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Moment-to-Moment Fluctuations in Sustained Attention in Individuals with Traumatic Brain Injury

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MOMENT-TO-MOMENT FLUCTUATIONS IN SUSTAINED ATTENTION IN INDIVIDUALS WITH TRAUMATIC BRAIN INJURIES (TBI)

BY

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ABSTRACT

MOMENT-TO-MOMENT FLUCTUATIONS IN SUSTAINED ATTENTION IN INDIVIDUALS WITH TRAUMATIC BRAIN INJURY

By

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Introduction: The present study examined moment-to-moment variations in reaction time (RT) using the Complexity Estimate (CE), a measure of system entropy. The primary hypothesis explored whether system entropy (CE) is higher in mild TBI (TBI) compared to neurologically healthy controls. The secondary hypothesis was to examine whether system entropy increases with task difficulty in both populations, but to a greater extent in those who have experienced TBI.

Methods: 27 individuals who had experienced a TBI and 22 neurologically healthy individuals aged between 18-35 years were recruited to the Cognition, Brain, and Language Team (CoBALT) lab at the University of New Hampshire Department of Communication Sciences and Disorders research laboratories. The *Starry Night* task was employed to measure sustained attention in individuals with TBI and the control group, in order to investigate whether processing speed in individuals with TBI is more variable than neurologically healthy individuals. This study is a retrospective analysis of a repeated measures design that uses a mixed model to explore the effect of Group (TBI versus control), Task Complexity, and their interaction on the response variable of the Complexity Estimate, which is an index of reaction time (RT) variability.

Results: Task Complexity and Group were both significant predictors of RT Complexity. There was a significant interaction between Task Complexity and Group (F Ratio = 4.28, *p*-value = 0.0167), indicating that the effect of Group on RT Complexity depends on the level of the Task Complexity. This implies that reaction time complexity is influenced by both the participant's group and the complexity of the task they are performing. It was observed that there was no difference in RT complexity for the control group, however in the TBI group, there was a difference in reaction time based on the task's complexity. The variance component of the random effect (Study Subject) was 0.118 (CI: 0.002 to 0.235, Wald *p*-value=0.0469), indicating that there is significant variability in RT Complexity among individuals in response to Task Complexity and Group.

Discussion: The study results suggest that system entropy is higher in individuals with TBI compared to neurologically healthy individuals. Additionally, as task difficulty increases, system entropy increases in both populations, with a greater increase observed in individuals with TBI. Measures of RT complexity proved to be a valuable indicator of increased system entropy resulting from task difficulty. Together these findings offer insight into how individuals with TBI prioritize and allocate their attention in complex environments, which can assist in developing interventions that address attentional deficits in individuals with TBI.

INTRODUCTION

Traumatic brain injury (TBI) is a major healthcare crisis in the United States as indicated by the Center for Disease Control and Prevention (CDC). The CDC estimates that approximately 1.5 million Americans sustain a TBI each year. Of those individuals, 230,000 are hospitalized. Moreover, approximately 5.3 million Americans presently live with impairments because of TBI (CDC, 2016; George & Das, 2022; Neurology, 2010; Stierwalt & Murray, 2002). To further support the need for research in the area of concussions/TBI, it is known that there are 611 TBI-related hospitalizations, and 176 TBI-related deaths occur each day in the United States (CDC, 2016). From a global perspective, it is estimated that 50% of the world's population will sustain a TBI in their lifetime, costing the global economy $400 billion USD per year and this cost does not reflect the potential loss of individuals from the workforce (Chan, 2022). This introduction will discuss (1) primary symptoms in TBI, (2) models of attention, (3) the *Starry Night* task, and (4) the purpose of the present study.

Primary Symptoms in TBI

TBI is caused by an external force, such as a blow to the head, and can result in physical, cognitive, and psychosocial impairments (CDC, 2019). One of the most common and debilitating effects of TBI is difficulty sustaining attention, which can have a dramatic impact on one's quality of life. The primary symptoms of TBI can vary depending on the severity of the injury and its primary location in the brain but include deficits in sustained attention, memory, problem-solving, and executive control (Bagiella et al., 2010; Stuss, 1999).

