Deficits in visual attention after mild and severe traumatic brain injuries

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List of abbreviations and technical terms

α	parameter top-down control
%	percent
°	degree
ANOVA	analysis of variance
B	backward
C	perceptual processing speed
CBN	colour-bar naming condition (Stroop)
cf.	conferre, compare
cm	centimetre/s
CT	computer tomography
CWR	colour-word reading condition (Stroop)
D	distractor
d	effect size
Dev(w_{lat})	imbalance index of attentional weighting
DTI	diffusion tensor imaging
e.g.	exempli gratia, for example
et al.	et alii (and others)
et seq. / seqq.	et sequentes (and the following)
f	female
F	forward
fMRI	functional magnetic resonance imaging
FWIT	Farb-Wort-Interferenz-Test (German Stroop task)
GCS	Glasgow Coma Scale
I	interference condition (Stroop)
i.e.	id est (that is)
IQ	intelligence quotient
K	WM storage capacity
L	left
LOC	length of loss of consciousness
MRI	magnetic resonance imaging
ms	millisecond/s
MWT-B	Mehrfachwahl-Wortschatz-Intelligenz-Test B (verbal intelligence screening test)
n / N	number
NP	Neuropsychology
Nr.	subject number
p	level of significance
p. / pp.	page/s
PC	personal computer
PTA	post-traumatic amnesia
pts.	points
PR	partial report paradigm
R	right
r	correlation coefficient
r^2	explained variance
RT	reaction time
SD	standard deviation
SE	standard error
sec	second/s
SEL	selectivity index corrected for naming speed (Stroop)
T	target
t_0	perceptual threshold
TAP	Test for Attentional Performance
TBI	traumatic brain injury
TVA	theory of visual attention
VGA	Video Graphics Array
VMS	Visual Memory Span (WMS-R)
VS	Visual Scanning (TAP)
WAIS-III	Wechsler Adult Intelligence Scale
w_{lat}	laterality index of attentional weighting
WM	Working memory
WMS-R	Wechsler Memory Scale – Revised Edition
WR	whole report paradigm

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1. Introduction

This dissertation consists of three empirical studies on visual attention deficits following traumatic brain injury (TBI). As argued before in a review of previous clinical studies on the basis of the theory of visual attention (TVA; Bundesen, 1990, 1998; Bundesen & Habekost, 2014; Habekost, 2015), the TVA model provides an appropriate theoretical framework for investigating deficits in visual attention in various clinical conditions. The studies presented in this dissertation were set out to systematically assess potential attentional deficits in a TBI population with TVA-based paradigms.

According to TVA, due to the limited processing capacity of the cognitive system, different objects of the visual field compete for the allocation of processing resources. Thus, only parts of the visual objects get consciously represented, while the rest is lost. The visual selection process is driven by bottom-up salience aspects and top-down controlled aspects of behavioural prioritization (e.g. task related weighting). Those elements of the visual field receiving higher attentional weights are more effectively (i.e. faster) processed than others receiving lower attentional weights. Therefore, TVA can be considered as a race model, which assumes that the cognitive system processes all objects in the visual field independently, and in parallel, but not with the same processing speed. A higher attentional weight for an object raises its probability to enter the working memory store, which is limited to a few objects (about 3 or 4 in healthy individuals). In order to protect the cognitive system from information overload, the adequate allocation of attentional resources is highly important for efficient information selection, considering the diversity and overwhelming multitude of visual stimuli in daily life. Numerous brain regions and large-scale anatomical networks are involved in the fairly complex process of visual attention. Damage to the brain, such as vascular disease (e.g. stroke), neurodegenerative disease (e.g. progressive loss of neurons in Alzheimer's disease), brain tumours, brain infections (e.g. Creutzfeldt-Jacob disease), or traumatically induced injury (TBI), can affect this process dramatically and lead to visual attention deficits and further sequels (cf. Habekost, 2005).

Each year, approximately 40.000 people sustain a TBI in Germany (Rickels et al., 2006) with highest incident rates in mild TBI (> 90%). The severity of the TBI is most commonly determined by the Glasgow Coma Scale (GCS; Teasdale & Jennett, 1974), which represents a neurological screening tool administered for recording the consciousness state of a person for initial assessment by three aspects of behaviour:

motor responsiveness, verbal performance, and eye opening, giving a score from 3 to 15 (most to least severe).

The general aim of this dissertation was to examine deficits in visual attention after TBI. For this purpose, the present work was designed to investigate selective visual attentional functions in TBI patients compared to healthy control subjects based on Bundesen's TVA (1990, 1998, 2002; Bundesen et al., 2005; Bundesen, Habekost, & Kyllingsbæk, 2005; Bundesen & Habekost, 2014). This theoretical framework allows the quantification of mathematically independent measures which are derived from the accuracy data of two tasks – the whole and partial report paradigm. A TVA-based framework instead of conventional tests was used for studying a TBI population due to a number of important strengths. One lies in the sound theoretical grounding provided by the TVA. A second is the high cognitive specificity of the TVA measures that reflect five central but different and independent aspects of visual attention: the visual processing speed, the storage capacity of visual working memory, the visual perceptual threshold, the efficiency of top-down controlled selection, and the spatial laterality of attentional weighting. These parameters are derived from two highly comparable tasks, the whole and partial report of briefly presented letters. Furthermore, given that the TVA assessment tools (whole and partial report) require nonspeeded verbal responses rather than reaction time measures, possible motor disturbances do not influence task performance. The task instructions are simple, allowing also the testing of patients that show notable cognitive impairments, as found for example in patients with severe TBI. This allows to validly assess and to compare attentional parameters across distinct levels of trauma severity (e.g., mild vs. severe TBI).

TVA-based whole and partial report paradigms were used in numerous studies investigating attentional deficits in various clinical conditions such as neurological and psychiatric patient groups (an overview is given in section 3.3., pp. 22 et seq.; for a review see Habekost, 2015). Despite this wide range of research interest in clinical TVA-based assessment, to the best of my knowledge, no systematic assessment of attentional impairments in TBI patients was carried out so far. There have been several reasons for the selection of this population: First, TBI is a very common type of brain damage with a distinctive prevalence across the age spectrum and a high clinical relevance. TBI-induced damage mostly affects several areas of the brain, which is for instance characteristic for the coup-contre-coup mechanism and/or lesions in white matter fibre tracts. Given the heterogeneous lesion locations and the complex

pathological features, such as extra-axial lesions (epidural or subdural hematoma, subarachnoid haemorrhage), contusions or diffuse axonal injuries, in TBI, in this dissertation I did not try to map lesion anatomy and cognitive functions. The purpose was rather to establish, for the first time, a profile of deficits in visual attention in a TBI population based on the sound theoretical grounding provided by the TVA model. The aim of the three studies presented in this thesis was to advance the clinical understanding of TBI by revealing characteristic patterns of impairments in processing capacity and/or attentional weighting in mild and severe TBI. Such knowledge completes and probably enriches the basis for practical evaluation and rehabilitation of this patient group.

In the subsequent chapter 2, brief summaries of the three studies presented in chapters 4 to 6 are provided. In chapter 3, the theoretical and methodological framework of TVA is described in more detail (pp. 19 et seqq.), and a short overview of clinical TVA-based studies is given (section 3.3., pp. 22 et seq.).

2. Synopsis

This section is divided into three subsections, presenting English synopses of the three studies presented in chapters 4 to 6. The German synopses are given in chapter 8 (pp. 70 et seqq.).

Deficits in attention are among the most common impairments in patients suffering traumatic brain injury (TBI; Sturm, 2005; Huang et al., 2014). TBI can lead to a general non-specific slowing of information processing as well as to specific functional impairments in various attentional domains (Bigler, 2001; Sturm, 2005; Kraus et al., 2007; Zihl & Almeida, 2015). However, different authors suggest different underlying mechanisms that could lead to performance deficits in various tasks. Some authors suggest that the very basic impairment that mediates deficits in various cognitive functions is a slowing in processing speed (e.g. Ponsford & Kinsella, 1992; Spikman, van Zomeren, & Deelman, 1996). Conversely, other authors assume that an underlying deficit in working memory (WM) leads to generally low task performance in patients with TBI (e.g. McAllister et al., 2004). Finally, it was also suggested that TBI patients suffer from higher-order control deficits that could also lead to impairments in various cognitive tasks (Ciaramelli et al., 2006).

Neuropsychological assessment tools which enable to specify deficits in attention resulting from a mild or severe TBI are highly important in order to establish an appropriate neuropsychological diagnosis and to launch a suitable rehabilitation program. The purpose of this dissertation was to better identify deficits in visual attention following TBI by implementing an integrated parameter-based test procedure, which demonstrated its clinical utility in a wide range of clinical conditions (Habekost, 2015). In combination with Bundesen's theory of visual attention (TVA; Bundesen, 1990, 1998, 2002; Bundesen et al., 2005; Bundesen & Habekost, 2008, 2014), two paradigms that are highly homogeneous with respect to stimulus and response requirement – computerized whole and partial report paradigms – allow the estimation of several latent, mathematically independent and quantitative parameters. The present thesis was performed in order to contribute to improving the knowledge in both the clinical TVA-based research and the neuropsychology of TBI. More precisely, the purpose of this thesis was to investigate the following topics:

- Study 1 was dedicated to analyse potential attentional capacity deficits following TBI by the use of a whole report paradigm that permits to quantify visual WM storage capacity and visual processing speed;
- Study 2 complemented study 1 by assessing spatial and task-related selectivity aspects of attentional processing (attentional weighting) in TBI subjects;
- The aim of study 3 was to establish the relation between TVA parameters and other clinical measures in a TBI population, in order to explore whether potential relations are comparable to the correlations demonstrated in healthy subjects presented by Finke et al. (2005), or whether other associations emerge.

The subsequent synopses provide brief summaries of these three studies.

2.1. Study 1

Both, impairments in processing speed and working memory (WM) are frequently reported as a consequence of TBI. In the literature it is debated whether processing speed might mediate the relation between TBI and other impaired cognitive functions such as in WM or whether, the other way round, WM deficits themselves lead to low performance in various tasks (e.g., Ponsford & Kinsella, 1992; Spikman, van Zomeren, & Deelman, 1996; McAllister et al., 2004). The aim of study 1 was to investigate whether deficits in both cognitive functions following TBI might be detectable independently from each other across the spectrum of severity. It was argued, in the first study (see chapter 4, pp. 24 et seqq.) that an integrated parameter-based estimation of the capacity of visual attention might serve that purpose.

Bundesen's theory of visual attention (TVA; 1990, 1998) was used as a theoretical framework to analyse the visual attention processing capacity in 25 patients with mild TBI (mTBI; all of them with complicated mTBI, as evidenced by intracranial lesions), 23 patients with severe TBI (sTBI), and 24 healthy control subjects, matched for gender, age, and education. From the accuracy data in a whole report task requiring verbal report of briefly presented letters, three parameters were derived: perceptual threshold t_0, processing speed C, and WM storage capacity K.

The results of study 1 showed that patients suffering from sTBI presented impairments in all TVA parameters, while mTBI patients were solely impaired in visual processing speed. Interestingly, processing speed performance was similar in both TBI groups. WM storage capacity K was correlated with trauma severity (assessed with

the Glasgow Coma Scale). Furthermore, visual processing speed *C* and WM storage capacity *K* correlated significantly in the sample of TBI patients.
The present study delivers a first integrated parameter-based analysis displaying a systematic pattern of slowing of visual processing speed post TBI, however irrespective of trauma severity, and reduction of WM storage capacity after severe TBI.

2.2. Study 2

In addition to reduced information processing speed, TBI can result in more specific functional deficits for example in task related selective attention and/or shifting spatial attention. For instance, visual search with high target-distractor similarity seems to be slowed in TBI patients (e.g. Schmitter-Edgecombe & Robertson, 2015; Bate, Mathias, & Crawford, 2001a; Rasmussen et al., 2008). However, impairments in visual search tasks might result from various underlying mechanisms, such as basic slowing in processing speed, deficits in top-down control or spatial attention deficits. However, this cannot be disentangled based on the performance scores. Such disentanglement is possible based on an integrated parameter-based approach for assessing selective visual attention. The second study (see chapter 5, pp. 41 et seqq.) examined whether TVA-based parameters of spatial laterality and top-down control are affected in mild and sTBI.
Visual selective attention was investigated in 23 patients with mTBI, 23 patients with sTBI, and 23 healthy control subjects, matched for age, gender and educational level. Patient groups were assigned according to the Glasgow Coma Scale (GCS). In combination with Bundesen's theory of visual attention (TVA; 1990, 1998), two mathematically independent and quantitative parameter estimates were derived from a partial report of briefly presented letter arrays: top-down control of attentional selection, representing task-related attentional weighting for prioritizing relevant visual objects (parameter α), and spatial distribution of attentional weights across the left and right hemifield (parameter w_{lat}).
Compared to controls, sTBI patients showed significantly reduced top-down controlled selection and a significantly unbalanced attentional weighting across hemifields, while mTBI patient's performance did not significantly differ from control participants. Parameter α was correlated with trauma severity (GCS).
The TVA-based partial report provides a novel approach in the assessment of spatial and task-related attentional weighting in TBI. Further research is required to clarify

the underlying neuropathology of impairments in both aspects of visual selective attention after sTBI.

2.3. Study 3

Studies analysing the relation of TVA parameters to other clinical measures are limited to a small number of studies (cf. Habekost, 2015). Using the same whole and partial report paradigms as used in study 1 and 2, Finke et al. (2005) correlated the TVA parameters with established clinical tests in young healthy participants and found higher correspondences of TVA parameters with theoretically related, as compared to unrelated, measures. The third study (see chapter 6, pp. 57 et seqq.) was dedicated to the question, whether the TVA parameters are also related to clinically established tests in patient groups who actually suffer from attentional impairments, e.g. in TBI. For this, the same neuropsychological tests were used as in the study by Finke et al. (2005). In a sample of 51 TBI patients (27 patients with mTBI and 24 patients with sTBI, as assessed with the Glasgow Coma Scale), the correlation matrix showed comparable correlations as found by Finke et al. (2005) in healthy subjects, but also unexpected associations between TVA parameters and conventional neuropsychological tests. The results showed significant correlations between processing speed (parameter *C*) with all three baseline Stroop conditions as well as with the visual scanning time in the TAP-subtest. That indicates that in tasks, where many visual stimuli have to be processed before a participant can react, performance is determined by a basic slowing of processing.

2.4. Conclusions and perspectives

The aim of this dissertation was to investigate probable deficits in visual attention in mTBI and sTBI patients using the whole and partial report based on Bundesen's theory of visual attention (TVA; 1990, 1998). The results of the three studies suggest considerable attentional deficits in sTBI patients presenting impairments of pre-attentive processing (perceptual threshold, t_0), processing capacity (perceptual processing speed, *C*, and WM storage capacity, *K*) as well as in task-related (top-down control, α) and spatial weighting [imbalance of attentional weighting, Dev(w_{lat})]. Apart from deficits in perceptual processing speed, aspects of pre-attentive processing,

WM storage capacity as well as task-related and spatial weighting were intact in the mTBI group compared to healthy matched control subjects.

In conclusion, the results of these studies showed that processing speed is affected by TBI, irrespective of the trauma severity as assessed with the Glasgow Coma Scale. Additional impairments in the processing capacity and attentional weighting are more specific to severe brain injury, suggesting a graded pattern of attentional changes. The correlation analysis between TVA parameters and conventional neuropsychological tests measuring similar constructs showed comparable correlations as previously presented by Finke et al. (2005) in healthy subjects, but also unexpected associations.

In future studies, the additional use of neuroimaging methods as for instance MRI diffusion tractography would be significant to establish the interaction between impaired TVA parameters and the underlying neuropathology following TBI, in order to get a better understanding of the complex process of TBI.

3. Theory of visual attention (TVA)

Before explaining the three studies in detail, a brief introduction to the TVA model is given in this section (see Bundesen & Habekost, 2008, for a more detailed description).

3.1. The TVA model

Bundesen (1990, 1998) introduced the theory of visual attention (TVA) as a unified theory of attentional selection and visual recognition. In Bundesen's theory, filtering is defined as the selection of objects from the visual field. In TVA, an object in the visual field is consciously recognized when it is selected. Selection corresponds to encoding the object's properties into a visual working memory (WM) store which has a limited capacity (about 3 or 4 items in young healthy individuals). In TVA, the encoding process takes the form of a competitive race between the objects. In this race, all objects in the visual field are processed independently and in parallel, but not equally fast. The filtering mechanism has the effect that objects belonging to a target category are favoured over objects belonging to another category by receiving higher attentional weights. For example, in a task where red letters are to be selected while green letters are to be ignored, the pertinence value of the perceptual category "red" would be higher than the pertinence value of the perceptual category "green". Therefore, the speed of perceptual processing and the identification probability of red letters would be higher than for green letters.

TVA is a mathematical model with strong relations to the biased competition model (Desimone, 1998; Desimone & Duncan, 1995). Coupled with two experimental tasks, whole and partial report, TVA can provide exact predictions for attentional performance. Both tasks model different components of visual attention: the general processing efficiency of the information processing system (visual processing speed and WM storage capacity), and attentional weighting (top-down-control and spatial distribution of attention).

The general efficiency is assessed by a whole report paradigm, in which subjects are asked to identify as many objects as possible out of a very briefly presented set of stimuli. An exponential growth function describes the relation between exposure duration and the subject's accuracy of report. The slope of the curve at its initial, steepest point is a measure of the processing rate (processing speed C, expressed in

numbers of elements processed per second). The asymptote of the curve indicates the maximum number of objects that can be consciously maintained in parallel in WM (parameter *K*). The function originates from a threshold value t_0, the time at which the processing race starts (visual objects begin to have an above-zero probability of being recognized) and beneath which nothing is perceived (see Figure 1).

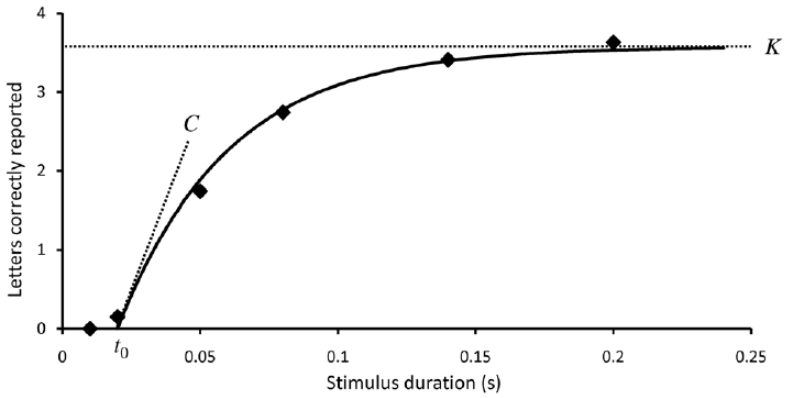


Figure 1: Typical performance in a whole report experiment
The mean number of correct reports (the score) is shown as a function of exposure time. Solid curves represent maximum likelihood fits to the observations based on TVA analysis. Three TVA parameters that can be derived from whole report data: perceptual threshold t_0, visual processing speed *C*, and storage capacity of visual WM memory *K* (taken from Habekost, 2015, p. 3).

Aspects of attentional weighting are estimated from a partial report task. In this task subjects have to identify pre-specified target objects (e.g., with respect to colour) and to ignore distractor objects. From the probability of target identification, attentional weights are derived for both targets (w_T) and distractors (w_D).The attentional weight of a target vs. a distractor object is a measure of the efficiency of top-down control of attention, defined as the ratio w_D/w_T (parameter α). Thus, an α value of 0 implies perfect selection, low α-values (close to zero) indicate high selectivity, while high α-values (close to one) indicate unselective processing. Averaging across targets and distractors, attentional weights of objects in different parts of the visual field (e.g., left vs. right) provide a measure of spatial attentional weighting (parameter w_{lat}), defined as the ratio $w_L/(w_L + w_R)$. Values of w_{lat} range from 0 to 1. Symmetrical attentional weighting (or balanced weighting to the left and to the right visual field) corresponds to a value of 0.5, while values of $w_{lat} > 0.5$ indicate a leftward, and values of $w_{lat} < 0.5$ a rightward spatial bias.

One of the most important strengths of TVA-based assessment is its method's high specificity, which allows for measuring five different components of visual attention separately. Another main strength of TVA-based assessment is that it abandons reaction time based measurement. This means that motor processes or confounds by motor dysfunction do not influence the performance significantly: the report is non-speeded and the accuracy of the report is the dependent variable. The method is also characterized by four central strengths: sensitivity to subtle attentional deficits, specificity, reliability and validity (Finke et al., 2005; Habekost et al., 2014; Habekost, 2015).

3.2. TVA-based assessment

The basic method of TVA-based assessment was introduced in a clinical study by Duncan et al. (1999), who used a whole and a partial report task in a patients sample suffering from neglect following stroke in the right hemisphere. In the whole report task, patients were presented a vertical column of five letters on either to the left or the right side of a central fixation point. Letters were exposed at three individually adapted exposure times (see Figure 2A). Subjects were asked to report as many letters as possible. Based on report accuracy, three separate TVA parameters were estimated: the perceptual threshold t_0, the WM storage capacity K as the number of items that are processed simultaneously, and processing speed C, which describes the identification rate in elements per second (as described in section 3.1.). In the partial report task, subjects were asked to maintain fixation before being presented with one or two letters (either one single target letter, or a target letter presented with a distractor letter or a target letter presented with a second target letter) on four possible equidistant positions round the fixation cross (see Figure 2B). Targets and distractors were defined by colour (targets: red letters, distractors: green letters). Exposure duration was constant and individually adapted, and all stimuli were post-masked. The task of the patients was to report the target letters only and to ignore the distractor letters. Two components of TVA were obtained by the partial report paradigm: top-down control, which describes the selection effectiveness of a target category relative to a distractor category (parameter α), and attentional weights as the index of attentional weighting attributed to particular item in the visual field (parameter w_{lat}; see also section 3.1.).

