of visual processing speed with multiple networks. Those older adults with a FC in the cingulo-opercular network that is more ‘youth-like’, i.e., higher (Lindenberger et al., 2014; see also Ruiz-Rizzo et al., 2018; 2019), seem to profit more from alertness training in terms of an enhanced visual processing speed. This is in agreement with the concept of ‘brain maintenance’ (Nyberg et al., 2012) that raises the possibility that relatively preserved brain structures and functions (on top of compensation) can also lead to a cognitive performance in older adults that resembles that of younger adults. The fact that those individuals with a more ‘youth-like’ FC profited more from training seems like a type of ‘magnification effect’: those who already present with less brain decline also benefit more from alertness training cognition-wise. In the limitations and outlook, I will present possible future directions to exploit this finding in order to supply individuals with the combination of interventions they need for optimal benefits.

It is important to note that we assume networks to be a unity and significant clusters merely as sites of representation of an association (see also Ruiz-Rizzo et al., 2019). However, it is worth mentioning that the superior middle frontal gyrus – where we found the significant cluster related to training-induced gain in visual processing speed – and the close by supplementary motor area have fittingly been implicated in motor and task speed (Floden & Stuss, 2006) as well as temporal aspects of tasks (Coull, Cheng, & Meck, 2011).

4.2.5 TVA-based assessment is a valid and sensitive measure to investigate age-related deficits as well as plasticity of visual attention capacity

All three studies in this thesis add to the evidence that TVA-based assessment is a valid and sensitive measure to investigate deficits as well as positive plasticity of visual attention capacity. First, we replicated former studies which found age-related differences in visual attention capacity (e.g., McAvinue et al., 2013; Habekost et al., 2013). In study 1, older compared to younger adults had a higher visual threshold, a lower vSTM capacity, and – at least numerically – a slower visual processing speed. Moreover, TVA-based assessment enabled us to pinpoint the exact location of a deficit in motor-cognitive DT abilities. Numerous other TVA studies, particularly those conducted in diverse patient groups, already provided evidence for this kind of specificity (for a review, see Habekost, 2015).

Furthermore, studies 2.1 and 2.2 corroborate that parametric assessment based on TVA is an appropriate tool to evaluate positive plasticity in visual attention capacity. This is in line with other intervention studies which have shown specific effects of medication (Finke et al., 2010), meditation (Jensen et al., 2010), video games (Schubert et al., 2015), transcranial magnetic stimulation (TMS; Kraft et al., 2015) or transcranial direct current stimulation (tDCS; Gögler et al., 2017) on specific TVA parameters before.

Collectively, our studies suggest that aging is more than the decline in just one parameter. On the one hand, older adults seem to suffer from a slowing of visual processing speed. But on top of this deficit, we find an additional decrement in DT situations which does not seem to concern speed, but rather vSTM. Our results, based on three studies and involving the replication of a specific training effect, are further proof for TVA's applicability in assessing both deficits and positive plasticity in visual attention capacity.

4.3 Limitations and outlook

On top of those caveats already given in the previous paragraphs, in the following, I will list some limitations of the presented studies to inform future work in the area of aging and cognitive enhancement.

4.3.1 General limitation

A general limitation of many aging studies is that the participant samples are often made up of more active, high-functioning older adults – because these are the individuals interested in taking part in research studies. It is not clear whether our results would hold up for those who are less active. However, unveiling age-related deficits and successful cognitive enhancement even in a comparably high-functioning sample speaks to the sensitivity of our applied measures. Furthermore, as study 2.2 shows, we did still find inter-individual differences in performance and training response. Nevertheless, it might be insightful to repeat these studies for less active older adults or even for patients with specific deficits in visual attention capacity (see, e.g., Duncan et al., 2003, Bublak et al., 2006, 2011; Ruiz-Rizzo et al., 2017; Gögler et al., 2017).

4.3.2 Dual task situations

The impact on vSTM capacity that we found for cognitive-motor DT situations (study 1) might be limited to a concurrent manual motor task. It might be interesting to explore ways to combine TVA-based assessment with some form of walking task to investigate how this would affect visual attention parameters. One would have to find creative solutions to enable such a combination while still ensuring the participants' safety as well as valid assessment. One example could be the use of head-mounted displays while walking on a treadmill specifically designed for older adults.

Furthermore, our investigation of DT effects on visual attention caused by a concurrent motor task was limited to visual attention capacity. It might be interesting to look at DT effects in selective attention, i.e., TVA-based partial report.