Perhaps the most consistent deficits across all individuals with TBI are cognitive in nature involving attention, memory, problem-solving, and executive control. Of these symptoms, impairments in attention may be the most common and have the greatest impact on participation in life (Bagiella et al., 2010; Dikmen et al., 2009; Stuss, 1999). In particular, people with TBI are known to have difficulty sustaining attention (Robin et al, 1999). The ability to sustain attention is critical for performing everyday tasks and engaging in a productive life. Hence, the impairment in sustained attention in TBI can result in substantial impact on the ability to engage in activities of daily living as most require the ability to focus for varying lengths of time. As well, deficits in sustained attention include increased distractibility, difficulty focusing on task, and troubles with priority assignment associated with allocating attention to the most important task at hand. Because individuals with TBI demonstrate a significant impairment in the ability to sustain attention, they exhibit inaccurate and variable task performance and respond more slowly than neurologically healthy individuals (Bonnelle et al., 2011; Kim et al., 2009; Slovarp et al., 2012). To further understand the nature of the sustained attention deficit in TBI, it is important to model the attentional processing as a limited capacity system that drives the allocation of resources to a particular task; assigning priority to those tasks that require high attention focus (i.e., complex tasks) or tasks that must be completed quickly, and directing attention accurately to specific aspects of a task in order to ensure correct completion. Given this, this experiment is structured around Kahneman's (1973) Limited Capacity model of attention which is discussed below.

Kahneman's Limited Capacity Model of Attention

Kahneman's (1973) limited capacity model emphasizes task complexity effects on the amount of resources needed to complete a given task. Based on task demands and capacity limitations, when stressed by high task complexity and/or when capacity is reduced (e.g., brain injury) people have an increased sense of mental effort. This increased effort can result in cognitive fatigue which then impairs performance. Specifically, the Kahneman model focuses on resource availability, limited resource capacity, task complexity and their associated sense of effort, mental fatigue, and ultimate task performance.

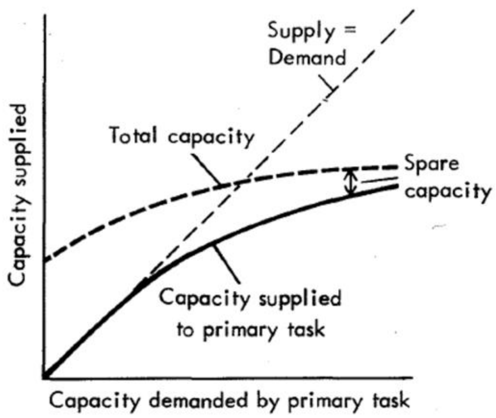


Figure 1. The supply of effort as a function of demands on the primary task (Kahneman, 1973, Figure 2-1).

Figure 1 depicts Kahneman's limited capacity model emphasizing that the amount of attentional resources available to complete tasks is finite (Kahneman, 1973). According to this model, there is a limited capacity to the total amount of attention that can be utilized at one time and that once one's capacity limit is reached, sense of effort increases as more attentional resources are required to execute a task. However, when the capacity is reached and exceeded, errors in performance occur (Bruya & Tang, 2018; Kahneman, 1973). Moreover, under conditions where capacity limitations are reached, priority assignment and focus of attention falter. Assigning priority to specific tasks is critical as most situations require the need to engage in multitask processing. If there is an attentional impairment, the multiple demands needed to successfully complete a task compete for the same attentional resource and completion of one or both tasks will suffer (e.g., driving a car while having a conversation) (Kahneman, 1973).

The limited capacity model can be used to understand and model the sustained attention deficits experienced by individuals with TBI. The limited capacity model suggests individuals with TBI have reduced attentional resources which makes their ability to sustain attention on task more effortful and they reach their capacity limit more quickly than neurologically healthy individuals. As tasks become more complex, individuals with TBI perform more slowly (e.g., increased reaction time, RT) and inaccurately on tests of attention compared to healthy individuals (Bonnelle et al., 2011; Docktree et al., 2006; Slovarp et al., 2012). As time on task increases, RT increases, and accuracy decreases (Bonnelle et al., 2011; Docktree et al., 2006; Slovarp et al., 2012). Regardless of TBI severity, errors and increases RT occurs across time-sensitive sustained attention tasks (Bonnelle et al., 2011). Thus, the supply of attentional resources is closely associated with the degree of mental effort needed, which likely increases over time if the task or time needed to attend is longer than a one-time rapid task. This situation then leads to a depletion of cognitive resources, increased cognitive fatigue, and decreased performance accuracy. Support for a resource model to understand how people with TBI perform comes from extensive data showing that cognitive load and mental effort are critical to normal and impaired processing and impact RT and accuracy when completing tasks (Bonnelle et al., 2011; Docktree et al., 2006; Slovarp et al., 2012).