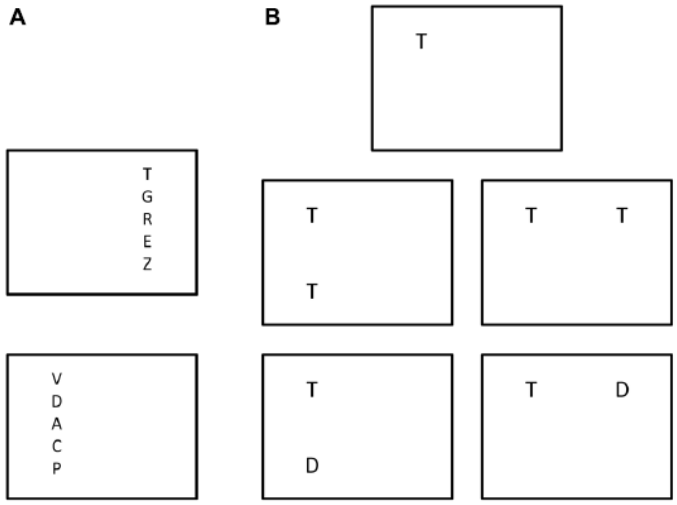


Figure 2: Basic method of TVA-based assessment introduced by Duncan et al. (1999)
(A) Different trial types of the whole report experiment. **(B)** Different trial types of the partial report experiment with targets (marked as "T") and distractors (marked as "D"; taken from Habekost, 2015, p. 3).

The experimental design developed by Duncan et al. (1999) has been used since in many clinical studies (e.g., Bublak et al., 2005; Bublak, Redel, & Finke, 2006; Redel et al., 2010; Finke et al., 2011, 2012) as well as with healthy subjects (e.g., Finke et al., 2005). The analysis of performance accuracy across the whole and the partial report paradigms was modeled by a TVA-based algorithm using a maximum likelihood method (see Kyllingsbæk, 2006). The same author provided a fitting program for automated analysis, which has been used in many TVA-based studies (e.g., Bublak et al., 2011; Redel et al., 2012).

3.3. Clinical TVA-based studies

TVA accounts for many empirical findings in the research of visual attention and has been widely applied to clinical studies of attention. The pioneering clinical TVA-based study was conducted by Duncan et al. (1999). Since that first publication, about 30 studies have used TVA-based assessment to investigate attentional deficits in various neurological and psychiatric conditions. Habekost (2015) presented an overview of these studies and regrouped them in four main research areas: (1) neglect and related conditions, (2) reading disturbances, (3) ageing and neurodegenerative diseases, and (4) neurodevelopmental disorders. These studies allowed insights of pre-

served and impaired attentional functions in various patient populations. Reductions in speed of processing have been found in different neuropsychological conditions, suggesting that parameter *C* is vulnerable to disturbance in many different brain regions (see Habekost, 2015). The anatomical network of the two main parameters of visual capacity, *C* and *K*, seem to depend on large and overlapping brain areas (including white matter connectivity), a lesion in each part can lead to impairments (see also Habekost & Rostrup, 2007; Bundesen & Habekost, 2014; Habekost, 2015, for a more detailed description). This could explain why brain damage rarely leads to impairments selectively in one of both parameters (Bundesen & Habekost, 2014).

In contrast to findings with deficits on *C* and *K* in various neurological and psychiatric samples, clinical findings on impairments on *α* have been relatively sparse and are limited to a few studies. It is expected that the efficiency of top-down control is more robust to many kinds of brain disturbances than the other TVA parameters (Habekost, 2015). A study of Peers et al. (2005) showed that lesion volume, but not lesion location, correlated with reduced *α* values in patients suffering from focal brain damage after stroke in the parietal and frontal lobe. Bublak et al. (2005) conducted a similar examination of the effects of focal brain damage after stroke in the frontal or parietal cortex. This study was based on two case investigations, where Bublak et al. disclosed a double dissociation of attentional impairments: A patient with inferior parietal damage showed a rightward spatial bias (parameter w_{lat}), and preserved top-down control (parameter *α*), while the other patient with a circumscribed damage in the superior frontal lobe showed the opposite pattern of impairment (deficit in parameter *α*, but not in parameter w_{lat}). Parameter w_{lat} is a measure of lateral attentional bias in visual perception and, clinically, a sensitive indicator of brain asymmetry (Habekost, 2015).

4. Study 1: Attentional deficits following TBI, evaluated with the whole report paradigm

4.1. Abstract

A whole report paradigm was used to quantify three different components of attention related to visual processing capacity: perceptual threshold, processing speed, and working memory (WM) storage capacity in patients with traumatic brain injury (TBI). The subjects sample was composed of 25 patients with mild TBI (mTBI), 23 patients with severe TBI (sTBI), and 24 matched healthy control subjects. Patient groups were assigned according to the Glasgow Coma Scale. Patients of the mTBI group presented intracranial lesions (termed complicated mTBI). Bundesen's theory of visual attention (TVA; Bundesen, 1990, 1998) served as a theoretical framework for the analysis of the results. Results indicated augmented perceptual thresholds, as well as impairment in processing speed and WM storage capacity in sTBI, while mTBI showed solely deficits in processing speed. WM storage capacity was associated with trauma severity. The probable importance of white matter connectivity on these impaired parameters is discussed.

4.2. Introduction

Traumatic brain injury (TBI) is defined as an insult to the brain that occurs by an external contact and/or mechanical forces such as acceleration and deceleration. TBI may result in either "focal" or "diffuse" injury or, as in many cases, a combination of both (Graham et al., 2000; Povlishock & Katz, 2005). As a result of heterogeneous neuropathology, TBI typically leads to various functional impairments, such as cognitive slowing and more specific functional deficits in the domains of memory and executive function (Bales et al., 2009; Lehtonen et al., 2005; O'Jile et al., 2006; Vakil, 2005; Zihl & Almeida, 2015), as well as in aspects of attention (Chan, 2000; Mangels et al., 2002; Leclercq et al., 2000; Rios, Perianez, & Munoz-Cespedes, 2004; Hart et al., 2006; Johansson, Berglund, & Rönnbäck, 2009).

However, there is limited agreement in respect to which functions in the domain of attention are effectively affected by TBI and how those are related to each other. It was repeatedly suggested that the disruption of core abilities might lead to below-average performances in other cognitive domains. For instance, McAllister et al.

(2004) claim that deficits in attention and other cognitive domains could be subsumed under the construct of WM. Others suggest a pervasive influence of reduced speed of information processing on attentional performance (e.g., Ponsford & Kinsella, 1992; Spikman, van Zomeren, & Deelman, 1996; Flemingham, Baguley, & Green, 2004; Dymowski et al., 2015). In line with this assumption, Willmott et al. (2009) found that reduced speed of processing does significantly contribute to impaired performance in diverse attention tasks, but not WM. Others claim however, that deficits in tasks assessing strategic control of attention persist after controlling for reduced speed of processing (Asloun et al., 2008; Serino et al., 2006).

Furthermore, the majority of studies focused on the consequences of either mild (mTBI; e.g. Frencham, Fox, & Mayberg, 2005) or severe TBI (sTBI; e.g. Flemingham, Baguley, & Green, 2004; Mathias & Wheaton, 2007; Fong, Chan, Ng, & Ng, 2009), while studies comparing mild and severe TBI are limited (e.g., Perlstein et al., 2004; Tombaugh et al., 2007). The study by Tombaugh et al. (2007) suggests that deficits on processing speed following TBI increase with severity of TBI and task difficulty. However, complex information processing interacts with high-order cognitive processes (Chiaravalloti et al., 2003). Thus, again, it is not clear whether additional processes might have contributed to low task performance.

Based on methodological differences between studies with respect to the tasks used, the relation between reduced speed of processing and other cognitive domains such as WM remain inconclusive. Conventional tests are hardly appropriate in investigating this subject, since all these cognitive functions typically interact with each other and their respective contribution to low task performance cannot be disentangled. Furthermore it is problematic that most established attention tasks require fast motor responses, i.e., that they use reaction time (RT) based measurements. Given that, due to the trauma mechanisms in falls or vehicle accidents, deficiencies in the motor system are frequently associated to TBI, these measures are confounded by motor speed changes.

The purpose of this study therefore was a systematic analysis of the attentional capacity parameters visual processing speed and visual WM storage capacity in patients with TBI using a paradigm that is appropriate to deliver distinct, independent measures of these functions and that is not confounded by motor speed impairments. Furthermore, a second aim of this investigation was to assess whether TBI severity is

related to potential decreases in visual processing speed and/or visual WM storage capacity.

Parametric measurements based on a theory of visual attention (TVA), proposed by Bundesen (1990, 1998), can identify precisely which attentional function(s) is or are affected following TBI in general and which of them might be differently affected by mTBI vs. sTBI. Combining TVA with a whole report paradigm of brief letter arrays allows the estimation of both, visual WM storage capacity and visual processing speed. Parametric values are mathematically independent, quantitative measures of attentional components. Therefore, the estimated WM storage capacity derived from whole report accuracy is controlled for the influence of speed of visual processing and vice versa. The tasks used require only nonspeeded vocal responses. The method was previously used in a patient population with severe motor problems, i.e., patients with Huntington's disease (Finke et al., 2006) and even in patients with advanced cognitive decline due to Alzheimer's disease (Bublak et al., 2011; Redel et al., 2012).

TVA assumes that objects in the visual field are processed in parallel and compete for being selected into a WM-store. In TVA, the entry into the WM-store corresponds to their conscious representation. The general information processing efficiency is assessed by the whole report task. The probability of identification is modelled by an exponential growth function. The slope of the curve at its steepest point is a measure of the processing rate (processing speed *C*, expressed in numbers of elements processed per second). The asymptote of the curve indicates the maximum number of objects that can be consciously maintained in parallel in WM (parameter *K*). The TVA model provides a third parameter, t_0, which represents the time at which the processing race starts and visual objects begin to have an above-zero probability of being recognized. A clinical study by Espeseth et al. (2014) suggests that t_0 might be associated with changes in white matter connectivity. Since disruptions of white matter fibre tracts can be a consequence of TBI, a further aim of this study was to explore a plausible impact of TBI on this parameter.

The purpose of the present study was to characterize the consequences of TBI on both speed of visual processing and visual WM storage capacity within the TVA framework, allowing a systematic and independent analysis of WM and processing speed, and to analyse whether these consequences differ between mTBI and sTBI patients. Participants with mTBI and sTBI were assessed with the TVA-based whole

report paradigm and the resulting attentional parameter values were compared between patient groups and to a healthy control group. Given the heterogeneous spectrum of pathology following TBI (focal or diffuse injury or the co-existence of both), it was hypothesized that TBI patients would demonstrate impaired visual processing speed and visual WM storage capacity, and that these impairments would be more pronounced in sTBI compared to mTBI patients. The present study is unique in that it utilized only one measure for assessing both attentional aspects independently within a theoretical framework across the spectrum of injury severity.

4.3. Materials and methods

4.3.1. Participants

The total study sample comprised 72 participants, 25 patients with mild TBI (the mTBI group), 23 patients with severe TBI (the sTBI group) and 24 matched healthy control subjects. Further biographical and detailed clinical information of each subject group is listed in Table 1. Patients were recruited at the Berufsgenossenschaftliche Unfallklinik (BGU), a specialized regional trauma facility located at Murnau, Germany. Parameter values for control participants were taken from the dataset of a previous study and matched according to age, gender, handedness, pre-morbid IQ and education. Written informed consent was obtained from all participants or their legal representatives. Selection criteria were: (1) normal or corrected-to-normal vision (e.g., no diplopic images), (2) no colour blindness (assessed with the Ishihara Colour Test, Ishihara, 1917), (3) age between 18 and 70 years, (4) absence of a psychiatric or neurological history (apart from TBI in the patients), and (5) fluency in German. In TBI patients, severity of TBI was classified according to their Glasgow Coma Scale score as follows (GCS; Teasdale & Jennett, 1974): severe (score < 9); moderate (score of 9-12); minor (score of 13-15). The GCS scores were collected from medical records.

Table 1: WR: Demographic information for both TBI groups and controls
sTBI and mTBI: severe TBI respectively mild TBI; *p*: level of significance; m: male; f: female; R/L: right- respectively left-hander; Age in years; Education in years; IQ: intelligence quotient; time since TBI (to the instant of testing) in weeks; GCS: Glasgow Coma Scale; M (SD): mean score and standard deviation. Significant differences are marked in bold.

	sTBI	**mTBI**	**Controls**	***p***
Gender (m/f)	18/5	24/1	19/5	.152
R/L	22/1	24/1	23/0	.609
Age, M (SD)	38.0 (13.9)	41.0 (13.6)	37.6 (10.6)	.597
Education, M (SD)	10.6 (1.4)	9.9 (1.1)	10.4 (1.1)	.263
IQ estimate, M (SD)	102.9 (15.1)	100.6 (10.7)	105.8 (6.9)	.280
Time since TBI, M (SD)	15.8 (15.6)	7.8 (8.3)		**.030**
GCS score, M (SD)	4.9 (2.3)	14.4 (0.8)		**.000**

Patients were assigned to the sTBI group if their GCS scores indicated that they had either moderate or severe impairment of consciousness in the acute stage of trauma (n = 21) and to the mTBI group if the score indicated a mild impairment (n = 23). Length of loss of consciousness and/or post-traumatic amnesia were used to assess acute brain injury severity when the GCS score was not available (n = 4). Information was acquired from medical record reviews or from patient interviews or family reports. Patients were assigned to the mTBI group when the length of loss of consciousness ranged between 0-30 minutes and/or post-traumatic amnesia was less or equal to 1 day (n = 2) and to the sTBI group when the length of loss of consciousness was longer than 24 hours and/or the post-traumatic amnesia lasted longer than 7 days (n = 2; cf. Malec et al., 2007). None of these patients meet the criteria for moderate TBI according to length of loss of consciousness (30 minutes to 24 hours) and/or post-traumatic amnesia (24 hours to 7 days).

Groups did not differ significantly from each other in gender, handedness (assessed by the Edinburgh Handedness Inventory; Oldfield, 1971), age, years of education, or crystallized IQ (assessed with the MWT-B; Lehrl et al., 1995). The mTBI group differed significantly from the sTBI group in terms of time since injury to testing and GCS score. The average GCS score of the sTBI indicates a severe impairment of consciousness in the acute state of TBI, while this was minor in the mTBI group. The difference in time since injury is related to the fact that, following sTBI, a longer period of recovery was necessary before patients were able to participate in a cognitive assessment. The fact that patients with mTBI can be tested much sooner after their injuries than patients with sTBI is in line with previous findings (e.g., Schretlen & Shapiro, 2003).

4.3.2. Initial lesion analysis in the mTBI group

Mild TBI patients presenting an intracranial lesion are termed complicated mTBI (e.g., Williams, Levin, & Eisenberg, 1990; Kashluba et al., 2008). Studies suggest that patients with complicated mTBI were at risk of worse outcomes (Miller, Murray, & Teasdale, 1990; Iverson et al., 2006, 2012; Lange et al., 2009). To check for this circumstance, an initial lesion analysis was conducted. According to this criterion, MRI and CT-scans of mTBI patients were retrospectively analysed by a neurosurgeon, who was blinded to the subject matter, to investigate if intracranial lesions were present in this group. This analysis revealed that all TBI patients in this sample presented intracranial abnormalities. More precisely, all mTBI patients but one suffered from intracranial bleeding (one presented a subdural haemorrhage).

4.3.3. Experimental procedure

Visual processing capacity was assessed with a whole report task, similar to that introduced by Duncan et al. (1999), and also used in previous studies (Bublak et al., 2005; Finke et al., 2005, 2006; Redel et al., 2011).

The patients were tested in hospital, and the control subjects in a university laboratory in a dimly lit room. Stimuli were presented on a 17'' VGA monitor (1,024 x 768 pixel screen resolution; 70 Hz refresh rate). Viewing distance was approximately 50 cm.

At each trial, a column of five equidistant letters was presented 2.5° of visual angle to the left or the right of fixation (see Figure 3). All letters were either red or green. Subjects were instructed to maintain fixation and, after the presentation of the letters, to verbally report all the letters they were fairly sure they had recognized. Letters could be reported in any order, and there was no emphasis on speed of report. The experimenter entered the reported letter(s) on the computer keyboard and initiated the next trial after the subject had indicated that it was ready. The experiment comprised two phases: in phase 1 (pre-test phase), three exposure durations were determined for phase 2 (the experimental session), in which the data were collected.

In phase 1, the three exposure durations were determined individually for each subject and then introduced into the experimental assessment phase. In the pre-test phase 24 masked trials (12 for each hemifield) were displayed, to ascertain whether a subject could report, on average, one letter per trial correctly (i.e., 20% report accuracy). The resulting “effective” exposure duration was then used as the intermediate exposure duration in the experimental session, together with a half as long (“short”

presentation time) and a twice as long (“long” presentation time) exposure duration. The resulting six “effective” exposure durations were expected to generate a broad range of performance, tracking the early and the late parts of the accuracy/exposure duration function. The “intermediate” presentation time was on average M = 137 ms (SD = 68.3) for healthy subjects, M = 171 ms (SD = 66.1) for mTBI subjects, and M = 191 ms (SD = 62.8) for sTBI subjects. Stimuli were presented in four blocks of 48 trials each. Within each block, all conditions were equally frequent.

The letters presented at each trial were either all red or all green and appeared at high contrast on a black background. For a given trial display, letters were randomly chosen from the alphabet excluding „C, D, G, I, O, Q, U, V", with a particular letter appearing only once. Letter size was 0.5° of visual angel in height and 0.4° in width. Half of the trails were masked. Masks consisted of letter-sized squares (of 0.5°) filled with a “+” and an “x” and presented for 500 ms at each letter location. The distance of the letter column from the vertical meridian was 2.5° of visual angle.

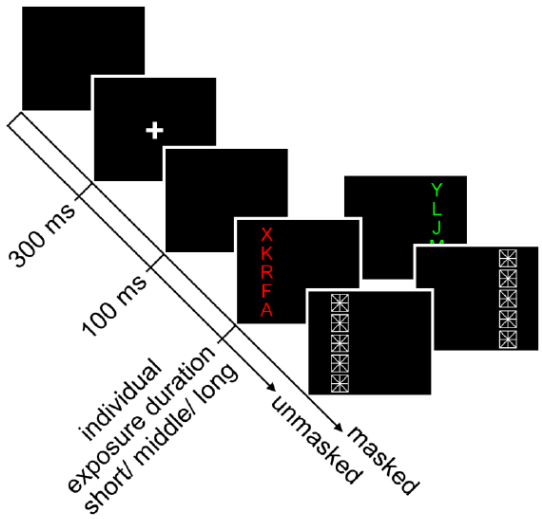


Figure 3: WR: Schematic illustration of the TVA-based whole report experiment
First, a central fixation cross is presented for 300 ms. Then, after a gap of 100 ms, the letter display is presented for a pre-determined exposure duration. 50% of trails were masked with white square masks at each previous letter position (taken from Redel, 2010, p. 40).

4.4. Results

4.4.1. Raw data

Figure 4 illustrates the qualitative pattern of performance for three representative subjects, one for each of the three groups.