In studies 2.1 and 2.2, we have shown that it is possible to enhance TVA parameters in healthy older adults via cognitive training. Thus, another interesting question would be whether the age-related decline in DT abilities could also be mitigated by an intervention. For example, it might be possible to enhance vSTM capacity in older adults to a degree at which a simple concurrent tapping task would not cause any more DT decrements. While in general, TVA parameter visual processing speed seems to be more malleable to changes than vSTM capacity (cf. Brosnan et al., 2018; see, e.g., Matthias et al., 2010; Finke et al., 2010; Vangkilde et al., 2011), a few interventions have shown some form of impact on TVA parameter *K* (Jensen et al., 2012; Kraft et al., 2015; Finke et al., 2010). It would also be interesting to explore whether training one or both of the tasks would change the performance in DT situations, e.g., through automatization of the tapping task (Wu, Kansaku, & Hallett, 2004).

4.3.3 Cognitive training

We did not measure FC in the cingulo-opercular network after training. However, a post-measurement was not necessary for our research question of whether we could find a link between FC assessed before training and subsequent training gain in visual processing speed. In future studies, it would be interesting to investigate whether the alertness training itself also influences FC (e.g., like Ross et al., 2018; Cao et al., 2016).

Furthermore, we found a form of a magnification effect in study 2.2, in that those older adults with a more preserved or 'youth-like' (i.e., higher) FC in the cingulo-opercular network profited more from alertness training in the form of an enhanced visual processing speed. One could argue that this might be disheartening for those who have not been so lucky to stave off cognitive decline, as they seem to have a double disadvantage. However, studies have shown that

FC is malleable to changes by interventions as well (e.g., Ross et al., 2018; Cao et al., 2016). The concept of brain maintenance (Nyberg et al., 2012) even states that it is the current lifestyle and mental activity that influence the preservation of brain structure and function more than factors such as education. A combination with other interventions might boost FC and lead to a subsequent higher benefit from alertness training in those with an initial lower FC in the cingulo-opercular network. One candidate for the combination with alertness training might be tDCS. It has, on the one hand, been shown to enhance visual processing speed *C* in patients with major depression (Gögler et al., 2017), and, on the other hand been found to lead to a heightened connectivity in the salience network (i.e., the cingulo-opercular network; Shahbabaie et al., 2018; Hunter et al., 2015). Moreover, tDCS combined with working memory training has been shown to lead to steeper learning curves and improved long-term effects compared to cognitive training without added active stimulation (Ruf, Fallgatter, & Plewnia, 2017; Katz et al., 2017; Park, Seo, Kim, & Ko, 2014). Thus, it is reasonable to assume that tDCS during alertness training could magnify training effects. For those with an initially lower FC within the cingulo-opercular network, tDCS might help bring FC back to more 'youth-like' levels and thus enable them to subsequently profit more from alertness training. One would have to investigate whether additional tDCS in those with an initially higher baseline FC would lead to even stronger improvements in *C*, or whether their higher baseline level could make them insusceptible to additional stimulation (similar to stimulant medication; see Finke et al., 2010). It seems that sometimes those with a higher baseline ability cannot profit as much from tDCS (e.g., Katz et al., 2017; Tseng et al., 2012). Other interventions that could have an increasing effect on FC might be neurofeedback (Ros et al., 2013) or physical exercise (Voss et al., 2011; Boraxbekk, Salami, Wåhlin, & Nyberg, 2016; see also Bullock & Giesbrecht, 2014, for a possible theoretical link between physical exercise and TVA parameters). In general, multi-domain interventions that combine different approaches seem to be promising (e.g., Ngandu et al., 2015).

Finally, it would be interesting to assess more long-term effects of alertness training on visual processing speed (cf. Rebok et al., 2014; Willis et al., 2016). In general, it is debatable whether we could expect that one training intervention spanning only a few weeks just by itself would have positive effects on cognition for years after. We would not intuitively expect that other interventions, such as a transient change in diet or a few weeks of physical exercise would have effects for years to come when not consistently pursued. Note, however, that this is what the ACTIVE study seems to have shown – a relatively circumscribed training seems to still entail positive consequences after up to 10 years (Rebok et al., 2014). One explanation for these long-lasting effects was proposed by Ross and colleagues (2018). They suggest that, for example, lasting changes in FC could be at the root of these long-lasting benefits. With more efficient neural functioning, it might be possible that the trained individuals were more likely to profit from other forms of mental or physical activity, or pursued more of such activities because of their newly enhanced processing speed. Not surprisingly, those participants in the ACTIVE study who received booster training at 11 and 35 months after completion of the initial training intervention showed magnified effects (Ball et al., 2002). Thus, conceptualizing studies with a more long-term design might be beneficial to find out whether alertness training helps stave off or slow down cognitive decline in the long run (see also Lövdén et al., 2012, for an example of training-related brain maintenance).