It is also known that attention varies over the course of a given task. For example, Docktree et al. (2006) reported that “drifts” (increased variability) in attention coincided with performance on complex cognitive tasks. While not part of the current study, a long-term goal in understanding attention and mental effort in TBI is that a model of attention that subsumes impairments found in TBI, can aid in the development of interventions to improve sustained attention and cognitive performance in individuals with TBI. One test of sustained attention that has received empirical support in TBI is the Starry Night Test of Sustained Attention which is discussed below.

Starry Night

In order to quantify sustained attention in TBI and explore performance variability, we used the Starry Night Test of Sustained Attention (Rizzo & Robin, 1990), which requires participants to identify the appearance or disappearance of a single star amongst a large number of distractors. Specifically, Starry Night quantifies accuracy (d'), RT, and response bias (β) associated with the ability to sustain visuospatial attention over an 8–12-minute period. Rizzo & Robin (1990) originally used Starry Night to analyze the sustained visuospatial attention abilities of individuals with simultanagnosia, a disorder associated with bilateral lesions of the visual cortex, where "subjects complain of piecemeal perception of the visual environment wherein objects may look fragmented or even appear to vanish from direct view" (Rizzo & Robin, 1990, p. 448). The Starry Night task involves responding as rapidly as possible to events (i.e., the appearance or disappearance of a star) by quickly pressing a button; this provides accuracy and a RT measure for each response. The task has been standardized on three levels of increasing complexity (i.e., star density) that are 50, 250, and 1,000 stars respectively (Rizzo & Robin, 1990).

In individuals with TBI, Robin et al. (1999) demonstrated lower accuracy and longer reaction times (RTs) compared to controls. Moreover, individuals with TBI showed decreasing accuracy and increasing RT over the course of a single session. Robin et al. (1999) only used the 250-star condition, so it is unknown if performance changes differentially depending on task complexity. The study also found that β did not differentiate between groups (Robin et al., 1999). At that time, it was hypothesized that the poorer performance of the TBI group was associated with a greater sense of effort leading to cognitive fatigue in a relatively short period of time. Reductions in the attentional capacity and the ability to allocate attentional resources appropriately are known to lead to an increased sense of effort leading to mental fatigue (Robin et al., 1999; Kahneman, 1973). As predicted by Kahneman's limited capacity model of attention, when tasks become increasingly complex, attentional resources deplete and the allocation of attention and effort becomes chaotic/entropic (noisy). Increases in chaos are reflected by increases in performance variability (Kahneman, 1973). Thus, we hypothesize that as star density on the Starry Night task increases, the demands on attention and mental effort increase. Increased complexity also impacts the ability to allocate resources. In summary, the impact of deficits in sustained attention are many and one area not well studied is the determination of performance variability associated with predicting future resource needs.

Based on the above, the current study examined moment-to-moment variations in RT using the Complexity Estimate (CE), as the measure of system entropy. The primary hypothesis is that system entropy (CE) is higher in TBI than in neurologically healthy controls. The study also tested the secondary hypothesis that system entropy increases with increased task complexity in both populations, but the increase will be proportionally higher in people who have experienced a TBI.

II. METHODS

Participants

Study participants were forty-nine individuals, aged 18-35 years (mean = 21.9, 36 females, 13 males) who were recruited to the Cognition, Brain, and Language Team (CoBALT) lab at the University of New Hampshire Communication Sciences and Disorders research laboratories. All participants provided written informed consent for participation per an approved and monitored Institutional Review Board (No. 6646).