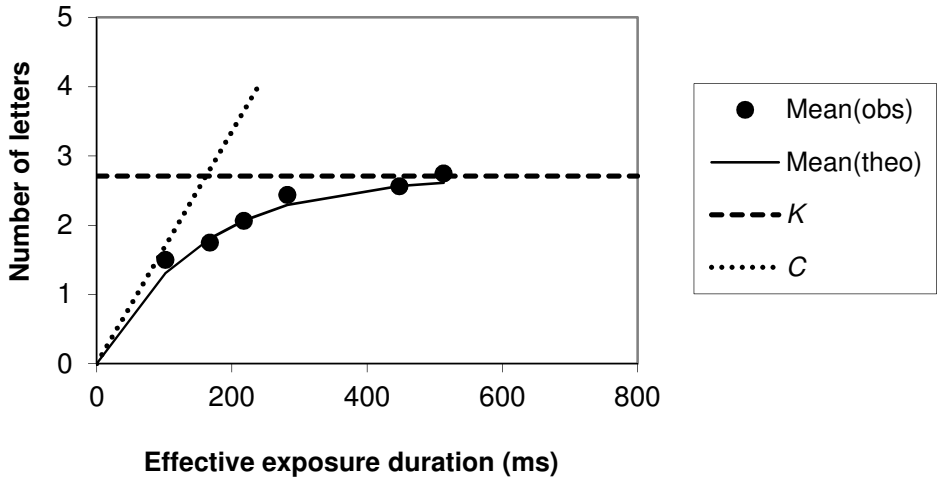
A

sTBI subject

GCS: 7

C = 16.76

K = 2.71



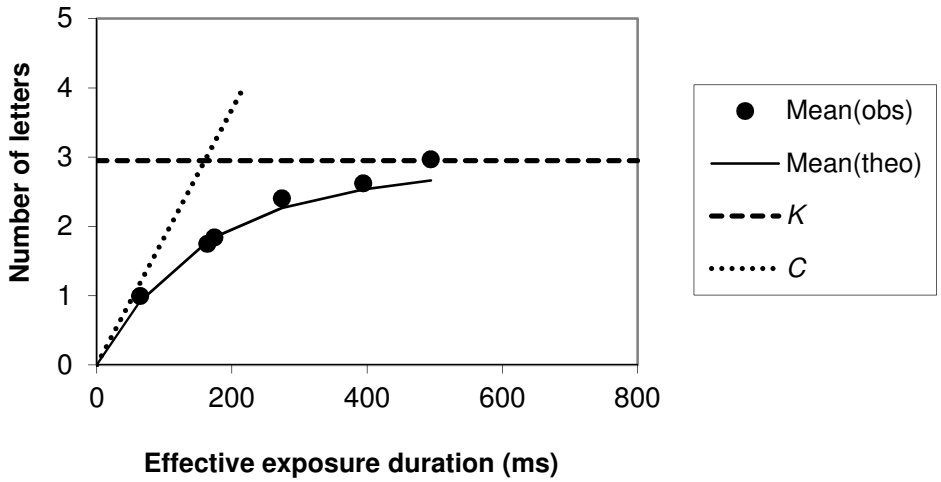
B

mTBI subject

GCS: 15

C = 18.45

K = 2.95



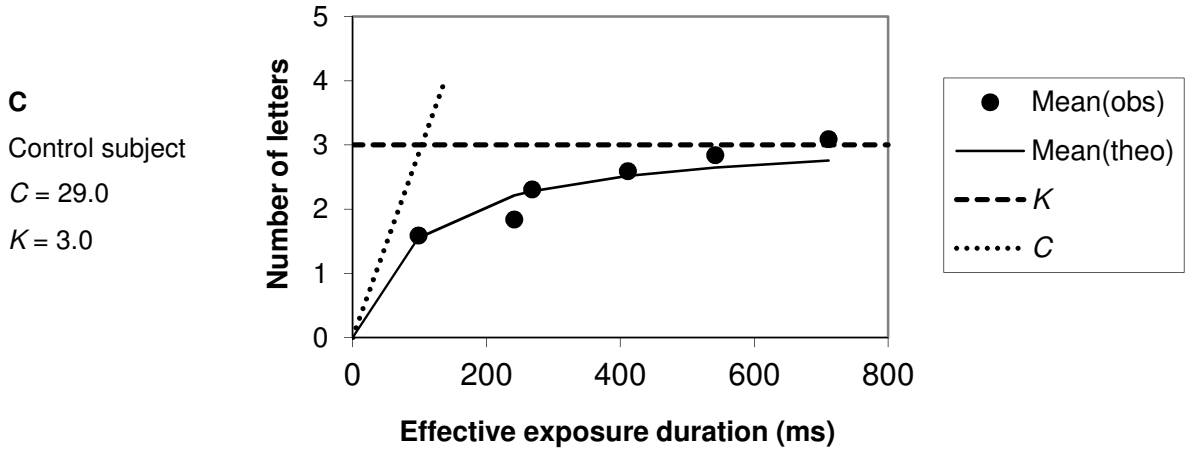


Figure 4: WR: Whole report performance of a representative subject for each group: One sTBI patient subject (A), one mTBI patient subject (B), and one healthy control subject (C)
The mean number of correctly reported letters is shown as a function of effective exposure duration. Solid curves represent the best fits of the TVA-based model to the observed values. The resulting estimates of WM storage capacity *K* are marked by a dashed horizontal line (asymptote of the curve), the estimates of visual perceptual processing speed *C* are shown as a dotted tilted line. Numerical values of these parameters, as well as the GCS score for both TBI patients are also provided.

In Figure 4, mean(theo) represents the theoretically derived function. The function illustrates the course of letter report accuracy with increasing effective exposure duration. In both TBI patients (subjects A and B) the slope of the function (dotted tilted line) at the point (0) is less steep compared to the healthy control subject (subject C), indicating a reduced speed of visual processing (parameter *C*). With increasing exposure duration (about a few hundred milliseconds) the curves of the mTBI patient (subject B) and of the control subject (subjects C) approach a comparable asymptotic level of about 3 reported letters (the dashed horizontal lines), indicating an equivalent WM storage capacity (parameter *K*). In contrast, the asymptotic level of the sTBI patient (subject A) is slightly lower than that of the subjects B and C, demonstrating an inferior WM storage capacity in sTBI.

4.4.2. Parameter estimates

TVA-based quantitative descriptions of the whole report data pattern were derived for each subject. The accuracy of letter report as a function of effective exposure duration was modelled by a TVA-based function representing the best fit of the raw data according to a maximum likelihood method (see e.g., Ross, 2000). Table 2 presents

the parameter estimates obtained for each subject. Overall, the scores predicted by the individual TVA models correlated highly, on average, with the observed scores across the task conditions. The average correlation between the observed values and the TVA best data fits was $r = .92$ (SD = .06) for the group of healthy control subjects, $r = .93$ (SD = .03) for the mTBI group, and $r = .94$ (SD = .03) for the sTBI group. The predicted values accounted for $r^2 = 84\%$ (SD = .10) of the variance of the observed mean score in controls, for $r^2 = 87\%$ (SD = 0.05) in mTBI patients, and $r^2 = 89\%$ (SD = 0.06) in sTBI patients.

Table 2: WR: Parameter estimates for the control subject group and both TBI patient groups
C: visual processing speed (elements/s); *K*: visual WM storage capacity (number of elements); SD: standard deviations of the estimates

	Parameter *K*			**Parameter *C***		
Participant	**Controls**	**mTBI**	**sTBI**	**Controls**	**mTBI**	**sTBI**
1	3.9	2.7	2.0	43	17	08
2	3.0	2.7	2.8	13	14	13
3	3.0	3.4	2.7	20	16	14
4	2.9	2.7	2.6	16	22	13
5	2.9	3.2	2.9	14	27	23
6	3.0	2.6	2.9	29	09	16
7	3.8	3.7	3.0	19	22	20
8	3.8	2.6	3.6	33	22	26
9	2.5	2.9	2.4	14	20	11
10	2.7	2.5	3.0	20	11	27
11	2.8	2.5	1.8	15	10	21
12	2.6	2.8	2.7	14	11	22
13	3.8	3.0	2.7	54	18	14
14	3.7	3.4	2.8	60	17	28
15	2.8	2.8	2.8	30	18	27
16	3.5	3.4	2.9	14	21	20
17	3.8	3.8	3.0	36	17	27
18	3.0	2.6	2.8	15	14	14
19	3.6	2.8	2.0	35	16	14
20	3.7	2.7	2.7	29	17	17
21	2.8	2.9	2.0	25	22	20
22	3.6	3.8	2.8	21	36	23
23	3.8	2.4	2.6	54	14	28
24	2.4	3.7		26	36	
25		3.7			21	
Mean (SD)	**3.2 (0.50)**	**3.0 (0.47)**	**2.7 (0.41)**	**27.1 (14.0)**	**18.8 (6.8)**	**19.3 (6.2)**

4.4.3. Data analyses

The Data were initially analysed for possible outliers ($z \geq 3.29$ or $z \leq -3.29$). Parameter estimates were tested for normal distribution using the Shapiro-Wilk test. Comparisons between groups (healthy control subjects, mTBI, and sTBI) were conducted by means of analyses of variance (ANOVA) and post hoc tests. A non-parametric analysis (Mann-Whitney *U*-test) was additionally piloted, when parameter values were not normally distributed. Pearson correlations were calculated (1-sided) between parameter estimates and severity of trauma according to GCS across both TBI groups.

4.4.4. Visual processing speed

An ANOVA of parameter *C* revealed a significant effect of group [$F(2, 69) = 5.58$, $p = 0.006$]. As depicted in Figure 5, post-hoc tests revealed that perceptual processing speed was impaired in both severe and mTBI patients compared to healthy control subjects. While both TBI groups were comparable to each other in processing speed (sTBI: M = 19.3 elements/sec, SD = 6.2; mTBI: M = 18.8 elements/sec, SD = 6.8, $p = .778$), control subjects were able to process a significantly larger number of items per second (M = 27.1 elements/ sec, SD = 14.0; $p = .022$ respectively $p = .011$). Since parameter *C* did not meet parametric assumptions for normal distribution (Shapiro-Wilk), significant group differences were confirmed non-parametrically using Mann-Whitney *U*-tests ($p = .026$ respectively $p = .023$, 1-tailed). The result showed no significant correlation between perceptual processing speed and trauma severity ($r = -.09$, $p = .28$).

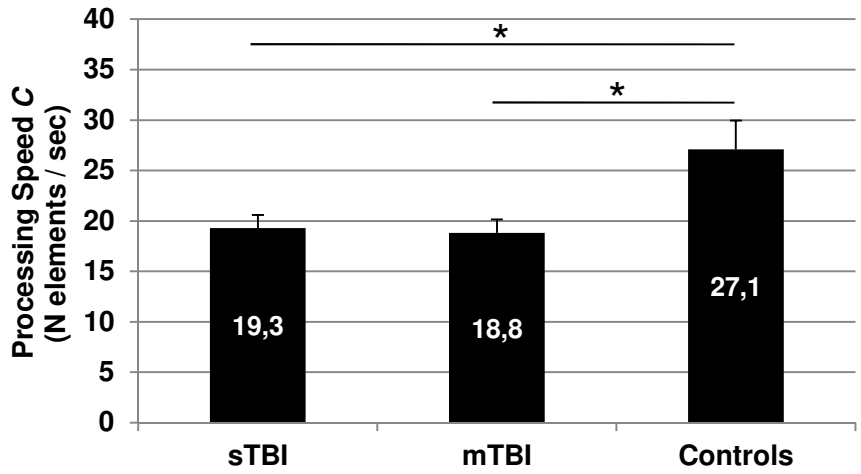


Figure 5: WR: Mean values of the estimated processing speed *C* for healthy controls, mTBI and sTBI subjects Error bars indicate the standard error of the mean.

4.4.5. WM storage capacity

An ANOVA of parameter *K* revealed a significant effect of group [$F(2, 69) = 8.68$, $p < 0.001$]. As depicted in Figure 6, sTBI subjects' WM storage capacity was significantly lower (M = 2.7 elements, SD = 0.4) than that of controls (M = 3.2 elements, SD = 0.5; $p < 0.001$). However, patients with mTBI did not differ significantly from healthy control subjects in terms of WM storage capacity ($p = .313$). The difference between mTBI (M = 3.0 elements, SD = 0.5) and sTBI patients was significant ($p = .039$). Parameter *K* did not meet parametric assumption for normal distribution (Shapiro-Wilk), subsequently significant group differences were reanalysed non-parametrically using Mann-Whitney *U*-tests. This analysis confirmed the difference between controls and sTBI patients ($p < .001$, 1-tailed). However, the difference between mTBI and sTBI patients did not reach significance non-parametrically ($p = .056$, 1-tailed). A significant correlation emerged between parameter *K* and the GCS score ($r = 0.32$, $p = 0.17$), indicating that a more severe trauma in the acute stage of brain injury as assessed by the GCS was related to a lower outcome in WM storage capacity in this sample.

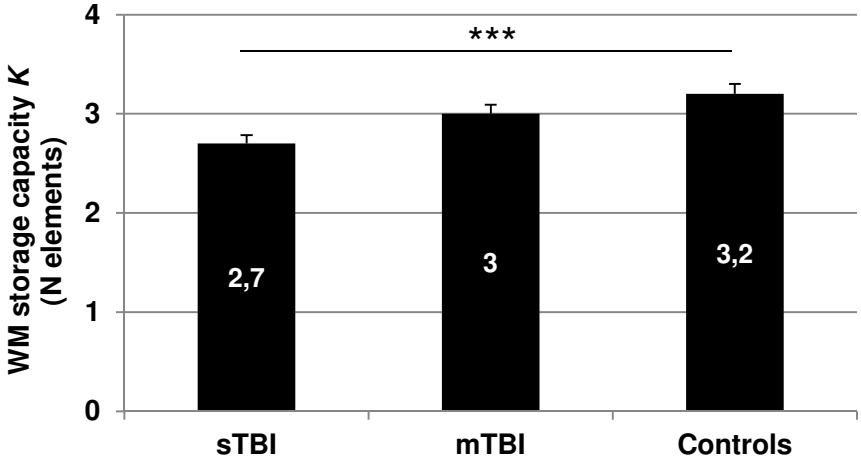


Figure 6: WR: Mean values of the estimated WM storage capacity *K* for healthy controls, mTBI and sTBI subjects
Error bars indicate the standard error of the mean.

4.4.6. Perceptual threshold

In an initial analysis, one outlier in t_0 in the mTBI group with $z > 3.29$ ($t_0 = 136.1$) was removed from the sample for further analysis. An ANOVA of parameter t_0 revealed a significant effect of group [$F(2, 68) = 3.58$, $p = 0.033$]. Figure 7 presents the group means for the threshold separately for each group. Post-hoc tests revealed that sub-

jects with sTBI displayed a significantly elevated threshold compared to healthy control subjects (M = 31.7 ms, SD = 36.1 respectively M = 12.9 ms, SD = 19.5; p = .042), while the difference between mTBI (M = 16.3 ms; SD = 17.5) and controls was non-significant (p = .526). The difference between both TBI groups was also not significant (p = .129). Again, this parameter did not meet parametric assumptions for normal distribution. A Mann-Whitney *U*-test confirmed the difference between healthy controls and sTBI patients (p = .01, 1-tailed). The result showed no significant correlation between t_0 and trauma severity (r = -.21, p = .09).

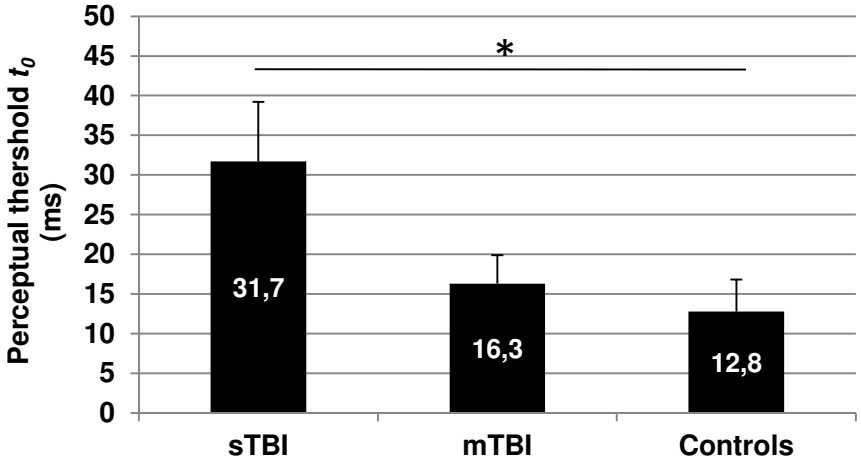


Figure 7: WR: Mean values of the estimated perceptual threshold t_0 for healthy controls, mTBI and sTBI subjects
Error bars indicate the standard error of the mean.

4.4.7. Parameter inter-correlation

A significant and substantial parameter inter-correlation was found between the WM storage capacity *K* and parameter visual processing speed *C* (r = 0.60, p < 0.001). Significant, albeit modest negative correlations were found between parameter t_0 and the two other parameters (r = -0.32, p = 0.006 for *C* and r = -0.30, p = 0.012 for *K*).

4.4.8. Medication

A minor amount of subjects of the TBI group were prescribed anticonvulsants [4% in mTBI (n = 1), and 8.7% in the sTBI (n = 2)] or narcotic analgesics [36% in mTBI (n = 9), and 17.4% in the sTBI (n = 4)]. There was no difference between TBI groups concerning medication with anticonvulsants (p = .601) or narcotic analgesics (p = .200). The significant effect of groups on speed of processing, WM storage capacity and

perceptual threshold remained significant when controlling for medications, which were entered as covariates into the model (all *p*'s < .041).

4.5. Discussion

The present study investigated visual processing capacity using a whole report paradigm based on Bundesen's TVA (1990, 1998) allowing the assessment of three independent psychophysical parameters. As a result of this systematic quantitative assessment, the following pattern of impairments in visual processing capacity post TBI was generated: patients suffering from a sTBI presented impaired attentional components in perceptual processing speed, WM storage capacity and perceptual threshold; in mTBI patients, processing speed was to a comparable level impaired as in sTBI patients, while storage capacity and perceptual threshold were both intact in this patient group. Investigations using conventional tasks that capture single attentional aspects cannot provide such a detailed pattern. Deficits post TBI in tasks that require fast information processing and/or holding and manipulating information temporarily in mind were already described in the literature. However, the present study delivers, to my knowledge, the first integrated parameter-based analysis displaying such a systematic pattern in TBI.

Contrary to the hypothesis there was not any indication that severity of TBI affects processing speed, as both TBI groups did not differ and as also the GCS score did not predict speed. This result suggests that any brain lesion altering functional connectivity can cause impairments in visual processing speed, irrespective of trauma severity as assessed with the GCS. All patients in the mTBI group presented an intracranial abnormality (all but one patient out of this group presented an intracranial bleeding), and would be therefore categorized as complicated mTBI according to a more morphological (as opposed to the clinical) scale. Generally, patients with mTBI complicated by an intracranial lesion have poorer outcomes than those with uncomplicated mTBI (Iverson et al., 2006, 2012; Borgaro et al., 2009; Lange et al., 2009). To my knowledge, this is the first study demonstrating that complicated mTBI and sTBI showed similar reductions in processing speed. Conversely, other authors showed that speed of information processing decreases with increasing severity of TBI in more complex reaction time tasks (e.g., Tombaugh et al., 2007). However, more complex tasks interact with a number of interrelated high-order cognitive processes (Chiaravalloti et al., 2003). Therefore, such tests are not specific to pro-

cessing in the visual system. Previous findings in the clinical TVA-based research show reductions on *C* across various neuropsychological conditions. This suggest that the parameter is vulnerable to disturbance in many different brain regions (Habekost & Starrfelt, 2009; Habekost, 2015), making the parameter a sensitive marker for the general processing efficiency of the brain. Some studies suggest an association between aspects of attention and axonal swelling or diffuse axonal injury (van Zomeran & Brouwer, 1994; Felmingham, Baguley, & Green, 2004), also in mTBI (Bazarian et al., 2007; Niogi, et al., 2008), while others find no such relationship (Ilvesmäki et al., 2014). However, a more precise analysis of lesion location was not conducted as no homogeneous lesion imaging was carried out in this sample. Future studies using, for instance, diffusion tractography might be supportive to clarify the nature of this alteration following complicated mTBI and sTBI.

WM storage capacity was impaired in sTBI, but not complicated mTBI, and parameter *K* was positively correlated to trauma severity, indicating that patients with low WM storage capacity suffer from more severe brain injuries, probably including focal mass lesions and/or diffuse axonal injury. WM impairments in sTBI patients were shown in previous research (Park et al., 1999; Leclercq et al., 2000; Perlstein et al., 2004). However, the tasks used in these studies possibly engage also other processes in addition to those considered central to WM such as difficulties coordinating higher cognitive demands or processing speed (cf. Perlstein et al., 2004). This study provides first evidence of impaired WM storage capacity in sTBI using an integrated parameter-based approach. Generally, WM is often associated with prefrontal cortex functions (Cohen et al., 1994; Braver et al., 1997) which are particularly susceptible to TBI (Wallesch et al., 2001a, 2001b). However, due to the multiplicity of cognitive disturbances that originate from frontal lobe damage, it is difficult to establish a relationship between neuropsychological performance on the one hand and frontal damage on the other in patients with TBI (e.g., Goldenberg et al., 1992; Lee et al., 2008; Di Paola et al., 2015). Findings on the clinical TVA-based literature indicate that WM storage capacity depends on large anatomical networks that involve many parts of the brain including white matter connections (Habekost & Rostrup, 2007; Habekost & Starrfelt, 2009; Finke et al., 2015; Habekost, 2015).

Parameter *C* and *K* correlated significantly in this sample, as already discussed in previous TVA-based studies (Finke et al., 2005; Habekost, 2015). This correlation may be explained by a shared neural basis, indicating that both functions depend on

largely overlapping networks of brain areas (Habekost & Starrfelt, 2009; Habekost, Petersen, & Vangkilde, 2013). There is also evidence for independence of both parameters, e.g. independent physiological correlates (Wiegand et al., 2013), distinct cueing effects (Matthias et al., 2010) and selectively impaired functions in clinical groups (Finke et al., 2015). Given that visual processing speed is not necessarily accompanied by impairment of WM storage capacity, the results support the assumption of theoretical independence of these parameters that is also suggested in the TVA. Thus, the brain networks involved might also differ to a certain degree. In this study, again, a more precise analysis of lesion location was not conducted as no homogeneous lesion imaging was carried out in this sample.

The visual threshold was also affected only in the sTBI group. Espeseth et al. (2014), found a significant relation between white matter mean diffusivity scores and t_0 values in elderly participants. As discussed by Habekost (2015), this result underlines the role of thalamo-cortical projections for visual attentional computations as presented by Bundesen et al. (2005). While brain imaging data is not available to support this assumption in the present sample, patients with high t_0 scores might be those that suffer from reduced connectivity in thalamo-cortical fibers.

A number of patients of this sample were on anticonvulsant or narcotic analgesic medication. However, there was not any evidence for an effect of medication on the three parameter estimates.

Of important significance is the finding that processing speed is impaired in both TBI groups, indicating specific intervention strategies for remediation of reduced processing speed following TBI. Another clinical aspect could be to investigate the effects of cognitive training on visual processing capacity as assessed with a TVA-based whole report in TBI patients. A number of prior TVA-based studies documented significant effects of cognitive or physiological interventions on TVA parameters in healthy participants such as for example video-game-based training (Schubert et al., 2015), transcranial magnetic stimulation (Hung et al., 2005, 2011), or pharmacological intervention (Finke et al., 2010; Vangkilde et al., 2012). Thus, a longitudinal study design could monitor the clinical effects of neuropsychological interventions in TBI patients. These results imply that such trainings should focus primarily on processing speed and, in patients with sTBI, on WM.

Nevertheless, a limitation has to be taken into account. A so-called complicated mTBI is not representative for mTBI patients as a whole. The reason for this selection bias

within this group might be due to the fact that more severely injured patients were presented for neuropsychological testing. More severely impaired TBI patients might differ from mTBI patients without intracranial lesion in their neuropsychological outcome such as shown, for example, by Borgaro et al. (2009). Thus, future studies should aim to clarify this issue by directly comparing complicated with uncomplicated mTBI through the use of the TVA-based whole report, whether the reduction of visual processing speed might be a general finding in mTBI, or in which respect both injury variants differ from each other.