4.4 Concluding thoughts

Collectively, the studies presented in this dissertation provide insights into age-related changes in visual attention capacity and potential for specific enhancement. Our results corroborate that TVA-based parametric assessment is an excellent way to measure both attentional deficits as well as positive plasticity in healthy older adults. On the side of age-related changes, we found that visual attention capacity is affected more strongly by a concurrent manual motor task in older compared to younger adults, and that the complexity of the concurrent task seems to play a role in these age-related differences. Furthermore, we identified vSTM capacity as the main culprit in DT decrements in younger and older adults provided that a sufficiently complex motor task was simultaneously applied to TVA-based assessment. Based on our results, it does not seem to be advisable to perform multiple tasks at the same time for more allegedly efficient performance. Rather, performance declines in at least one of the tasks can be expected. It should be kept in mind that these effects also exist in younger adults under certain circumstances, but are even more pronounced in older adults. This is an important factor that should be considered, for example when designing technical devices especially for older adults.

In terms of the enhancement of visual attention capacity, we found that alertness training specifically enhanced latent visual processing speed in healthy older adults. Furthermore, a more positive training response was linked to a higher, i.e., more ‘youth-like’ FC in the cingulo-opercular network. These results could constitute an initial step in the direction of personalized medicine, in that baseline FC in the cingulo-opercular network could function as a neural marker to predict who will profit from the alertness training program. To answer the far too broadly posed question ‘Does cognitive training work?’ (see Katz et al., 2018): Yes, the alertness training program we applied seems to ‘work’ in specifically increasing latent visual processing speed in healthy older adults. Cognitive training might not be a ‘magic bullet’ to cure all maladies

(Simons et al., 2016), but it seems to be an important ingredient in reaching the goal of enhancing (or possibly maintaining) cognitive function. Even when we are aiming for an ultimately more complex multimodal solution to counteract age-related decline, we have to specifically evaluate the impact of each intervention component, and additionally consider synergistic effects. In the end, it is not the goal to wildly combine interventions, but to add together those active ingredients from which a given individual can profit the most with the least amount of effort and an ‘enjoyment factor’ that is as high as possible (Simons et al., 2016). The very specific links we have shown – between alertness training and the enhancement of visual processing speed, as well as between the FC in the cingulo-opercular network before training and this specific enhancement – could help inform such future combinations. Health costs are rising and we need to find new solutions to tackle these problems (Jin, Simpkins, Ji, Leis, & Stambler, 2015). Encouragingly, older adults seem to be willing to devote a significant amount of time to an intervention when they believe that it will positively affect the length of their independence (Harrell, Kmetz, & Boot, 2019). We already have possibilities such as regular physical check-ups at the doctor’s office or constantly updated workout schedules in gyms. One day, it might be possible for us to go to an ‘intervention center’ with trained personnel who would regularly compile our neurocognitive profiles and adjust our individual adaptive ‘intervention schedules’ to ensure the best and most enjoyable outcome for each of us, enabling structure also for those who might otherwise not know where to start on their way to a more active and cognitively healthy life (see, e.g., Stathi, McKenna, & Fox, 2010). Until then, we still have a long way to go, and this way will involve the specific evaluation of both age-related deficits and every possible intervention component.

5. References (Abstract, general introduction and general discussion)

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Appendix

List of publications and manuscripts

Künstler, E. C.*, **Penning, M. D.***, Napiórkowski, N., Klingner, C. M., Witte, O. W., Müller, H. J., Bublak, P.†, & Finke, K. † (2018). Dual task effects on visual attention capacity in normal aging. *Frontiers in psychology*, *9*.

Penning, M. D.*, Ruiz-Rizzo, A. L.*, Redel, P., Müller, H. J., Salminen, T., Strobach, T., Mölbert, S., Schubert, T., Sorg, C., & Finke, K. (*in preparation*). Alertness training increases visual processing speed in healthy older adults.

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