In sum, the present study indicates slowed information processing after TBI, while sTBI patients display additionally impaired WM memory capacity. The present study delivers the first integrated parameter-based analysis displaying such a systematic pattern in TBI, using a whole report paradigm based on Bundesen's TVA (1990, 1998). These findings underscore the importance of the TVA-based methodology in clinical neuropsychological testing.

5. Study 2: Attentional deficits following TBI, evaluated with the partial report paradigm

5.1. Abstract

Through the use of a partial report task, visual selective attention was assessed in 23 patients with mild traumatic brain injury (mTBI), and 23 patients with severe TBI (sTBI). Patient groups were assigned according to the Glasgow Coma Scale (GCS). Based on Bundesen's theory of visual attention (TVA; 1990, 1998), two parameters were estimated out of the accuracy data of the task performance: top-down control of attentional selection (parameter α), representing task-related attentional weighting for prioritizing relevant visual stimuli, and spatial distribution of attentional weights across both hemifields (parameter w_{lat}). Compared to the task performance of 23 healthy matched control subjects, sTBI patients displayed significantly reduced efficiency of top-down control selection and a pathological imbalance of spatial attentional weighting across hemifields. The performance of mTBI patients was intact in these measures. Parameter α was correlated with the GCS score. On the basis of the literature on clinical TVA-based assessment, the impact of very large lesion types (e.g., contusions) on impaired top-down control as well as the role of an interhemispheric imbalance on the unbalanced attentional weighting in the sTBI group are discussed.

5.2. Introduction

Patients with traumatic brain injury (TBI) do not present an entirely consistent or uniform pattern of attentional deficits (Barlow-Ogden & Poynter, 2012). Reduced information processing and mental speed are frequently reported after TBI and are considered as more global and unspecific cognitive dysfunctions, frequently associated with diffuse axonal injury (Sturm, 2005; Zihl & Almeida, 2015). Additionally, TBI can result in more specific deficits in selective attention, or shifting of spatial attention (orienting function).

Selection is a fundamental process of visual attention. In order to shield the visual system from information overload, only a limited number of objects can be selected out of the multitude of stimuli being presented. Selection of objects may be controlled by the task set, that specifies which stimuli are relevant targets (e.g. red letters) and which to-be-ignored distractors (e.g. green letters); this is referred to as task-related,

or top-down controlled, selection. By contrast, visuospatial selection depends on the distribution of attention across the visual field (cf. Redel et al., 2012). Here attention may be equally distributed (e.g. healthy subjects) or biased towards one hemifield (e.g. neglect patients).

Visual search tasks have been used to examine task-related selection in TBI patients, showing that individuals with TBI require more time to search for target items when the target and distractor items have a high degree of feature overlap (e.g., Schmitter-Edgecombe & Robertson, 2015; Bate, Mathias, & Crawford, 2001a; Rasmussen et al., 2008). However, in these studies rather indirect measures of task-related selection were conducted. Therefore, an aim of this study was to analyse the individual efficiency of top-down controlled selection more directly.

Furthermore, impairments in visual search tasks might result from various underlying mechanisms, such as basic slowing in processing speed, deficits in top-down control or visuospatial attention deficits (Cremona-Meteyard & Geffen, 1994; Bate, Mathias, & Crawford, 2001a, 2001b; Flemingham, Baguley, & Green, 2004; Halterman et al., 2006; Pavlovskaya et al., 2007). For clinical neuropsychologists it is important to determine which aspects of attention are affected by TBI and what measures to use when assessing attention. However, these different components of visual attention cannot be disentangled based on the performance scores of conventional neuropsychological tests. The purpose of this study was to provide such disentanglement through the use of an integrated parameter-based approach for assessing selective visual attention.

The “attention network test” (ANT; Fan et al., 2002) is required to deliver a pattern of selection impairments. Results suggest that the orienting and executive components of attention are most susceptible to the effects of mild TBI (mTBI; van Donkelaar et al., 2005; Halterman et al., 2006; Catena et al., 2009). The ANT is however a reaction time (RT) based measurement. Deficiencies in the motor system are frequently associated with TBI (after falls or vehicle accidents). Therefore, a probable confounding with motor speed changes cannot be excluded. Furthermore, little is known about how top-down controlled and visuospatial selection varies with TBI severity, since investigations focus mainly on either severity levels or other aspects such as divided attention (e.g., Mangels et al., 2002). A study from Scheibel et al. (2009) found that the degree of neural activation in TBI patients as measured through fMRI during an attentional task (including aspects of orientation and executive functioning) is, in part,

mediated by TBI severity. Insights into the impact of severity of TBI on the degree of impairment of attentional aspects beyond clinical scales such as the Glasgow Coma Scale (GCS; Teasdale & Jennet, 1974) might contribute to a more specific selection of treatment programs. Therefore, a second objective of this investigation was to assess whether TBI severity is related to potential decreases in selective attentional functions through the use of a method that provides disentanglement between spatial and task-related attentional weighting.

A task that seems particularly well suited for investigating this issue is the partial report of briefly presented letters, based on Bundesen's formal theory of visual attention (TVA; 1990, 1998). TVA is a computational model that describes the effectiveness of processing by attentional weights, which were described by two parameters: the visual selectivity, α (task-related weighting: the ability to focus on targets rather than distractor objects) and spatial weighting, w_{lat} (the relative attentional weighting of stimuli in different parts of the visual field: e.g., left vs. right hemifield). From the accuracy of correct target identification, attentional weights are estimated for both hemifields (w_{left} and w_{right}). In TVA, the laterality index of attentional weighing w_{lat} is defined as the ratio w_{left} / (w_{left} + w_{right}). A value of w_{lat} = 0.5 indicates balanced weighting (w_{left} = w_{right}), values of $w_{lat} > 0.5$ indicate a leftward and values of $w_{lat} < 0.5$ a rightward spatial bias. Parameter α designates whether attentional weights for targets (T) are higher than for distractors (D). Alpha is defined as the ratio w_D / w_T. In unselective processing, the processing weight of targets and distractors would be equal (α = 1), prioritization of task-irrelevant distractors would give $\alpha > 1$, while $\alpha < 1$ indicates more efficient top-down control.

The model has been shown to possess the sensitivity and specificity necessary for studies in a wide range of neurological and pathological conditions, and also for patients with milder deficits (see Habekost, 2015 for an overview). For example, Redel et al. (2012) demonstrated in a sample of individuals with mild cognitive impairment significant deficits in both α and w_{lat} compared to control subjects. By individually adjusting the stimulus presentation times, comparable levels of task difficulty can be ensured across subjects. Furthermore, in contrast to a visual search paradigm, the partial report paradigm does not rely on RT-based assessment and thus eliminates a general slowing of motor performance as a potentially confounding factor.

A TVA-based partial report paradigm was considered to be appropriate for assessing and quantifying spatial and task-related aspects of attentional processing in TBI sub-

jects presenting different levels of severity (mild vs. severe). Employing this task, the present study was conducted in order to complement the TVA-based investigation of study 1, which did not assess selective weighting aspects. Patient's performance was compared to healthy matched control subjects. The study is novel in terms of use of a TVA-based partial report for examining the consequences of TBI on visual attention across TBI severity. It was hypothesized that TBI patients would demonstrate impaired task related and spatial weighting, and that these impairments would be more pronounced in sTBI compared to mTBI patients. In addition and complementary to the results of study 1, this study will help to establish quantitative profiles of distinct aspects of visual attention across the spectrum of severity post TBI.

5.3. Materials and methods

5.3.1. Participants

The total study sample comprised 69 participants, 23 patients with mild TBI (mTBI group), 23 patients with severe TBI (sTBI group), and 23 matched healthy control participants. Further biographical and detailed clinical information of each subject group is listed in Table 3. Patients were recruited at the Berufsgenossenschaftliche Unfallklinik (BGU), a specialized regional trauma facility located at Murnau, Germany. Parameter values for control participants were taken from the data set of a previous study and matched according to age, gender, handedness, pre-morbid IQ and education. Written informed consent was obtained from all participants or their legal representatives. Selection criteria were: (1) normal or corrected-to-normal vision (e.g., no diplopic images), (2) no colour blindness (assessed with the Ishihara Colour Test, Ishihara, 1917), (3) age between 18 and 70 years, (4) absence of a psychiatric or neurological history (apart from TBI in the patients), and (5) fluency in German. In TBI patients, severity of TBI was classified according to their Glasgow Coma Scale score (GCS; Teasdale & Jennett, 1974) as follows: severe (score < 9); moderate (score of 9-12); minor (score of 13-15). The GCS scores were collected from medical records.

Table 3: PR: Demographic information for TBI and control participants
sTBI and mTBI: severe respectively mild TBI; *p*: level of significance; m: male; f: female; R/L: right- respectively left-hander; Age in years; M (SD): mean score and standard deviation; Education in years; IQ: intelligence quotient; time since TBI (to the instant of testing) in weeks; GCS: Glasgow Coma Scale. Significant differences are marked in bold.

	sTBI	**mTBI**	**Controls**	***p***
Gender (m/f)	18/5	22/1	20/3	.216
R/L	21/2	22/1	22/0	.365
Age, M (SD)	39.1 (13.4)	42.2 (13.6)	38.7 (10.8)	.601
Education, M (SD)	10.4 (1.4)	9.8 (1.0)	10.3 (1.7)	.286
IQ estimate, M (SD)	103.1 (15.0)	101.0 (11.0)	104.7 (5.9)	.547
Time since TBI, M (SD)	17.7 (17.3)	7.8 (8.5)		**.017**
GCS score, M (SD)	4.9 (2.4)	14.4 (0.7)		**.000**

Patients were assigned to the sTBI group if their GCS score indicated that they had either moderate or severe impairment of consciousness (n = 20; 43%), and to the mTBI group if the GCS score indicated a mild impairment (n = 21; 46%). Length of loss of consciousness (LOC) and/or post-traumatic amnesia (PTA) were used to assess acute brain injury severity when GCS scores were not available (n = 5; 11%). Information was acquired from medical record reviews or from patient interviews. Patients were assigned to the mTBI group when LOC = 0-30 minutes and/or PTA ≤ 1 day (n = 2) and to the sTBI group when LOC > 24 hours and/or PTA > 7days (n = 3); cf. Malec et al., 2007). None of them met the criterion for moderate severity according to LOC (30 minutes to 24 hours) or PTA (24 hours to 7 days). Groups did not differ significantly from each other in gender, handedness (assessed by the Edinburgh Handedness Inventory; Oldfield, 1971), age, years of education, or crystallized IQ (assessed with the MWT-B; Lehrl et al., 1995). The mTBI group differed significantly from the sTBI group in terms of time since injury to testing and GCS score. The average GCS score of the sTBI group indicates a severe impairment of consciousness in the acute state of TBI, while this was minor in the mTBI group.

5.3.2. Experimental procedure

Visual selective attention was assessed by a partial report task, similar to those introduced by Duncan et al. (1999), and also used in previous studies (Bublak et al., 2005; Finke et al., 2005, 2006; Redel et al., 2010).

The patients were tested in hospital and the control subjects in a university laboratory in a dimly lit room. Stimuli were presented on a 17" VGA monitor (1,024 x 768 pixel screen resolution; 70 Hz refresh rate). Viewing distance was approximately 50 cm.

First, subjects were instructed to fixate a central white digit, (0.3° visual angle) presented for 300 ms. Then, after a time gap of 100 ms red and/or green letters (0.5° high x 0.4° wide) were presented on a black background for a brief predetermined exposure duration. The letters for a given trial were randomly chosen from the prespecified set (ABEFHJKLMNPRSTWXYZ), with the same letter appearing only once in a trial display. Each subject received the same displays in a random sequence. Stimuli were all masked. Masks consisted of squares of 0.5° filled with a "+" and an "x" presented for 500 ms at each stimulus location. In Figure 8, the sequence of events on an experimental trial is illustrated. The experimenter entered the reported letter(s) on the keyboard and started the next trial. The verbal report was performed in arbitrary order and without speed stressing. Subjects were instructed to report only those letters they had surely recognized.

In each trial, a single target (letter), or a target plus a distractor (letter), or two targets (see Figure 9) were presented at the corners of an imaginary square with an edge length of 5°, centered on the screen. Both stimuli were presented horizontally or vertically (but never diagonally). Subjects had to report only target letters.

A pre-test period was used to equate the baseline performance across participants. The pre-test phase presented 32 trials with masked single targets, to ascertain whether a subject could report the letter correctly with a probability of about 80% accuracy on single letter trials. In the experimental phase, the total number of trials was 288, divided into 6 blocks of 48 trials with equal frequency of conditions. To avoid anticipatory responses by the subjects, stimuli were displayed randomly at all possible positions in prespecified combinations and with respect to visual hemifield. All stimuli displays were presented for the individually adjusted exposure duration. A mean exposure duration of 175 ms (SD = 64.8) was used for sTBI patients, of 149 ms (SD = 52.6) for mTBI patients, and of 104 ms (SD = 42.1) for control subjects.

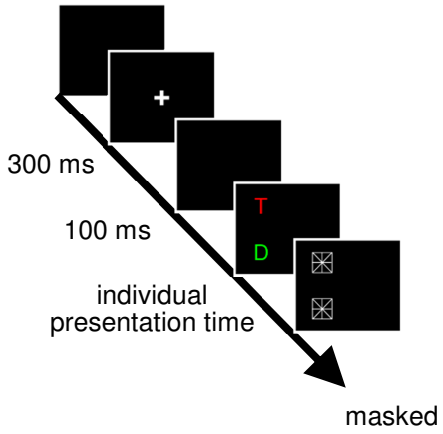


Figure 8: PR: Partial report paradigm (taken from Redel, 2010, p. 68)

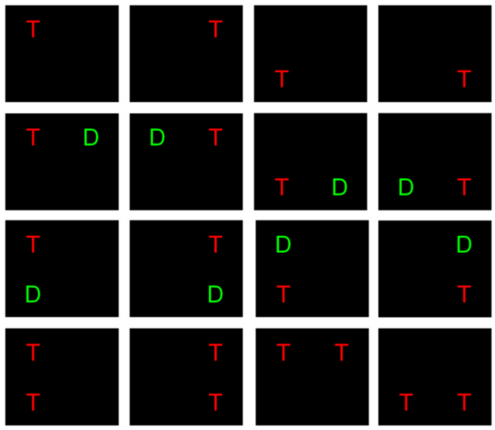


Figure 9: PR: Illustration of the partial report paradigm with 16 different trial types
Different trial types in the partial report paradigm with red targets letters (depicted as "T") and green distractor letters (depicted as "D"). Presentation of a single target (at the top), of a target accompanied by a distractor in the same or the opposite visual hemifield (left and right center) and of two targets in the same or in the opposite hemifield (taken from Redel, 2010, p. 68).

Each participant's accuracy in the partial report task was fitted by the computational TVA model (see Kyllingsbæk, 2006, for mathematical details of the model fitting procedure). This produces estimates of attentional weights assigned to targets or, respectively, distractors at each of the four display locations used in the experiment. Based on these eight weight estimates, for each participant, two parameters were estimated: spatial distribution of attention (parameter w_{lat}), and efficiency of top-down control (parameter α).

5.4. Results

In this section, the results for task-related and for spatial weighting are presented. The qualitative pattern of performance produced by the three groups in the partial report task is described and the degree of correspondence between the observed data and those predicted by the TVA model-based parameter estimates is reported. Figure 10 shows the mean accuracy scores for both patient groups and control subjects in each condition, for each hemifield, separately for the five experimental conditions: single target letter; target accompanied by a distractor in the same or the oppo-

site hemifield; and target accompanied by a second target in the same or in the opposite hemifield. The performance pattern found in control subjects resembles that of earlier reports (Duncan et al., 1999; Habekost & Bundesen, 2003; Finke et al., 2005, 2006) and was in accordance to the prediction from the TVA model: commonly, there were only minor differences between both hemifields. In general, accuracy was highest when only a single target was presented, decreased in target plus distractor conditions and was lowest in conditions with a second target stimulus.

In the single target baseline condition, all three groups showed a comparable accuracy level [$F(2, 66) = 2.09$, $p = 0.132$] and, on average, reached the 80% accuracy criterion (controls: M = 81.78, SD = 7.41; mTBI patients: M = 80.89, SD = 5.14; sTBI patients: M = 84.79, SD = 7.20).

A visual comparison of performance for left- and right-sided targets indicates no visual field differences. In the single target condition, accuracy was comparable for both hemifields in all three groups. However, in the sTBI patient group, the accuracy in the target plus distractor condition approaches more that for the dual target than that for the single target condition, compared to controls, indicating more difficulties in differentiating targets from distractors. Thus, the sTBI patient group seems to attribute higher attentional weights to irrelevant distractors compared to controls. The mTBI group did not show such a pronounced accuracy decrement, indicating that distractors could be more efficiently ignored.

TVA model based estimates of attentional weights were determined for each participant that represented the best fit of their partial report performance. The quality of fit of the TVA model to the empirical data for each participant is indicated by the correlation between the observed position scores (the probability of reporting a letter at a given display position in a certain experimental condition) and those predicted by the TVA model. The mean scores for the different partial report conditions and those predicted based on the best fits of the TVA model parameters showed a high correspondence, with a mean correlation of $r = 0.78$ (SD = 0.19) for controls, of $r = 0.75$ (SD = 0.18) for mTBI patients and of $r = 0.81$ (SD = 0.17) for sTBI patients. The predicted values accounted for $r^2 = 64\%$ (SD = 0.25) of the variance of the observed mean score in controls, for $r^2 = 60\%$ (SD = 0.22) in mTBI patients and $r^2 = 69\%$ (SD = 0.24) in sTBI patients.

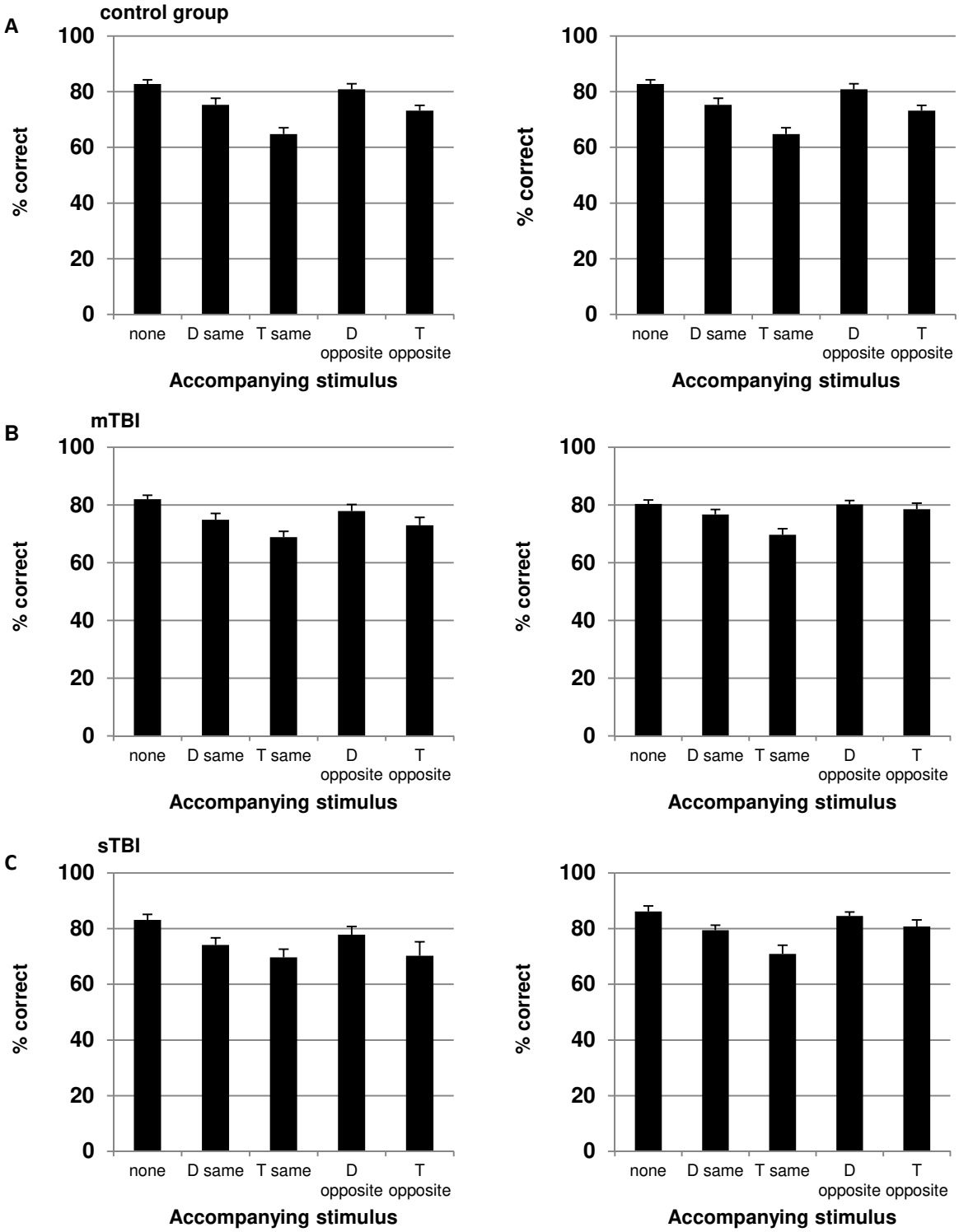


Figure 10: PR: Partial report results
Mean percentage of correctly reported targets presented either in the left or the right hemifield for the control group (A), the mTBI group (B), and the sTBI group (C). Each bar represents the mean in one condition: Target presented alone, target accompanied by a second target (T) in the same hemifield, target accompanied by a distractor (D) in the same hemifield, target accompanied by a distractor in the opposite hemifield, target accompanied by a second target in the opposite hemifield. Error bars represent the standard errors of the mean.

From the estimated attentional weights, parameter estimates were derived for the spatial distribution of attention w_{lat} and the efficiency of top-down control α. Parameter estimates and standard errors are presented in Table 4.

Table 4: PR: Parameter estimates for each participant: laterality index of attentional weighting (w_{lat}), efficiency of top-down control of attention (α)
Standard deviations of the estimates are given in parentheses.

	Parameter α			Parameter w_{lat}		
Participant	**Controls**	**mTBI**	**sTBI**	**Controls**	**mTBI**	**sTBI**
1	0.42	0.57	0.71	0.47	0.49	0.41
2	0.56	0.39	0.13	0.43	0.54	0.18
3	0.40	0.29	0.72	0.31	0.32	0.52
4	0.20	0.22	0.67	0.56	0.50	0.49
5	0.35	0.47	0.49	0.54	0.48	0.51
6	0.27	0.37	1.02	0.51	0.39	0.36
7	0.37	0.65	0.38	0.45	0.50	0.62
8	0.40	0.62	0.37	0.53	0.41	0.50
9	0.30	0.55	0.59	0.48	0.49	0.58
10	0.51	0.37	0.68	0.60	0.54	0.46
11	0.18	0.32	0.16	0.55	0.47	0.26
12	0.28	0.64	0.39	0.50	0.41	0.44
13	0.42	0.53	0.51	0.51	0.39	0.46
14	0.38	0.12	0.86	0.44	0.51	0.48
15	0.54	0.51	0.64	0.59	0.46	0.44
16	0.26	0.36	1.23	0.51	0.51	0.48
17	0.34	0.40	0.45	0.47	0.50	0.32
18	0.30	0.59	0.90	0.48	0.44	0.23
19	0.30	0.41	0.16	0.57	0.48	0.62
20	0.26	0.49	0.74	0.46	0.55	0.53
21	0.65	0.56	0.65	0.44	0.58	0.31
22	0.51	0.40	0.50	0.49	0.44	0.57
23	0.30	0.45	0.24	0.54	0.43	0.60
Mean (SD)	**.37 (.12)**	**.45 (.14)**	**.57 (.28)**	**.50 (.06)**	**.47 (.06)**	**.45 (.12)**

5.4.1. Data analyses

The data were initially analysed for possible outliers ($z \geq 3.29$ or $z \leq -3.29$). Parameter estimates were tested for normal distribution using the Shapiro-Wilk test. Comparisons between groups (healthy control subjects, mTBI, and sTBI) were conducted by means of analyses of variance (ANOVA) and post hoc tests. A non-parametric analysis (Mann-Whitney *U*-test) was additionally piloted, when parameter values were not normally distributed. Pearson correlations were calculated (1-sided) between parameter estimates and GCS scores across both TBI groups.

5.4.2. Efficiency of top-down control

In this section, the estimates of the parameter efficiency of top-down control *α* across subject groups were compared. An ANOVA of the *α* parameter revealed a highly significant effect of group [$F(2, 66) = 6.60$, $p = 0.002$]. As depicted in Figure 11, post-hoc tests revealed that top-down control was impaired in sTBI patients compared to healthy control subjects ($p = .002$). The difference between mTBI and sTBI patients showed a trend for a difference ($p = .087$). Top-down control values were not significantly different between the mTBI group and the control group ($p = .530$). Since parameter *α* did not meet parametric assumptions for normal distribution (Shapiro-Wilk), the group difference was confirmed non-parametrically ($p = .003$, 1-sided). Based on the range of *α*-values in healthy subjects, the 90th percentile was selected to indicate a pathological top-down control (parameter $\alpha > 0.55$) in patients. A total of 20 subjects (29%) met this criterion: 12 patients out of the sTBI group (52%), 6 patients out of the mTBI group (26%), and, to the smallest portion, 2 subjects out of the control group (9%). The correlation between parameter *α* and the GCS score was significant ($r = -.29$, $p = .04$).

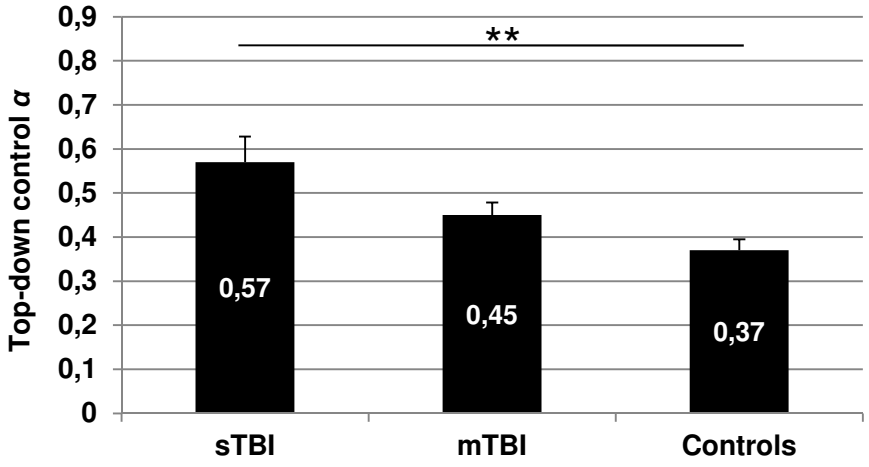


Figure 11: PR: Mean values of parameter top-down control *α* for healthy controls, sTBI and mTBI patients Error bars represent standard errors of the mean.

5.4.3. Spatial distribution of attention

An ANOVA of *w*-values showed no significant difference between groups [$F(2, 66) = 1.60$, $p = 0.209$], indicating no general left- or rightward bias in the patient groups. Besides, a spatial bias might be due to basic sensory effectiveness being reduced for one hemifield, leading to an imbalance in sensory processing between hemifields. To

test for pure sensory accuracy loss in either of the two hemifields (in contrast to true attentional stimulus processing), a laterality index for sensory effectiveness (A) was computed: lateralization of sensory effectiveness to the left visual hemifield is reflected by a value above 0.5 and lateralization of sensory effectiveness to the right is reflected by a value below 0.5.

Similarly, the index for the laterality of sensory effectiveness A did not differ significantly between subject groups (controls: A = 0.51, SD = 0.06; mTBI: A = 0.51, SD = 0.06; sTBI: A = 0.49, SD = 0.08) [$F(2, 66) = 0.54$, $p = 0.585$]. Neither the control group nor the patient group's index differed significantly from 0.5, which indicates equal sensory effectiveness on both sides (all p's > 0.488).

Completing this line of analysis, a possible attentional bias towards any of the two hemifields (in contrast to a more systematic bias towards one field across all patients) was tested by calculating an index of the subject's general ability to attend equivalently to both hemifields [Dev(w_{lat}), see also Finke et al., 2005]. A significant group effect was found for the imbalance index (controls: Dev(w_{lat}) = 0.05, SD = 0.04; mTBI: Dev(w_{lat}) = 0.05, SD = 0.05; sTBI: Dev(w_{lat}) = 0.10, SD = 0.09) [$F(2, 66) = 4.66$, $p = 0.013$]. As shown in Figure 12, post-hoc comparisons revealed significant differences between control subjects and sTBI ($p = 0.027$) as well as between sTBI and mTBI patients ($p = 0.035$). Severe TBI patients presented a more general inability to distribute attention across both hemifields, with a preference to the left or right, instead of an imbalance towards one specific hemifield. The group differences were confirmed non-parametrically (both $p = .003$, 1-sided).

Again, based on the range of Dev(w_{lat}) in healthy subjects, the 90th percentile was selected to indicate a pathological spatial imbalance [Dev$(w_{lat}) > 0.096$] in patients (cf. Redel et al., 2012): out of the control group, 2 subjects met this criterion (9%; one left, one right), three mTBI (13%; three left) and nine sTBI patients (39%; six left, three right) presented a pathological imbalance of attention.

The pathological imbalance index of spatial attentional weighting Dev(w_{lat}) was not correlated to the GCS score ($r = -20$, $p = .11$).

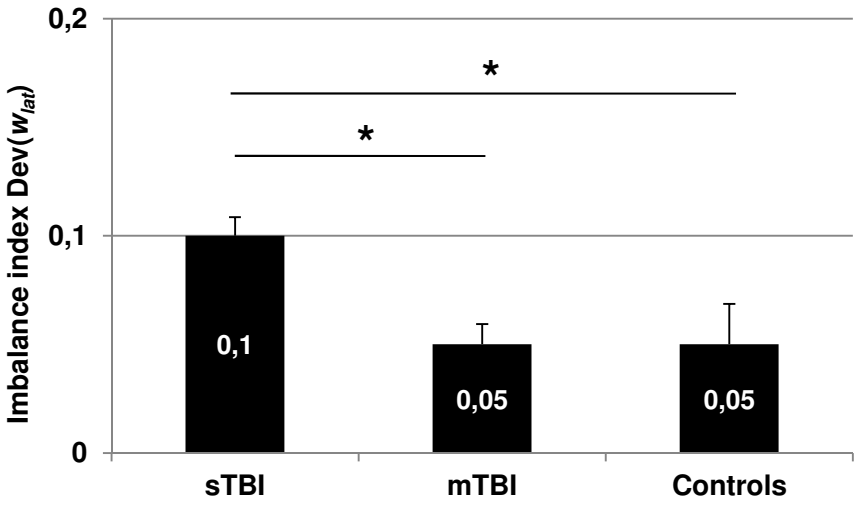


Figure 12: PR: Mean values of the imbalance index of attentional weighting Dev(w_{lat}) for healthy controls, sTBI and mTBI patients
Error bars represent standard errors of the mean.

5.4.4. Parameter inter-correlation

No significant parameter inter-correlation was found between the imbalance index of attentional weighting Dev(w_{lat}) and parameter top-down control α (p = 0.58). These results indicate that partial report parameters are independent of each other in this sample.

5.5. Discussion

In this study a partial report task based on Bundesen's theory of visual attention (TVA; 1990, 1998) was employed to evaluate the effect of mTBI and sTBI on two components of visual attentional weighting. From the qualitative performance pattern of the partial report, two independent quantitative parameters were estimated: spatial distribution of attention (parameter w_{lat}), and task-related efficiency of top-down control (parameter α), representing the amount of attentional weight allocated to distractors in comparison to targets. Patients after sTBI were impaired in both attentional components, while mTBI patients' task performance seemed to be normal compared to healthy controls. These results indicate that both attentional functions were relatively robust to mTBI, and, respectively, more vulnerable to severe injury. This was also confirmed by the fact that the parameter top-down control α was correlated with severity of trauma (as assessed with the Glasgow Coma Scale; GCS). However, it should be pointed out that at least a quarter of the mTBI group presented a patholog-

ical top-down control compared to control subjects (it was twice the amount in the sTBI group). The sTBI patients of this sample did not display a systematic spatial bias towards one specific hemifield (e.g., left or right). However, their significantly enhanced deviation from an optimal balance towards both sides of space indicated that sTBI patients showed a general inability to attend equivalently to both spatial hemifields. Dev(w_{lat}) was not associated with the GCS. In line with the theoretical assumptions of the TVA grounding, Dev(w_{lat}) and α were not correlated in this sample which indicates distinct underlying neuropathological mechanisms (cf. also Redel et al., 2012).

A number of previous studies had already reported impairments in spatial orientation and/or executive control in TBI using RT-based measurements (e.g., van Donkelaar et al., 2005; Halterman et al., 2006; Pavlovskaya et al., 2007; Catena et al., 2009). However, thus far and to my knowledge, no integrated parameter-based analysis examining both spatial and task-related aspects of visual attentional weighting across the TBI severity spectrum (mild vs. severe) was carried out. Since the partial report paradigm requires nonspeeded verbal responses rather than RT measures and parameters are derived from raw data accuracy measurement of correctly reported letters, interpretation of both parameter values is legitimate even if e.g. slowing of mental processing speed was a symptom of a patient (see study 1, chapter 4; cf. Redel, 2010). Interestingly, compared to the other TVA parameters such as processing speed or working memory storage capacity (assessed with a whole report paradigm, see chapter 3 and 4), clinical findings on α deficits have been surprisingly sparse and are limited to a few studies (see review by Habekost, 2015; Bublak et al., 2005; Peers et al., 2005; Redel et al., 2012). Habekost (2015) suggested the probability of the top-down selectivity in visual attention to be simply more robust to many kinds of brain disturbances than the other TVA parameters. Previous findings in clinical TVA-based assessment indicate that top-down control α is vulnerable to very large lesions (Peers et al., 2005) or damage to the superior frontal lobe after stroke (Bublak et al., 2005). A study by Redel et al. (2012) also showed reduced top-down controlled selection in patients with amnestic mild cognitive impairment, which was further deteriorated in Alzheimer's disease patients. Redel et al. (2012) discussed that impaired top-down control may be linked to an early dysfunction of fronto-parietal networks. Other studies suggest the importance of the anterior cingulate cortex for ignoring distracting stimuli (e.g., Casey et al., 2000; Fan et al., 2003). The fact that top-down

control *α* was affected in patients with sTBI thus probably indicates that these patients suffer from large lesions (e.g., large contusions) and/or diffusely distributed pathology (e.g., diffuse axonal injury) and that regions such as the superior frontal lobe and/or the anterior cingulate cortex might be involved. However, these conclusions remain speculative as a lesion analysis was not conducted in this sample.

Accuracy asymmetries in bilateral presentation conditions, as presented in the sTBI group, are most directly associated with visual extinction which is characterized by difficulty in the conscious perception of a contralesional stimulus when presented simultaneously with an ipsilesional stimulus. Under bilateral stimuli presentation, the contralesional stimulus is apparently ignored or distinguished (Bender, 1952). Extinction is associated with unilateral brain damage, characteristically in the parietal lobe (Vallar et al., 1994). Several studies discussed the importance of the right posterior middle temporal gyrus (Chechlacz et al., 2013; Meister et al., 2006) or the superior temporal gyrus (Karnath, Ferber, & Himmelbach, 2001) in relation to impaired bilateral processing and extinction behaviour. Recently, Beume et al. (2015) hypothesized that processing of bilateral stimuli cannot be attributed to one single cortical region, but rather depends on the functional resources of the entire visuospatial attention network. Using the same partial report paradigm, a pathological deviation of spatial attention was also obtained in patients with mild cognitive impairment and, more so, in Alzheimer's disease patients (Redel et al., 2012). Redel et al. claimed that an early temporo-parietal interhemispheric asymmetry might cause a pathological spatial bias. It is therefore feasible that in this sTBI patient sample, the pathological spatial bias might result from an underlying interhemispheric imbalance in temporo-parietal cortical interactions. Results of Peers et al. (2005) also support this assumption, as they showed that patients with parietal lobe lesions demonstrated a lateral spatial bias, which was associated with lesion volume.

Concerning the impact of severity the results showed, in sum, that only sTBI affects aspects of attentional weighting and that both, task-related and spatial weighting seem to be preserved in mTBI. Conversely, these results differ from results showing that the orienting and executive components of attention are most susceptible to the effects of mTBI (van Donkelaar et al., 2005; Halterman et al., 2006; Catena et al., 2009; Howell et al., 2013). This inconsistency might be due to possible differences in the neuropathology or to the different time of testing. One limitation of this study is that the point in time of testing with respect to that of injury was not standardized

across groups. In the current study, the mTBI patients' testing on average took place up to eight weeks post injury, therefore extending the amount of potential initial recovery from injury, and sTBI patients were tested at a later stage. Thus, we do not know whether those patients in the mTBI group, who showed performance outside the norm group's distribution, would have shown normal performance when tested later on, at a time point more comparable to that of the sTBI group.

In conclusion, both task-related selection and spatial distribution of attention are impaired in sTBI patients in this sample. Such impairments indicate large lesions and/or distributed pathology probably involving the fronto-parietal attention network as well as a disruption of the interhemispheric balance in cortical interactions.

6. Study 3: Relationship between TVA parameters and conventional neuropsychological tests in a TBI population

6.1. Abstract

In combination with Bundesen's theory of visual attention (1990, 1998), the whole and the partial report of briefly displayed letter arrays provide the estimation of psychophysical parameters related to the visual capacity and the attentional weighting of a given participant: visual perceptual threshold, visual processing speed, visual working memory storage capacity, spatial distribution of attention, and top-down control. Two previous studies of this dissertation (study 1 and 2, see chapter 4 and 5) have already demonstrated that patients with traumatic brain injury (TBI) show a decline in all of these parameters. The aim of the present study was to examine whether these parameters are related to other clinical measures in a TBI population, as demonstrated in a study by Finke et al. (2005) in healthy subjects. In a sample of 51 TBI patients (27 patients with mild and 24 patients with severe TBI, as assessed with the Glasgow Coma Scale), the correlation matrix showed correlations that were comparable to those obtained by Finke et al. (2005) for some measures. However, also unexpected associations between TVA parameters and conventional neuropsychological tests were found, indicating that the correlation pattern change in clinical groups when actual deficits are present. These results are discussed in respect to the potential mechanisms leading to these changes in a group of TBI patients.

6.2. Introduction

In combination with the theory of visual attention (TVA; Bundesen, 1990, 1998) the assessment tools whole and partial report were used in a number of studies investigating attentional deficits in neurological and psychiatric patient groups (see review from Habekost, 2015). Despite this high research interest in clinical TVA-based assessment, analyses of the relation between TVA parameters, and other clinical measures are limited to a small number of studies (Habekost, 2015). Habekost et al. (2014) conducted a comparison between the "attention network test" (Fan et al., 2002) and TVA parameters and found that correspondences between the measures of both tests were generally small and non-significant. Finke et al. (2005) found in 35 young healthy participants significant correlations between TVA parameters and es-

tablished clinical tests measuring similar constructs. More precisely, Finke et al. (2005) found a significant negative correlation between processing speed (*C*) and the simple response time of the "Alertness" task in the TAP battery (Zimmermann & Fimm, 1993) and a moderately significant correlation between working memory (WM) storage capacity (*K*) and the backward version of the Visual Memory Span from the WMS-R battery (Härting et al., 2000). The performance on a Stroop task (FWIT; Bäumler, 1985) was moderately correlated with top-down control efficiency (α), and highly significant negative correlations were found for the attentional weighting Dev(w_{lat}) with regard to both speed and accuracy performance in the visual scanning test from the TAP battery (Zimmermann & Fimm, 1993). Comparable significant relationships were not found with measures that are not assumed to be related to the TVA parameters. Thus, it was concluded that the TVA parameters obtain sufficient clinical validity.

An open question that remains despite these results is whether the TVA parameters are also related to clinical established tests in patient groups who actually suffer from attentional impairments. The studies 1 and 2 (see chapter 4 and 5, pp. 24 et seqq. respectively pp. 41 et seqq.) of this dissertation have shown that mTBI and sTBI lead to impairments in TVA parameters attentional functions. More specifically, perceptual processing speed (*C*) was impaired in both the mild (mTBI) and the severe TBI (sTBI) patient group compared to matched healthy control subjects. Furthermore, only sTBI patients additionally showed deficits in WM storage capacity (*K*), top-down control efficiency (α), and attentional weighting Dev(w_{lat}).

Therefore, the purpose of this study was to examine if and how the TVA parameters are related to conventional neuropsychological tests that address the same attentional aspects in a TBI sample. For this, the same neuropsychological tests were applied as in the study by Finke et al. (2005). The study focussed on whether significant comparable correlations between TVA-parameters and those neuropsychological measures that are assumed to measure equivalent constructs could be found. Furthermore, given that the mTBI and sTBI group differed significantly in Dev(w_{lat}) in study 2 but not in the other parameters (see study 1 and 2), a significant group difference was expected exclusively for the visual scanning test from the TAP battery addressing the same attentional component as Dev(w_{lat}).

6.3. Materials and methods

6.3.1. Participants and TVA-based assessment

The total study sample comprised 51 subjects, who participated in study 1 and 2 (for details on exclusion and diagnostic criteria, see chapter 4.3.1. and 5.3.1., pp. 27 et seq. respectively pp. 44 et seq.), resulting in 27 patients with mild (mTBI group) and 24 patients with severe TBI (sTBI group). Both TBI groups did not differ significantly from each other in gender, handedness, age, years of education, or crystallized IQ (all *p*'s > .088). The experimental procedure, stimuli and apparatus of the whole and partial report assessment were identical as described in study 1 and 2 (see chapter 4.3.3. and 5.3.2., pp. 29 et seq. respectively pp. 45 et seqq.).

6.3.2. Clinical neuropsychological tests

Four standard neuropsychological tests were selected to address the same attentional aspects as the four TVA parameters.

Processing speed. A simple response time task, the subtest "Alertness" from the TAP (Zimmermann & Fimm, 1993), was used to assess processing speed. This computerized task, requiring a speeded response to a visual stimulus, with or without a preceding warning signal, is assumed to measure tonic and phasic alertness.

Working memory storage capacity. The "Visual Memory Span" from the WMS-R (Härting et al., 2000) was used to measure WM storage capacity. The examiner points at a sequence of 2-8 blocks on a board. The subject is required to repeat the sequences, either forwards or backwards, depending on the test condition. The dependent variable was the number of correct sequences.

Spatial distribution of attention. The "Visual Scanning" TAP-subtest was used as a measure of spatial attentional bias. The subjects' tasks is to indicate by button press, whether a target "square" with a gap in the upper edge is present among a grid of "square" elements. In order to assess scanning performance across the whole display only target absent trials (50%) were considered. Speed (median response time) and accuracy (number of errors) were measured. The test is assumed to assess the ability of line-by-line scanning, which requires shifting attention from the left to the right and back. Any bias was assumed to interfere with shifting and become manifest in slower and more error-prone performance.

Top-down-control. A German Stroop task (FWIT; Bäumler, 1985) was used to assess top-down control. The test consists of three conditions: colour-word reading, colour-bar naming, and interference. The latter, in which the subject has to name the ink colours of incongruent colour words by suppressing the highly automatized reading of the words, is assumed to measure susceptibility to interference. Since the top-down control parameter α is also assumed to measure resistance to interference, it was assumed that low values of TVA α estimates would be related to higher speed in the interference condition. Since TBI patients presented a reduced visual processing speed in study 1 (see chapter 4, pp. 24 et seqq.), the naming speed corrected selectivity index (SEL) was used as a speed-corrected measure for concentrative resistance. SEL scores < 0 indicate longer reaction times (RT), and SEL scores > 0 shorter RTs than expected based on the naming speed.

6.4. Results

The TVA parameter estimates derived from the whole report, perceptual threshold t_0, processing speed C and WM storage capacity K, were the same as presented in study 1 (see chapter 4.4., pp. 31 et seqq.). Likewise, the partial report parameter estimates, top-down control α, and the spatial distribution of attentional weighting w_{lat} were as described in the second study (see chapter 5.4., pp. 47 et seqq.). Forty-three subjects (84.3%) completed both TVA tasks (in three patients from the mTBI group, the partial report task was not performed since the Ishihara test showed positive results, indicating colour-blindness).

6.4.1. Neuropsychological test results

The number of subjects within a group can be smaller than written in section 6.3.1., because of missing data for some patients in the neuropsychological tests: In two patients (3.9%), the Visual Memory Span Task was not performed (both from the mTBI group). Four patients out of the mTBI group (14.8%) and three patients out of the sTBI group (12.5%) did not perform the “Visual Scanning” task. In three patients from the mTBI group (7.8%) the Stroop test was not performed since the Ishihara test indicated colour blindness. One patient from the sTBI group (4.2%) missed to perform the Stroop test.

Table 5 shows the results of the standard neuropsychological tests for both TBI-groups. In an initial analysis, two outliers (+/- 3 standard deviations) were removed

for further analysis: one patient out of the sTBI group presented a highly elevated processing time in the interference condition of the Stroop test (183 ms) and one patient out of the mTBI group had an excessive scanning time (12455 ms). In line with the hypothesis, a t-test for independent samples revealed that subjects in the sTBI group displayed a significantly elevated visual scanning time compared to the mTBI group (p = .041, 1-tailed; Cohen's d = -.55). For the other neuropsychological test-scores, no significant differences between both TBI groups emerged (all p's > .161, 2-tailed).

Table 5: TVA+NP: Mean standard neuropsychological test scores for both TBI groups
sTBI and mTBI: severe and mild TBI; *p*: level of significance; SRT: simple response time in the TAP; Mdn without: Median response time without preceding auditory warning signal; Mdn with: Median response time with preceding auditory warning signal; VMS: subtest "Visual Memory Span" of the WMS-R; pts.: points; VS: subtest "Visual Scanning" of the TAP; T: response time; FWIT: processing time in the Stroop Colour-Word Interference Test. Standard deviations of the estimates are given in parentheses, and the comparisons between means. Significant differences are marked in bold.

		sTBI	**mTBI**	***p***
Neuropsychological test scores				
SRT	Mdn without (ms)	263 (39)	246 (48)	.161
	Mdn with (ms)	259 (50)	242 (44)	.157
VMS	Forwards (pts.)	7.8 (1.7)	8.5 (1.6)	.158
	Backwards (pts.)	7.7 (1.8)	8.0 (1.7)	.507
VS	(target absent) T (ms)	6287 (1799)	5436 (1243)	**.041***
FWIT	Colour-word reading (s)	38.70 (10.00)	36.08 (7.14)	.306
	Colour-bar naming (s)	54.65 (13.94)	51.38 (11.57)	.384
	Interference condition (s)	82.00 (24.40)	78.54 (16.55)	.574
	Selectivity	-5.82 (6.05)	-5.38 (6.45)	.812

6.4.2. Relationship between TVA parameter estimates and conventional neuropsychological tests

Across patients, Spearman correlations were calculated between TVA parameter estimates and conventional neuropsychological tests[1]. Significant correlations with tests addressing corresponding functions were obtained for parameter *K* and Dev*(w_{lat})*. As expected, parameter *K* was significantly correlated with the backward (not the forward) version of the block span test. A highly significant correlation was found for Dev*(w_{lat})* with the response time in visual scanning, suggesting that balanced weighting was associated with faster scanning. Since in the whole TBI sample only three errors in three subjects (all from the mTBI group) were made in the visual scanning test, no correlation was calculated between Dev*(w_{lat})* and accuracy. Neither for parameter *C*, nor for parameter *α* significant correlations with the respective measures were found (*C*: simple RTs in the "Alertness" tasks; *α*: Stroop interference condition and SEL; see Table 6).

Table 6: TVA+NP: Correlation coefficients between TVA parameter estimates and standard neuropsychological test scores

C: processing speed (elements/s); *K*: visual WM storage capacity (number of elements); Dev*(w_{lat})*: deviation from equal distribution of attentional weighting (*w_{lat}*): *α*: effectiveness of top-down control of attention; SRT: simple response time in the TAP; Mdn without: Median response time without preceding auditory warning signal; Mdn with: Median response time with preceding auditory warning signal; VMS: points in the subtest "Visual Memory Span" of the WMS-R; F: forward; B: backward; VS: subtest "Visual Scanning" of the TAP; T: response time; FWIT: processing time in the Stroop Colour-Word Interference Test; I: interference condition; SEL: selectivity index corrected for naming speed; CWR: colour-word reading condition; CBN: colour-bar naming condition. Correlations between TVA parameters and neuropsychological tests assessing analogous attentional functions are printed in bold.

**P* , .05; ***P* , .01 (1-tailed tests for convergent validity, 2-tailed tests for discriminant validity)

		C	***K***	**Dev*(w_{lat})***	***α***
SRT	Mdn without	**-.11**	-.04	.20	-.09
	Mdn with	**-.13**	.03	.11	-.13
VMS	F	.16	.23	-.30*	-.17
	B	.23	**.34****	-.34*	.05
VS	T	-.45**	-.54**	**.42****	-.23
FWIT	I	-.42**	-.13	.10	**.19**
	SEL	-.13	.11	-.19	**-.04**
	CWR	-.31*	-.24	.16	.19
	CBN	-.36*	-.19	.27	.23

[1] Since it was shown in study 1 that perceptual threshold (t_0) was impaired in sTBI patients (see chapter 4), any possible correlations with conventional neuropsychological measures were explored. However, no relation emerged to any of these measures (see Supplement D, Table 20, p. 96).

Furthermore, a number of correlations emerged with theoretically unrelated tests. Further significant negative correlations were found between processing speed (parameter *C*) with all three baseline Stroop conditions as well as with the visual scanning time in the TAP-subtest, between parameter *K* and speed of visual scanning in the TAP-subtest and between the index of spatial imbalance of attentional weighting Dev(w_{lat}) and both block span tests (for- and backward).

6.5. Discussion

The present study was conducted to investigate the association between components of selective visual attention, as assessed by a whole and a partial report task based on Bundesen's theory of visual attention (TVA; 1990, 1998), and standard neuropsychological tests that are assumed to address theoretically related attentional aspects in a sample of TBI patients with attentional deficits. Study 1 and study 2 had already revealed impairments in perceptual threshold, WM storage capacity, spatial distribution of attention, and top-down control following sTBI, and deficits in processing speed as a result of mTBI and sTBI (as assessed with the GCS). In TVA-based research, the relation to other clinical measures is limited to a somewhat small number of studies. However, especially for the clinical application of TVA-based assessment, the knowledge of the relationship to conventional tests in clinical populations that are actually affected by deficits in attention is also important.

The correlation matrix established in this TBI sample showed similarities, but also differences compared to the correlation coefficients found by Finke et al. (2005) in healthy subjects. In line with the previous results, WM storage capacity *K* showed a positive correlation with the backward visual span task, and Dev(w_{lat}) showed a significant positive correlation with response time in the TAP subtest "Visual Scanning". However, neither processing speed *C* nor top-down control α were significantly correlated to tests assumed to be related (simple response-times in the TAP "Alertness" test respectively the Stroop interference condition and the naming speed corrected selectivity index).

To interpret these results it is important to note that, while most of conventional tests involve RT measures (e.g., TAP battery, Zimmermann & Fimm, 1993) or are influenced by other motor processes as in the "Visual Memory Span" from the WMS-R, performance in TVA-based assessment is not significantly influenced by motor processes. On the one hand, this makes TVA-based tests applicable even to patients

with severe motor handicaps such as tetraplegia (Strubreither et al., 2015). On the other hand, this might influence the relationship between motor-speed based measures, such as the TAP scores, and the non-motor-based TVA scores. In fact this might be an explanation for the statistical independence between parameter *C* and the TAP Alertness measures. While TVA-based whole report provides a "pure" measure of processing speed, the TAP "Alertness" test is confounded with motor speed changes, which are found in TBI, and predominantly in polytrauma patients. While none of the examined patients reported any corporal motor complaints disabling their performance in the TAP tasks (neither in the "Alertness" nor in the "Visual Scanning" test), it might well be possible that they suffered from motor changes that are too subtle to be consciously perceived by the patients.

A second critical difference between conventional tests and TVA tests that might explain further unexpected findings is the fact that TVA-based testing allows to measure different attentional functions in an independent, cognitively specific manner, while performance in established neuropsychological tests is often influenced by several components, without the possibility of disentangling their respective contribution. This could explain, for example, the correlations between processing speed and diverse established cognitive measures on the one hand, and the lack of a significant correlation between Stroop task performance and TVA parameter top-down control on the other. Both, the partial report and the Stroop test are assumed to measure resistance to interference. However, in contrast to the findings by Finke et al. (2005) in normal subjects, the RT in the Stroop interference condition was not correlated with the parameter top-down control α in this sample. Again, the RT in the Stroop task was instead significantly related to parameter processing speed *C*. Thus, the non-significant correlation indicates that the performance in this conventional test is determined by basic deficits that cannot be disentangled. This means that performance in the Stroop interference task is not only influenced by top-down control efficiency, but that slow visual processing also leads to poor performance. This interpretation would be in line with previous findings suggesting that reduced processing speed may account for poor performance in response inhibition in the Stroop task (Ponsford & Kinsella, 1992; Mathias & Wheaton, 2007). However, parameter top-down control was also not correlated to the naming speed corrected selectivity index (SEL). The non-relationship between both measures suggests distinguishable interference control mechanisms (cf. Nigg, 2000; Dimoska-Di Marco et al., 2011). The Stroop test inter-

ference condition measures the inhibition of an inappropriate but highly automated and overlearned response tendency, while in the partial report task top-down control is required at a visual perceptual-discrimination level of stimulus processing. The results suggest that response inhibition and interference control might represent distinct processes of inhibitory control in patients suffering from attentional impairments (see e.g., Nigg, 2000; Dimoska-Di Marco et al., 2011).

In general, the significant correlations between parameter *C* with all three baseline Stroop conditions as well as with the visual scanning time in the TAP-subtest indicate that, in these tasks, where many visual stimuli have to be processed before a participant can react, performance is determined by a basic slowing of processing. This questions the validity of the application of such tasks in populations with visual processing slowing.

Furthermore, the negative correlations between the index of spatial imbalance of attentional weighting Dev(w_{lat}) and both block span tests (for- and backward) indicate that patients with attentional lateralization have problems encoding and maintaining spatial locations. Actually, it was demonstrated repeatedly that patients with visual hemineglect and a pronounced bias towards one visual hemifield display such deficits (see e.g., Pisella & Mattingley, 2004).

In line with the hypothesis, a significant group difference was found exclusively for the visual scanning test from the TAP battery. This result supports the assumption of a decisive role of spatial attentional weighting in the ability to visually scan matrices. It also indicates that the partial report represents a valid alternative for assessing patients with severe motor problems, when the “Visual scanning” test from the TAP is not administrable but the capacity to distribute attention adequately across the visual field is in question (cf. Strubreither et al., 2015).

Besides the important number of studies using TVA-based assessment in clinical populations over the last 15 years (see Habekost, 2015 for an overview), this is the first study to establish the relation to clinical measures that assess theoretically related constructs in a TBI population. The results of this study suggest that combining TVA with a whole- and a partial report allows a more valid assessment of attentional deficits in a TBI population than an assessment based on established clinical tools where performance values are generally confounded with motor speed on the one hand and visual processing speed on the other. However, several constraints should be mentioned. One important sequel after left-sided cerebral trauma can be aphasia

which renders assessment via letter report invalid. Secondly, the partial report is not executable in patients suffering from colour-blindness (three patients in this sample). Another important limitation for a broader clinical application is the lack of normative data. The study's result leads to the conclusion, that the parameter-based approach can be applied to TBI patients and delivers valid results. Expected correlations with established neuropsychological tools suggest that the TVA assessment tool measure functions that are also reflected in performance of tests measuring similar components of attention. Non-expected correlations can be explained by the fact that some attentional parameters (and particularly visual processing speed) are critical determinants of all tasks that require fast visual processing for obtaining normal performance scores. As exclusively TBI patients were tested who were at least classified as complicated mTBI as they suffered from intracranial lesions, the results cannot be generalized to patients with non-complicated mTBI.

7. General conclusions and perspectives

The present dissertation intended to examine visual attention in mTBI and sTBI patients as assessed with the Glasgow Coma Scale (GCS) in comparison to healthy matched control subjects using a whole and a partial report paradigm based on Bundesen's theory of visual attention (TVA; Bundesen, 1990, 1998, 2002; Bundesen et al., 2005; Bundesen & Habekost, 2008, 2014).

Taken together, more than 50 patients with TBI have been examined. Several of the empirical findings are relevant to clinical TVA-based research and the clinical neuropsychology of TBI. The results of studies 1 and 2 showed that sTBI patients displayed significant impairments in attentional capacity as measured with the whole report paradigm and in attentional weighting as assessed with the partial report paradigm. More precisely, patients suffering from a sTBI presented a pattern of impaired attentional components in perceptual processing speed, working memory (WM) storage capacity, and perceptual threshold (study 1) as well as an impaired top-down control and a pathological spatial imbalance (study 2). In contrast, mTBI patients solely presented a slowing of visual processing speed (see Table 7).

Table 7: WR-PR: Overview of impaired and intact TVA-based parameters in the mTBI and sTBI patient group compared to healthy controls
☒: impaired attentional parameter, ☑: intact attentional parameter.

Group	Perceptual threshold t_0	Processing speed C	WM storage capacity K	Spatial weighting w_{lat}	Top-down control α
mTBI	☑	☒	☑	☑	☑
sTBI	☒	☒	☒	☒	☒

Specific questions for further studies arise from these outcomes. As shown in study 1, all patients out of the mTBI group presented an intracranial lesion, termed complicated mTBI. However, complicated mTBI is not representative for this patient group as a whole, which might question the generalizability of these results for mTBI patients on the basis of their GCS score. Therefore, it would be of interest to contrast samples of mTBI patients (according to GCS) with and without intracranial lesion (complicated vs. uncomplicated mTBI) in order to elicit if impairments in processing speed might be a general aspect in mTBI.

Particularly, visual processing speed C was, to a comparable extent, impaired in both, sTBI and complicated mTBI, suggesting an analogous vulnerability of the asso-

ciated neural systems in both groups irrespective of trauma severity. A number of studies including study 1 showed a significant correlation between *C* and *K* (e.g., Finke et al., 2005; Habekost, 2015). These results indicate that both parameters share largely overlapping networks of brain areas. However, there is also indication of independence, e.g., independent physiological correlates (Wiegand et al., 2013), distinct cueing effects (Matthias et al., 2010) and selectively impaired functions in clinical groups (Finke et al., 2015). Given that visual processing speed is not necessarily accompanied by impairment of WM storage capacity, the results support the assumption of theoretical independence of these parameters that is also suggested in the TVA. In future studies, it would be interesting to investigate which brain region respectively which white matter tracts is/are related to reduced WM storage capacity respectively reduced processing speed by, for instance, the use of MRI diffusion tractography.

Furthermore, the underlying neuropathology of impairments in top-down control (parameter α) and, respectively, the imbalance index of attentional weighting Dev(w_{lat}) should be further examined. Both parameters were affected by sTBI. Based on the clinical TVA-based literature and findings from other neuropsychological studies, regions such as the superior frontal lobe and/or the anterior cingulate cortex are expected to be involved in the process of top-down selection. Also, a temporo-parietal interhemispheric asymmetry is assumed to lead to a pathological imbalance of spatial attentional weighting (Redel et al., 2012). As sTBI patients likely suffer from larger lesions (e.g., large contusions) and/or more diffusely distributed pathology (e.g., diffuse axonal injury) than mTBI patients, the probability that these critical regions and mechanisms are affected is higher in the former.

Finally, study 3 was conducted to investigate the association between components of selective visual attention, as assessed by a whole and a partial report task based on TVA, and standard neuropsychological tests that address theoretically the same attentional aspects in a sample of TBI patients. The correlation matrix of this study showed similarities, but also differences compared to the correlation coefficients presented in the study by Finke et al. (2005) in healthy subjects. Specifically, significant correlations between processing speed (parameter *C*) with all three baseline Stroop conditions as well as with the visual scanning time in the TAP-subtest indicate that, with these tasks, where many visual stimuli have to be processed before a participant can react, performance is determined by a basic slowing of processing. This result

questions the validity of the application of such tasks in populations with slowing of visual processing.

In conclusion, the main contribution of this dissertation was to systematically analyse and characterize the typical patterns of performance in respect to TVA parameters in patients with either mTBI on the one hand and sTBI on the other. The results clearly demonstrate a graded pattern of attentional changes that include speed of processing only in the mildly affected group and generalized changes in all tested parameters in the severely affected group.

8. Deutsche Zusammenfassung (German synopsis)

Aufmerksamkeitsstörungen gehören zu den häufigsten Beeinträchtigungen nach Schädelhirntrauma (SHT; siehe Sturm, 2005; Huang et al., 2014). Das SHT kann zu einer unspezifischen Verlangsamung der Informationsverarbeitung sowie zu spezifischen funktionalen Beeinträchtigungen in unterschiedlichen Aufmerksamkeitsbereichen führen (Birgler, 2001; Kraus et al., 2007; Zihl & Almeida, 2015). Verschiedene Autoren verweisen hingegen auf unterschiedliche Mechanismen, die den Leistungsbeeinträchtigungen bei den unterschiedlichen Aufgaben zugrunde liegen können. Einige Autoren gehen von einer Verlangsamung der Informationsverarbeitung aus, die zu Beeinträchtigung bei verschiedenen Aufgaben führt (z.B. Ponsford & Kinsella, 1992; Spikman et al., 1996). Andere Autoren vermuten eher eine Arbeitsgedächtnisstörung als Ursache (z.B. McAllister et al., 2004). Weiter wurde angenommen, dass SHT-Patienten unter einer Beeinträchtigung höherer kognitiver Kontrollprozesse leiden, welche zu Störungen in unterschiedlichen kognitiven Aufgaben führen (Ciaramelli et al., 2006).

Neuropsychologische Testinstrumente, die eine spezifische Untersuchung verschiedener Aufmerksamkeitsfunktionen nach leichtem oder schwerem SHT erlauben, sind für den Untersucher wichtig, um eine richtige Diagnose zu stellen und ein geeignetes Therapieprogramm einzuleiten. Ziel dieser Dissertation ist es, visuelle Aufmerksamkeitsstörungen nach SHT differenziert zu untersuchen, unter Verwendung eines Testverfahrens, dessen Anwendbarkeit sich bereits in unterschiedlichen klinischen Bereichen gezeigt hat (Habekost, 2015). Basierend auf Bundesens „Theorie der visuellen Aufmerksamkeit“ (TVA; Bundesen, 1990, 1998, 2002; Bundesen et al., 2005; Bundesen & Habekost, 2008, 2014) ist es möglich, mit zwei ähnlichen Paradigmen, dem computergestützten Ganz- und Teilbericht, latente, mathematisch unabhängige und quantifizierbare Parameter zu schätzen.

Die vorliegende Dissertation hat zum Ziel, sowohl zu unterschiedlichen Überlegungen im Bereich der klinischen TVA-basierten Forschung als auch im Bereich der Neuropsychologie nach SHT einen Beitrag zu leisten. Konkret sollten folgende Inhalte bearbeitet werden:

- Studie 1 hatte zum Ziel, potentielle Beeinträchtigungen in der Aufmerksamkeitskapazität nach SHT zu untersuchen, unter Verwendung des Ganzberichts, der es erlaubt, sowohl die Verarbeitungsgeschwindigkeit als auch die Arbeitsgedächtniskapazität zu bestimmen;

- Studie 2 komplettiert Studie 1, indem sie Aspekte der selektiven Aufmerksamkeit (die visuell-räumliche und aufgabenbezogene Selektivität) nach SHT untersucht;
- Ziel von Studie 3 war es, der Frage nachzugehen, ob sich in einer Stichprobe von SHT-Patienten Zusammenhänge zwischen TVA Parametern und anderen klinischen Testkennwerten finden lassen, wie sie bei gesunden Probanden in einer Studie von Finke et al. (2005) gezeigt wurden, oder ob sich andere Zusammenhänge zeigen.

Die nachfolgenden Synopsen beinhalten kurze Zusammenfassungen der drei Studien.

8.1. Studie 1

Ausgehend von der „Theorie der visuellen Aufmerksamkeit“ von Bundesen (TVA; 1990, 1998) wurde die visuelle Verarbeitungskapazität bei 25 Patienten mit leichtem SHT (aufgrund intrakranialer Verletzung als kompliziertes leichtes SHT einzuordnen), 23 Patienten mit schwerem SHT und 24 gesunden Kontrollprobanden untersucht (Kapitel 4, S. 24 ff.). Zwischen den Gruppen bestand kein Unterschied hinsichtlich Alter, Geschlecht oder Bildungsniveau. Basierend auf der Leistung in einem Ganzberichtsverfahren, in dem möglichst viele kurzzeitig auf einem Computerbildschirm präsentierte Buchstaben benannt werden sollten, konnten drei voneinander unabhängige Parameter ermittelt werden: perzeptuelle Verarbeitungsschwelle t_0, perzeptuelle Verarbeitungsgeschwindigkeit *C* und visuelle Arbeitsgedächtniskapazität *K*.

Im Gruppenvergleich wurde deutlich, dass Patienten mit schwerem SHT Defizite in allen drei TVA Parametern zeigten, während Patienten mit leichtem SHT lediglich in der Verarbeitungsgeschwindigkeit beeinträchtigt waren. Interessanterweise war die Verarbeitungsgeschwindigkeit in beiden SHT-Gruppen gleich. Die visuelle Arbeitsgedächtniskapazität *K* korrelierte signifikant mit dem Schweregrad des Traumas (entsprechend der Glasgow-Koma-Skala). Darüber hinaus zeigte sich ein signifikanter Zusammenhang zwischen der perzeptuellen Verarbeitungsgeschwindigkeit *C* und der visuellen Arbeitsgedächtniskapazität *K*.

In der vorliegenden Studie wurden erstmals beide Aufmerksamkeitskomponenten, basierend auf der TVA von Bundesen, systematisch und unabhängig voneinander in einer Stichprobe von SHT Patienten untersucht. Die Ergebnisse dieser Untersuchung deuten auf eine reduzierte Verarbeitungsgeschwindigkeit unabhängig vom Schwere-

grad des Traumas nach SHT hin, während Patienten mit schwerem SHT zusätzlich eine reduzierte visuelle Arbeitsgedächtniskapazität aufweisen.

8.2. Studie 2

Zusätzlich zu einer reduzierten Verarbeitungsgeschwindigkeit kann ein SHT zu spezifischeren Funktionsstörungen führen, z.B. in der visuell-räumlichen und/oder aufgabenbezogenen selektiven Aufmerksamkeit. Zum Beispiel konnte anhand visueller Suchaufgaben mit hoher Ähnlichkeit von Ziel- und Ablenkreiz eine Verlangsamung bei SHT-Patienten gezeigt werden (z.B. Schmitter-Edgecombe & Robertson, 2015; Bate, Mathias, & Crawford, 2001a; Rasmussen et al., 2008). Allerdings können Störungen bei visuellen Suchaufgaben aus unterschiedlichen zugrundeliegenden Mechanismen resultieren, wie z.B. eine reduzierte Verarbeitungsgeschwindigkeit, Störung in der Top-down Kontrolle oder visuell-räumliche Aufmerksamkeitsstörung. Diese Mechanismen können hingegen nicht anhand konventioneller Leistungstests getrennt voneinander untersucht werden. Für eine solche Untersuchung ist ein Testverfahren notwendig, das spezifische Ergebnisse über mögliche Beeinträchtigungen in der selektiven Aufmerksamkeit liefert. Studie 2 (Kapitel 5, S. 41 ff.) untersuchte die Auswirkungen von leichtem und schwerem SHT auf die TVA-basierten Parameter räumliche Aufmerksamkeitsgewichtung und Top-down Kontrolle.

Die visuellen selektiven Aufmerksamkeitsleistungen wurden bei 23 Patienten mit leichtem SHT, 23 Patienten mit schwerem SHT und 23 gesunden Kontrollprobanden untersucht. Die Gruppen waren hinsichtlich Alter, Geschlecht und Bildungsniveau vergleichbar. Die Patienten wurden entsprechend der Glasgow Koma Skala den Gruppen zugeordnet. Mit einem TVA-basierten Teilberichtsverfahren (Bundesen, 1990, 1998), bei dem die Aufgabe der Probanden darin bestand, kurzzeitig präsentierte Buchstaben zu benennen, wurden zwei mathematisch unabhängige und quantifizierbare Parameterwerte berechnet: die Top-down Kontrolle als Maß für die Fähigkeit, visuelle Zielreize gegenüber Ablenkreizen bevorzugt zu verarbeiten (Parameter α), und die räumliche Aufmerksamkeitsgewichtung über beide Gesichtsfelder (Parameter w_{lat}).

Im Vergleich zur Kontrollgruppe zeigten Patienten mit schwerem SHT eine signifikant reduzierte Top-down Kontrolle sowie eine beeinträchtigte räumliche Aufmerksamkeitsverteilung, während Patienten mit leichtem SHT keinen signifikanten Unter-

schied zu den Kontrollprobanden in diesen Parametern aufwiesen. Parameter *α* korrelierte mit dem Schweregrad des Traumas (Glasgow Koma Skala).
Das TVA-basierte Teilberichtsverfahren bietet einen neuen Ansatz zur Untersuchung der Top-down Kontrolle sowie der räumlichen Aufmerksamkeitsgewichtung nach SHT. Weitere Forschung ist erforderlich, um die zugrundeliegende Neuropathologie von Beeinträchtigungen nach schwerem SHT in beiden Aspekten der selektiven Aufmerksamkeit zu klären.

8.3. Studie 3

Nur wenige Studien haben Zusammenhänge zwischen TVA Parametern und anderen klinischen Instrumenten untersucht (vgl. Habekost, 2015). Finke et al. (2005) konnten mit den TVA-basierten Ganz- und Teilberichtsverfahren, wie sie in Studie 1 und 2 verwendet wurden, an einer Stichprobe von jungen und gesunden Probanden zeigen, dass TVA-basierte Parameterwerte höher mit klinischen Testverfahren korrelieren, die ein ähnliches Konstrukt erfassen, als mit solchen, die ein anderes Konstrukt messen. Die dritte Studie (Kapitel 6, S. 57 ff.) widmet sich der Frage, ob die TVA-basierten Parameterwerte bei einer Stichprobe, die durch eine Aufmerksamkeitsstörung z.B. in Folge eines SHTs charakterisiert ist, mit etablierten klinischen Testwerten in Zusammenhang stehen. Dazu wurden dieselben neuropsychologischen Tests verwendet wie in der Studie von Finke et al. (2005).
In einer Stichprobe von 51 SHT-Patienten (27 Patienten mit leichtem und 24 mit schwerem SHT) fanden sich sowohl vergleichbare Korrelationen zwischen TVA Parameterwerten und Testwerten konventioneller neuropsychologischer Tests, wie von Finke et al. (2005) bei gesunden Probanden gezeigt, als auch unerwartete Zusammenhänge. Signifikante Korrelationen ergaben sich zwischen der Verarbeitungsgeschwindigkeit (Parameter *C*) und allen drei Grundvariablen des Stroop-Tests sowie mit der Reaktionszeit im visuellen Scanning der TAP. Dies deutet darauf hin, dass in Aufgaben, in denen eine Vielzahl visueller Reize verarbeitet werden müssen bevor der Proband reagieren kann, eine reduzierte visuelle Verarbeitungsgeschwindigkeit die Testleistung beeinflusst.

8.4. Schlussfolgerungen und Ausblick

Die vorliegende Dissertation verfolgte das Ziel, mittels auf der „Theorie der visuellen Aufmerksamkeit“ (TVA; Bundesen, 1990, 1998) basierenden Verfahren Ganz- und Teilbericht mögliche Defizite in der visuellen Aufmerksamkeit bei Patienten mit leichtem und schwerem Schädelhirntrauma zu untersuchen.

Die Ergebnisse der drei hier vorgestellten Studien verweisen auf deutliche Aufmerksamkeitsdefizite bei schwerem SHT mit Beeinträchtigungen in der präattentiven Verarbeitung (perzeptuelle Wahrnehmungsschwelle t_0), in Komponenten der Verarbeitungskapazität (perzeptuelle Verarbeitungsgeschwindigkeit C und Arbeitsgedächtniskapazität K) sowie in der aufgabenbezogenen (Top-down Kontrolle α) und räumlichen Aufmerksamkeitsgewichtung [Dev(w_{lat})]. Patienten mit leichtem SHT zeigten im Vergleich zu einer gesunden Kontrollgruppe ebenfalls Beeinträchtigungen in der perzeptuellen Verarbeitungsgeschwindigkeit, während die präattentive Verarbeitung, Arbeitsgedächtniskapazität sowie aufgabenbezogene und räumliche Aufmerksamkeitsgewichtung intakt blieben.

Die Studien konnten zeigen, dass die Verarbeitungsgeschwindigkeit nach SHT beeinträchtigt ist, und zwar unabhängig vom Schweregrad, der hier mit der Glasgow Koma Skala erfasst wurde, während weitere Beeinträchtigungen in der Verarbeitungskapazität und Aufmerksamkeitsgewichtung eher nach schwerem SHT festzustellen sind. Die Korrelationsanalyse zwischen TVA Parametern und konventionellen neuropsychologischen Tests, die vergleichbare Konstrukte erfassen, zeigte vergleichbare Korrelationen wie sie zuvor von Finke et al. (2005) bei gesunden Probanden gezeigt wurden, aber auch unerwartete Zusammenhänge.

Zukünftige Studien mittels Diffusions-Tensor-Bildgebung könnten dazu beitragen, den Zusammenhang zwischen beeinträchtigen TVA Parametern und ihrer zugrundeliegenden Neuropathologie nach SHT besser zu verstehen.

Supplement A: Test instructions for the whole and partial report

Test instructions were provided in written form. The experimenter made sure that every single subject understood the instruction by requesting and further verbal explanation of the task, if necessary (especially with regard to patient data assessment).

Whole report instruction for patients in study 1 (German original version and English translation)

„Auf dem Bildschirm erscheint zuerst ein Kreuz. Schauen Sie dorthin, wo das Kreuz ist. Dann erscheinen fünf Buchstaben. Benennen Sie alle Buchstaben, die Sie sehen können. Die Buchstaben erscheinen nur ganz kurz. Es ist normal, dass Sie nicht alle Buchstaben erkennen werden. Nennen Sie einfach alle Buchstaben, die Sie erkannt haben."

"First you will see a cross at the screen. Fixate this cross. After the cross has disappeared, five letters will appear. Name as many letters as possible. Presentation time is very short. Therefore, it is normal that you are unable to recognize all letters. Just report all letters that you have seen."

Partial report instruction for patients in study 2 (German original version and English translation)

„Auf dem Bildschirm erscheint zuerst ein Kreuz. Schauen Sie dorthin, wo das Kreuz ist. Danach erscheinen rote oder grüne Buchstaben. Nur die roten Buchstaben sind wichtig. Benennen Sie nur die roten Buchstaben. Die grünen Buchstaben brauchen Sie nicht zu benennen. Die Buchstaben erscheinen nur ganz kurz. Es ist normal, dass Sie nicht alle roten Buchstaben erkennen werden. Nennen Sie einfach alle roten Buchstaben, die Sie erkannt haben."

"First you will see a cross at the screen. Fixate this cross. After the cross has disappeared, either red or green letters will appear. Name the red letters only. Only the red letters are of importance. You do not have to report the green letters. Presentation time is very short. Therefore, it is normal that you are unable to recognize all red letters. Just report all red letters that you have seen."

Supplement B: Whole report data (study 1)

Table 8: WR: Demographic data for healthy controls, mTBI and sTBI patients
M (SD): mean score and standard deviation; Age in years; m: male; f: female; Education in years; Premorbid IQ: assessed with the MWT-B, Lehrl et al. (1995); Handedness according to the Edinburgh Handedness Inventory (Oldfield, 1971); Time post injury in weeks (time between trauma and the instant of testing); GCS: Glasgow Coma Scale

Nr.	Age	Gender	Education	Premorbid IQ	Handedness	Time post injury	GCS
Healthy controls							
1	35	f	9	118	R	-	-
2	23	m	10	104	R	-	-
3	58	m	-	104	R	-	-
4	27	f	10	97	R	-	-
5	44	m	9	97	R	-	-
6	51	f	8	91	-	-	-
7	38	f	13	112	R	-	-
8	34	m	10	112	R	-	-
9	41	m	10	107	R	-	-
10	36	m	13	107	R	-	-
11	33	m	13	100	R	-	-
12	26	m	10	104	R	-	-
13	45	m	10	104	R	-	-
14	27	m	13	107	R	-	-
15	41	m	9	97	R	-	-
16	58	m	10	107	R	-	-
17	25	m	13	104	R	-	-
18	33	m	10	112	R	-	-
19	34	m	9	104	R	-	-
20	46	m	-	104	R	-	-
21	29	m	9	107	R	-	-
22	52	m	8	118	R	-	-
23	45	m	10	104	R	-	-
24	22	f	13	118	R	-	-
Mean (SD)	**37.7 (10.6)**	**5 f 19 m**	**10.4 (1.7)**	**105.8 (6.9)**	**23 R**	-	-

See below for mTBI patients.

Nr.	Age	Gender	Education	Premorbid IQ	Handedness	Time post injury	GCS
mTBI patients							
1	55	m	12	101	R	7	13
2	44	m	10	118	R	2	15
3	45	m	9	112	R	5	-
4	31	m	12	93	R	23	14
5	47	m	8	112	R	7	15
6	44	m	9	89	R	6	14
7	18	f	10	89	R	3	14
8	19	m	10	89	R	1	15
9	44	m	10	101	R	5	13
10	60	m	10	88	R	35	15
11	56	m	12	104	R	10	15
12	58	m	9	88	R	3	15
13	36	m	10	95	R	5	15
14	21	m	10	92	R	1	15
15	31	m	9	97	R	2	15
16	45	m	10	101	L	2	15
17	60	m	9	101	R	3	13
18	35	m	10	100	R	6	14
19	48	m	10	118	R	6	15
20	48	m	9	101	R	24	15
21	26	m	9	94	R	3	15
22	28	m	10	118	R	8	14
23	53	m	9	95	R	14	-
24	20	m	12	124	R	12	15
25	53	m	10	95	R	2	13
Mean (SD)	**41.0 (13.6)**	**1 f 24 m**	**9.9 (1.1)**	**100.6 (10.7)**	**24 R 1 L**	**7.8 (8.3)**	**14.4 (0.8)**

See below for sTBI patients.

Nr.	Age	Gender	Education	Premorbid IQ	Handedness	Time post injury	GCS
sTBI patients							
1	20	m	9	92	R	20	6
2	58	m	8	94	R	10	11
3	45	m	9	97	R	47	3
4	42	m	9	92	L	31	6
5	38	f	13	112	R	8	3
6	31	m	10	88	R	7	8
7	24	f	12	93	R	3	3
8	53	m	10	124	R	10	3
9	19	m	10	89	R	7	3
10	37	m	12	104	R	7	3
11	28	m	11	100	R	8	6
12	60	f	12	136	R	6	-
13	48	m	12	112	R	48	-
14	40	m	12	91	R	5	3
15	21	f	10	94	R	4	5
16	55	m	10	143	R	12	3
17	20	m	9	88	R	3	6
18	46	m	10	95	R	53	8
19	51	m	9	101	R	6	3
20	20	m	12	95	R	8	7
21	21	f	10	118	R	35	3
22	50	m	12	101	R	18	3
23	46	m	12	107	R	7	7
Mean (SD)	**38.0 (13.9)**	**5 f 18 m**	**10.6 (1.4)**	**102.9 (15.1)**	**22 R 1 L**	**15.8 (15.6)**	**4.9 (2.3)**

Table 9: WR: Individual exposure durations of mTBI and sTBI patients and healthy controls
50% of the trials were masked. M (SD): mean score and standard deviation

Nr. controls	Exposure durations (ms)			Nr. mTBI	Exposure durations (ms)			Nr. sTBI	Exposure durations (ms)		
1	43	86	157	**1**	79	173	346	**1**	146	306	599
2	67	120	240	**2**	93	186	359	**2**	173	346	706
3	109	199	399	**3**	86	171	343	**3**	106	199	399
4	79	159	333	**4**	57	114	228	**4**	106	199	399
5	79	159	306	**5**	57	114	229	**5**	79	146	306
6	157	300	600	**6**	143	286	571	**6**	106	226	439
7	157	300	600	**7**	57	114	229	**7**	79	146	306
8	53	119	226	**8**	71	143	286	**8**	86	171	343
9	79	159	306	**9**	71	143	286	**9**	57	114	229
10	86	157	300	**10**	143	286	571	**10**	100	200	400
11	86	157	300	**11**	168	336	672	**11**	57	114	229
12	79	159	306	**12**	95	190	380	**12**	86	171	343
13	26	39	79	**13**	110	220	440	**13**	86	171	343
14	27	43	86	**14**	90	180	360	**14**	71	143	286
15	86	157	300	**15**	71	143	286	**15**	57	114	229
16	83	150	300	**16**	71	143	286	**16**	93	185	370
17	43	86	157	**17**	135	270	540	**17**	86	171	343
18	79	159	306	**18**	62	124	248	**18**	150	300	600
19	39	79	173	**19**	86	171	343	**19**	86	171	343
20	39	79	159	**20**	71	143	286	**20**	115	230	460
21	79	159	306	**21**	43	86	172	**21**	130	260	520
22	86	157	300	**22**	43	86	172	**22**	86	171	343
23	26	39	79	**23**	86	171	342	**23**	67	134	268
24	33	67	133	**24**	43	86	172				
				25	100	200	400				
Mean (SD)	**72 (36)**	**137 (68)**	**269 (136)**		**85 (33)**	**171 (66)**	**342 (132)**		**96 (30)**	**191 (63)**	**383 (125)**

Table 10: WR: Individual parameter estimates for healthy controls, mTBI and sTBI patients
t_0: perceptual threshold (ms); *C*: perceptual processing speed (N elements/sec); *K*: visual WM memory storage capacity (N elements)

Nr. controls	t_0	*C*	*K*	Nr. mTBI	t_0	*C*	*K*	Nr. sTBI	t_0	*C*	*K*
1	0	43	3.9	**1**	24.3	17	2.7	**1**	119.6	8	2.0
2	3.3	13	3.0	**2**	32.8	14	2.7	**2**	90.8	13	2.8
3	24.4	20	3.0	**3**	0	16	3.4	**3**	18.8	14	2.7
4	23.2	16	2.9	**4**	0	22	2.7	**4**	21.7	13	2.6
5	0	14	2.9	**5**	0	27	3.2	**5**	14.6	23	2.9
6	59.7	29	3.0	**6**	22.6	9	2.6	**6**	15.6	16	2.9
7	60.3	19	3.8	**7**	0	22	3.7	**7**	39	20	3.0
8	0	33	3.8	**8**	47.2	22	2.6	**8**	0	26	3.6
9	0	14	2.5	**9**	9.4	20	2.9	**9**	0	11	2.4
10	0.5	20	2.7	**10**	55.1	11	2.5	**10**	72	27	3.0
11	44	15	2.8	**11**	136.1	10	2.5	**11**	0.5	21	1.8
12	2.7	14	2.6	**12**	15.4	11	2.8	**12**	7.4	22	2.7
13	0	54	3.8	**13**	45.8	18	3.0	**13**	10.9	14	2.7
14	0	60	3.7	**14**	14.3	17	3.4	**14**	31	28	2.8
15	0	30	2.8	**15**	0.6	18	2.8	**15**	1.8	27	2.8
16	9.8	14	3.5	**16**	0	21	3.4	**16**	60	20	2.9
17	2.7	36	3.8	**17**	36.4	17	3.8	**17**	5.9	27	3.0
18	26.1	15	3.0	**18**	0	14	2.6	**18**	75.4	14	2.8
19	0	35	3.6	**19**	25.2	16	2.8	**19**	19.8	14	2.0
20	39	29	3.7	**20**	28.2	17	2.7	**20**	13.2	17	2.7
21	10.7	25	2.8	**21**	0	22	2.9	**21**	100.1	20	2.0
22	0	21	3.6	**22**	0	36	3.8	**22**	0	23	2.8
23	0	54	3.8	**23**	19.2	14	2.4	**23**	10.3	28	2.6
24	2.5	26	2.4	**24**	0	36	3.7				
				25	14.3	21	3.7				
Mean (SD)	**12.9 (19.5)**	**27.1 (14.0)**	**3.23 (0.50)**		**21.1 (29.4)**	**18.8 (6.8)**	**3.01 (0.47)**		**32.7 (36.1)**	**19.3 (6.2)**	**2.67 (0.41)**

Table 11: WR: Lesion analyses in the mTBI group
CT: computer tomography; MRI: magnetic resonance imaging; x: intracerebral bleeding; y: extra axial bleeding

Nr. mTBI	CT	MRI
1	x	x
2	y	x
3	-	x
4	-	x
5	-	y
6	x	x
7	x	x
8	x	-
9	x	-
10	-	x
11	-	x, y
12	y	x
13	x	x
14	y	x
15	-	x
16	y	x
17	-	x
18	x	x
19	x, y	x
20	y	x
21	x	x
22	-	x
23	x	x
24	y	x
25	x	x

Table 12: WR: Medication in mTBI and sTBI patients
-: no medication; x: prescribed medication

Nr. mTBI	anticonvulsants	analgesics	Nr. sTBI	anticonvulsants	analgesics
1	-	-	**1**	-	-
2	-	x	**2**	-	-
3	-	-	**3**	-	-
4	-	x	**4**	-	-
5	-	-	**5**	-	-
6	-	-	**6**	-	x
7	-	x	**7**	-	x
8	-	-	**8**	-	-
9	-	-	**9**	-	-
10	-	-	**10**	-	-
11	-	-	**11**	-	-
12	-	-	**12**	-	-
13	-	-	**13**	-	-
14	-	x	**14**	-	x
15	-	x	**15**	-	-
16	-	-	**16**	-	-
17	-	-	**17**	-	-
18	-	x	**18**	x	-
19	x	x	**19**	-	-
20	-	x	**20**	-	-
21	-	-	**21**	-	-
22	-	-	**22**	x	x
23	-	-	**23**	-	-
24	-	-			
25	-	x			

Supplement C: Partial report data (study 2)

Table 13: PR: Demographic data for healthy controls, mTBI and sTBI patients
M (SD): mean score and standard deviation; Age in years; Education in years; Premorbid IQ: assessed with the MWT-B, Lehrl et al. (1995); m: male; f: female; Handedness according to the Edinburgh Handedness Inventory (Oldfield, 1971); Time post injury in weeks (time between trauma and the instant of testing); GCS: Glasgow Coma Scale

Nr.	Gender	Age	Education	Premorbid IQ	Handedness	Time post injury	GCS
Healthy controls							
1	m	55	10	101	R	-	-
2	m	23	10	104	R	-	-
3	m	58	-	104	R	-	-
4	f	27	10	97	R	-	-
5	m	44	9	97	R	-	-
6	f	51	8	97	-	-	-
7	f	38	13	112	R	-	-
8	m	34	10	112	R	-	-
9	m	41	10	107	R	-	-
10	m	36	13	107	R	-	-
11	m	33	13	100	R	-	-
12	m	26	10	104	R	-	-
13	m	45	10	104	R	-	-
14	m	27	13	107	R	-	-
15	m	41	9	97	R	-	-
16	m	58	10	107	R	-	-
17	m	25	13	104	R	-	-
18	m	35	10	107	R	-	-
19	m	33	10	112	R	-	-
20	m	34	9	104	R	-	-
21	m	46	-	104	R	-	-
22	m	29	9	104	R	-	-
23	m	52	8	107	R	-	-
Mean (SD)	**3 f 20 m**	**38.7 (10.8)**	**10.3 (1.7)**	**104.7 (5.9)**	**22 R**	**-**	**-**

See below for mTBI patients.

Nr.	Gender	Age	Education	Premorbid IQ	Handedness	Time post injury	GCS
mTBI patients							
1	m	44	10	118	R	2	15
2	m	59	9	94	R	3	-
3	m	45	9	112	R	5	-
4	m	31	12	93	R	23	14
5	m	47	9	112	R	7	15
6	m	44	8	89	R	6	14
7	f	18	10	89	R	3	14
8	m	19	10	89	R	1	15
9	m	44	10	101	R	5	13
10	m	60	10	88	R	35	15
11	m	56	12	104	R	10	15
12	m	58	9	88	R	3	15
13	m	51	10	97	R	8	14
14	m	31	9	97	R	2	15
15	m	45	10	101	L	2	15
16	m	60	9	101	R	3	13
17	m	35	10	100	R	6	14
18	m	48	10	118	R	6	15
19	m	48	9	101	R	24	15
20	m	26	9	94	R	3	15
21	m	28	10	118	R	8	14
22	m	20	12	124	R	12	15
23	m	53	10	95	R	2	13
Mean (SD)	**1 f 22 m**	**42.2 (13.6)**	**9.8 (1.0)**	**101.0 (11.0)**	**1 L 22 R**	**7.8 (8.5)**	**14.4 (0.7)**

See below for sTBI patients.

Nr.	Gender	Age	Education	Premorbid IQ	Handedness	Time post injury	GCS
sTBI patients							
1	m	20	9	92	R	20	6
2	m	58	8	94	R	10	11
3	m	45	9	97	R	47	3
4	m	42	9	92	L	31	6
5	f	38	13	112	R	8	3
6	m	31	10	88	R	7	8
7	f	24	12	93	R	3	3
8	m	53	10	124	R	10	3
9	m	19	10	89	R	7	3
10	m	37	12	104	R	7	3
11	m	28	11	100	R	8	6
12	f	60	12	136	R	6	-
13	m	48	12	112	R	48	-
14	m	40	12	91	R	5	3
15	f	21	10	94	R	4	5
16	m	55	10	143	R	12	3
17	m	20	9	88	R	3	6
18	m	46	10	95	R	53	8
19	m	51	9	101	R	6	3
20	m	46	9	100	L	52	-
21	f	21	10	118	R	35	3
22	m	50	12	101	R	18	3
23	m	46	12	107	R	7	7
Mean (SD)	**5 f 18 m**	**39.1 (13.4)**	**10.4 (1.4)**	**103.1 (15.0)**	**2 L 21 R**	**17.7 (17.3)**	**4.9 (2.4)**

Table 14: PR: Individual exposure durations of healthy controls, mTBI and sTBI patients
M (SD): mean score and standard deviation

Nr. controls	Exposure durations (ms)	Nr. mTBI	Exposure durations (ms)	Nr. sTBI	Exposure durations (ms)
1	239	**1**	186	**1**	346
2	106	**2**	266	**2**	226
3	146	**3**	136	**3**	186
4	106	**4**	81	**4**	266
5	106	**5**	129	**5**	146
6	128	**6**	200	**6**	266
7	157	**7**	71	**7**	186
8	66	**8**	155	**8**	143
9	106	**9**	129	**9**	100
10	71	**10**	250	**10**	81
11	86	**11**	210	**11**	129
12	79	**12**	175	**12**	200
13	79	**13**	153	**13**	129
14	43	**14**	129	**14**	150
15	157	**15**	129	**15**	100
16	87	**16**	200	**16**	143
17	71	**17**	114	**17**	143
18	106	**18**	175	**18**	280
19	79	**19**	129	**19**	163
20	79	**20**	110	**20**	129
21	133	**21**	90	**21**	200
22	66	**22**	71	**22**	160
23	100	**23**	161	**23**	143
Mean (SD)	**104 (42)**		**150 (53)**		**175 (65)**

Table 15: PR: Individual parameter estimates for healthy controls, mTBI and sTBI patients
α: Efficiency of top-down control; w: attentional weighting; Dev(w_{lat}): imbalance index of attentional weighting

Nr. controls	α	w	Dev(w_{lat})	Nr. mTBI	α	w	Dev(w_{lat})	Nr. sTBI	α	w	Dev(w_{lat})
1	0.42	0.47	0.03	**1**	0.57	0.49	0.01	**1**	0.71	0.41	0.09
2	0.56	0.43	0.07	**2**	0.39	0.54	0.04	**2**	0.13	0.18	0.32
3	0.40	0.31	0.19	**3**	0.29	0.32	0.18	**3**	0.72	0.52	0.02
4	0.20	0.56	0.06	**4**	0.22	0.50	0.00	**4**	0.67	0.49	0.01
5	0.35	0.54	0.04	**5**	0.47	0.48	0.02	**5**	0.49	0.51	0.01
6	0.27	0.51	0.01	**6**	0.37	0.39	0.11	**6**	1.02	0.36	0.14
7	0.37	0.45	0.05	**7**	0.65	0.50	0.00	**7**	0.38	0.62	0.12
8	0.40	0.53	0.03	**8**	0.62	0.41	0.09	**8**	0.37	0.50	0.00
9	0.30	0.48	0.02	**9**	0.55	0.49	0.01	**9**	0.59	0.58	0.08
10	0.51	0.60	0.10	**10**	0.37	0.54	0.04	**10**	0.68	0.46	0.04
11	0.18	0.55	0.05	**11**	0.32	0.47	0.03	**11**	0.16	0.26	0.24
12	0.28	0.50	0.00	**12**	0.64	0.41	0.09	**12**	0.39	0.44	0.06
13	0.42	0.51	0.01	**13**	0.53	0.39	0.11	**13**	0.51	0.46	0.04
14	0.38	0.44	0.06	**14**	0.12	0.51	0.01	**14**	0.86	0.48	0.02
15	0.54	0.59	0.09	**15**	0.51	0.46	0.04	**15**	0.64	0.44	0.06
16	0.26	0.51	0.01	**16**	0.36	0.51	0.01	**16**	1.23	0.48	0.02
17	0.34	0.47	0.03	**17**	0.40	0.50	0.00	**17**	0.45	0.32	0.18
18	0.30	0.48	0.02	**18**	0.59	0.44	0.06	**18**	0.90	0.23	0.27
19	0.30	0.57	0.07	**19**	0.41	0.48	0.02	**19**	0.16	0.62	0.12
20	0.26	0.46	0.04	**20**	0.49	0.55	0.05	**20**	0.74	0.53	0.03
21	0.65	0.44	0.06	**21**	0.56	0.58	0.08	**21**	0.65	0.31	0.19
22	0.51	0.49	0.01	**22**	0.40	0.44	0.06	**22**	0.50	0.57	0.07
23	0.30	0.54	0.04	**23**	0.45	0.43	0.07	**23**	0.24	0.60	0.10
Mean (SD)	**.37 (.12)**	**.50 (.06)**	**.05 (.04)**		**.45 (.14)**	**.47 (.06)**	**.05 (.05)**		**.57 (.28)**	**.45 (.12)**	**.10 (.09)**

Supplement D: TVA parameters and neuropsychological results (study 3)

Table 16: TVA+NP: Demographic data for mTBI and sTBI patients
M (SD): mean score and standard deviation; Age in years; m: male; f: female; Education in years; Premorbid IQ: assessed with the MWT-B, Lehrl et al. (1995); Handedness according to the Edinburgh Handedness Inventory (Oldfield, 1971); Time post injury in weeks (time between trauma and the instant of testing); GCS: Glasgow Coma Scale; Ishihara: p: positive, n: negative

Nr.	Age	Gender	Education	Premorbid IQ	Handedness	Time post injury	GCS	Ishihara
mTBI patients								
1	55	m	12	101	R	7	13	p
2	44	m	10	118	R	2	15	n
3	59	m	9	94	R	3	-	n
4	45	m	9	112	R	5	-	n
5	31	m	12	93	R	23	14	n
6	47	m	9	112	R	7	15	n
7	44	m	8	89	R	6	14	n
8	18	f	10	89	R	3	14	n
9	19	m	10	89	R	1	15	n
10	44	m	10	101	R	5	13	n
11	60	m	10	88	R	35	15	n
12	56	m	12	104	R	10	15	n
13	58	m	9	88	R	3	15	n
14	51	m	10	97	R	8	14	n
15	36	m	10	95	R	5	15	p
16	21	m	10	92	R	1	15	n
17	31	m	9	97	R	2	15	n
18	45	m	10	101	L	2	15	n
19	60	m	9	101	R	3	13	n
20	35	m	10	100	R	6	14	n
21	48	m	10	118	R	6	15	n
22	48	m	9	101	R	24	15	n
23	26	m	9	94	R	3	15	n
24	28	m	10	118	R	8	14	n
25	53	m	9	95	R	14	-	p
26	20	m	12	124	R	12	15	n
27	53	m	10	95	R	2	13	n
Mean (SD)	**42.0 (13.6)**	**1 f 26 m**	**9.9 (1.1)**	**100.2 (10.4)**	**1 L 26 R**	**7.6 (8.0)**	**14.4 (0.8)**	**3 n 24 p**

See below for sTBI patients.

Nr.	Age	Gender	Education	Premorbid IQ	Handedness	Time post injury	GCS	Ishihara
sTBI patients								
1	20	m	9	92	R	20	6	n
2	58	m	8	94	R	10	11	n
3	45	m	9	97	R	47	3	n
4	42	m	9	92	L	31	6	n
5	38	f	13	112	R	8	3	n
6	31	m	10	88	R	7	8	n
7	24	f	12	93	R	3	3	n
8	53	m	10	124	R	10	3	n
9	19	m	10	89	R	7	3	n
10	37	m	12	104	R	7	3	n
11	28	m	11	100	R	8	6	n
12	60	f	12	136	R	6	-	n
13	48	m	12	112	R	48	-	n
14	40	m	12	91	R	5	3	n
15	21	f	10	94	R	4	5	n
16	55	m	10	143	R	12	3	n
17	20	m	9	88	R	3	6	n
18	46	m	10	95	R	53	8	n
19	51	m	9	101	R	6	3	n
20	46	m	9	100	L	52	-	n
21	20	m	12	95	R	8	7	n
22	21	f	10	118	R	35	3	n
23	50	m	12	101	R	18	3	n
24	46	m	12	107	R	7	7	n
Mean (SD)	**38.3 (13.7)**	**5 f 19 m**	**10.5 (1.4)**	**102.8 (14.8)**	**2 L 22 R**	**17.3 (17.0)**	**4.9 (2.3)**	**24 n**

Table 17: TVA+NP: Individual exposure durations of mTBI and sTBI patients for the whole (intermediate exposure duration) and the partial report
M (SD): mean score and standard deviation

Nr. mTBI	WR exposure durations (ms)	PR exposure durations (ms)	Nr. sTBI	WR exposure durations (ms)	PR exposure durations (ms)
1	173	-	**1**	306	346
2	186	186	**2**	346	226
3	-	266	**3**	199	186
4	171	136	**4**	199	266
5	114	81	**5**	146	146
6	114	129	**6**	226	266
7	286	200	**7**	146	186
8	114	71	**8**	171	143
9	143	155	**9**	114	100
10	143	129	**10**	200	81
11	286	250	**11**	114	129
12	336	210	**12**	171	200
13	190	175	**13**	171	129
14	-	153	**14**	143	150
15	220	-	**15**	114	100
16	180	-	**16**	185	143
17	143	129	**17**	171	143
18	143	129	**18**	300	280
19	270	200	**19**	171	163
20	124	114	**20**	-	129
21	171	175	**21**	230	-
22	143	129	**22**	260	200
23	86	110	**23**	171	160
24	86	90	**24**	143	143
25	171	-			
26	86	71			
27	200	161			
Mean (SD)	**171 (66)**	**150 (53)**		**191 (63)**	**175 (65)**

Table 18: TVA+NP: Individual parameter estimates for mTBI and sTBI patients
t_0: perceptual threshold (ms); *C*: perceptual processing speed (N elements/sec); *K*: visual WM memory storage capacity (N elements); α: Efficiency of top-down control; Dev(w_{lat}): imbalance index of attentional weighting; M (SD): mean score and standard deviation

Nr. mTBI	t_0	*C*	*K*	Dev(w_{lat})	α	Nr. sTBI	t_0	*C*	*K*	Dev(w_{lat})	α
1	24.3	17	2.7	-	-	**1**	119.6	8	2.0	0.09	0.71
2	32.8	14	2.7	0.01	0.57	**2**	90.8	13	2.8	0.32	0.13
3	-	-	-	0.04	0.39	**3**	18.8	14	2.7	0.02	0.72
4	0	16	3.4	0.18	0.29	**4**	21.7	13	2.6	0.01	0.67
5	0	22	2.7	0.00	0.22	**5**	14.6	23	2.9	0.01	0.49
6	0	27	3.2	0.02	0.47	**6**	15.6	16	2.9	0.14	1.02
7	22.6	9	2.6	0.11	0.37	**7**	39	20	3.0	0.12	0.38
8	0	22	3.7	0.00	0.65	**8**	0	26	3.6	0	0.37
9	47.2	22	2.6	0.09	0.62	**9**	0	11	2.4	0.08	0.59
10	9.4	20	2.9	0.01	0.55	**10**	72	27	3.0	0.04	0.68
11	55.1	11	2.5	0.04	0.37	**11**	0.5	21	1.8	0.24	0.16
12	136.1	10	2.5	0.03	0.32	**12**	7.4	22	2.7	0.06	0.39
13	15.4	11	2.8	0.09	0.64	**13**	10.9	14	2.7	0.04	0.51
14	-	-	-	0.11	0.53	**14**	31	28	2.8	0.02	0.86
15	45.8	18	3.0	-	-	**15**	1.8	27	2.8	0.06	0.64
16	14.3	17	3.4	-	-	**16**	60	20	2.9	0.02	1.23
17	0.6	18	2.8	0.01	0.12	**17**	5.9	27	3.0	0.18	0.45
18	0	21	3.4	0.04	0.51	**18**	75.4	14	2.8	0.27	0.90
19	36.4	17	3.8	0.01	0.36	**19**	19.8	14	2.0	0.12	0.16
20	0	14	2.6	0.00	0.40	**20**	-	-	-	0.03	0.74
21	25.2	16	2.8	0.06	0.59	**21**	13.2	17	2.7	-	-
22	28.2	17	2.7	0.02	0.41	**22**	100.1	20	2.0	0.19	0.65
23	0	22	2.9	0.05	0.49	**23**	0	23	2.8	0.07	0.50
24	0	36	3.8	0.08	0.56	**24**	10.3	28	2.6	0.10	0.24
25	19.2	14	2.4	-	-						
26	0	36	3.7	0.06	0.40						
27	14.3	21	3.7	0.07	0.45						
Mean (SD)	**21.1 (29.4)**	**18.8 (6.8)**	**3.01 (0.47)**	**.05 (.05)**	**.45 (.14)**		**32.7 (36.1)**	**19.3 (6.2)**	**2.67 (0.41)**	**.10 (.09)**	**.57 (.28)**

Table 19: TVA+NP: Standard neuropsychological test scores for both TBI groups (means, standard deviations, and comparisons between means)
SRT: simple response time in the TAP; Mdn without: Median response time without preceding auditory warning signal; Mdn with: Median response time with preceding auditory warning signal; VMS: subtest "Visual Memory Span" of the WMS-R; F: forward; B: backward; VS: subtest "Visual Scanning" of the TAP; T: response time; E: error rate; FWIT: processing time in the Stroop Colour-Word Interference Test; CWR: colour-word reading; CNB: colour-bar naming; I: interference; SEL: selectivity index corrected for naming speed

mTBI	**SRT**		**VMS**		**VS**		**FWIT**			
	Mdn without	**Mdn with**	**F**	**B**	**T**	**E**	**CWR**	**CNB**	**I**	**SEL**
1	250	225	9	10	5323	0	-	-	-	-
2	229	238	11	8	4968	0	41	57	99	-2
3	216	206	-	-	4547	0	35	54	87	-4
4	263	282	9	5	4063	0	27	57	93	-5
5	230	226	12	9	4826	0	28	46	68	-6
6	257	210	9	10	-	-	39	55	75	-12
7	296	319	8	7	7223	0	37	48	62	-12
8	331	327	9	10	4540	0	37	65	104	-5
9	211	212	8	7	4495	0	51	77	98	-16
10	186	188	10	10	5767	1	30	37	62	1
11	280	250	11	9	5552	0	48	52	93	0
12	303	293	9	8	7414	1	36	82	107	-16
13	239	243	7	6	7163	0	39	48	79	-2
14	248	232	8	7	12455	0	33	46	67	-6
15	212	238	-	-	-	-	-	-	-	-
16	215	223	11	9	5538	0	28	40	56	-7
17	248	259	7	6	-	-	28	42	60	-6
18	332	325	8	9	6133	0	44	61	99	-6
19	368	317	8	9	4657	0	43	48	95	6
20	185	176	7	8	4879	0	39	43	64	-4
21	247	243	5	10	6816	0	33	44	67	-4
22	212	226	7	6	6730	1	26	34	59	4
23	232	236	8	6	5990	0	29	42	64	-3
24	178	172	9	9	-	-	48	57	75	-14
25	265	251	7	6	6664	0	-	-	-	-
26	210	203	7	6	3217	0	32	54	65	-16
27	189	205	9	10	3080	0	35	44	87	6
Mean (SD)	**246 (48)**	**242 (44)**	**8.5 (1.6)**	**8.0 (1.7)**	**5741 (1902)**	**0.13 (0.34)**	**36.1 (7.1)**	**51.4 (11.6)**	**78.5 (16.6)**	**-5.38 (6.45)**

See below for sTBI patients.

sTBI	SRT		VMS		VS			FWIT		
	Mdn without	Mdn with	F	B	T	E	CWR	CNB	I	SEL
1	233	229	4	6	8989	0	59	86	163	1
2	293	255	7	8	6880	0	36	54	90	-2
3	250	231	10	10	4748	0	51	74	120	-6
4	284	317	7	7	6544	0	66	71	83	-21
5	196	198	11	8	4060	0	32	43	76	3
6	241	225	5	5	8788	0	39	84	183	-
7	262	256	9	10	4790	0	42	52	75	-9
8	246	256	8	8	5585	0	26	40	71	3
9	213	214	7	5	5899	0	28	61	98	-6
10	234	210	9	9	3138	0	27	36	52	-5
11	248	236	8	8	9350	0	34	46	73	-3
12	273	274	7	6	6518	0	30	46	57	-13
13	266	269	8	10	6594	0	39	60	90	-8
14	256	245	6	10	4403	0	36	43	64	-4
15	279	233	9	8	4464	0	32	41	57	-7
16	257	261	11	9	3935	0	30	41	59	-6
17	358	372	9	11	7176	0	34	60	86	-10
18	343	324	7	7	-	-	45	57	96	-3
19	236	240	10	8	8075	0	48	62	80	-15
20	244	270	8	8	-	-	-	-	-	-
21	225	186	8	7	7649	0	44	50	94	4
22	260	222	6	4	6483	0	36	51	77	-7
23	335	337	7	6	-	-	39	59	82	-7
24	285	364	7	6	7955	0	37	40	61	-11
Mean (SD)	**263 (39)**	**259 (50)**	**7.8 (1.7)**	**7.7 (1.8)**	**6287 (1799)**	**0.0 (0.0)**	**38.7 (10.0)**	**54.7 (13.9)**	**86.4 (31.8)**	**-5.82 (6.05)**

Table 20: TVA+NP: Correlation coefficients between perceptual threshold (t_0) and standard neuropsychological test scores

t_0: perceptual threshold (ms); SRT: simple response time in the TAP; Mdn without: Median response time without preceding auditory warning signal; Mdn with: Median response time with preceding auditory warning signal; VMS: points in the subtest "Visual Memory Span" of the WMS-R; F: forward; B: backward; VS: subtest "Visual Scanning" of the TAP; T: response time; FWIT: processing time in the Stroop Colour-Word Interference Test, I: interference condition; SEL: selectivity index corrected for naming speed; CWR: colour-word reading condition; CBN: colour-bar naming condition

Neuropsychological test		t_0
SRT	Mdn without	.15
	Mdn with	.08
VMS	F	-.08
	B	.04
VS	T	.09
FWIT	I	.17
	SEL	.13
	CWR	.30
	CBN	.09

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Declaration

I hereby confirm that this work submitted for assessment “Deficits in visual attention after mild and severe traumatic brain injuries” is my own and is expressed in my own words, except where otherwise stated. Any uses made of the work of other authors are properly acknowledged at the point of their use. A full list of the references employed has been included.

This dissertation has not already been accepted for any degree, and is also not being concurrently submitted for any other degree.

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Ingo Pals