Participants in the experimental group had to meet specific criteria, including having an intermediate level of English proficiency, being between the ages of 18 and 35, having experienced at least one but no more than five concussions and, the most recent concussion occurring between one month and five years before registration for the study (Ramage et al., 2019). Control participant inclusion criteria were an intermediate level of English proficiency, being neurologically healthy adults between the ages of 18 and 35, and having no prior history of neurological disorders or head trauma (Ramage et al., 2019). Additional exclusion criteria were having experienced a penetrating head trauma, having poor vision without correction, having a seizure disorder, having a history of psychosis, taking antipsychotic medication(s), or using narcotic pain medication (Ramage et al., 2019). Of the fifty original participants, forty-nine were included in this study. Twenty-seven participants made up the TBI group. TBI-related events occurred between six months to seven years prior to the start of the study, with an average of 2.02 years. Twenty-two neurologically healthy individuals made up the control group. All individuals completed the Fatigue Severity Scale, Insomnia Severity Scale, Headache Impact Test, and Beck Depression Inventory (Beck et al., 1996; Kosinski et al., 2003; Krupp et al., 1989; Morin, 1993). More details about these individuals may be found in Table 1.

Table 1. Demographic information for all subjects.

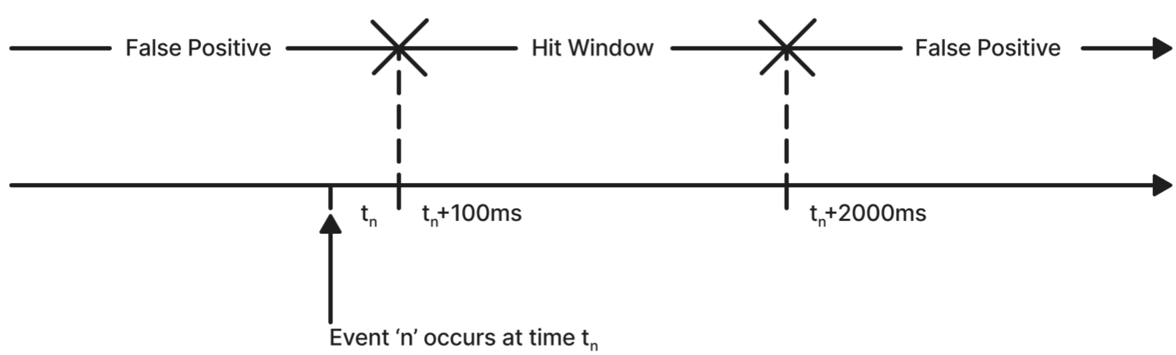
Measure	**TBI**	**Control**
n	27	22
Age	21.3 ± 4	22 ± 4
Gender (F:M)	22:05	14:08
Race		
Asian, White	0	1

African American	1	1
White	26	20
# Concussions per lifetime		
One concussion	11	-
Two concussions	7	-
Three concussions	6	-
Four concussions	3	-
How injuries were sustained		
Sports-related accidents	18	-
Falls	4	-
Blunt-force trauma	4	-
Motor-vehicle accidents	2	-
Fatigue Severity Scale*	3.6 ± 2	2.7 ± 1
Insomnia Severity Scale*	11.0 ± 6	4.6 ± 3
Headache Impact Test*	54 ± 8	42.4 ± 5
Beck Depression Inventory	11.0 ± 10	4.2 ± 4
* $p < .05$ (Bonferroni correction)		

Procedure and Design

The Starry Night task was used to quantify sustained attention individuals with mild TBI and a control group to examine if processing speed in individuals with mild TBI are more variable than neurologically healthy individuals. The task is a measure of sustained attention over a visual spatial array (computer screen) and resembles a night sky filled with stars. There were three background conditions: 50, 250, and 1,000 stars corresponding from low-to-high complexity levels, respectively. Participants responded to an appearance or disappearance of a star with a button press. Task difficulty ranged between 50, 250, or 1,000 identical and spatially random distractor elements (stars) and a minimum of 200 trials (see Figure 2). Participants were required to respond to 200 instances of stars appearing or disappearing. Stars appeared and disappeared at random intervals and spatial locations (Rizzo & Robin, 1990, 1996; Robin et al., 1999). Time on task lasted between five and twelve minutes at each complexity level across participants. Responses were recorded as a hit, miss, or a false positive. A response was considered a hit if the response fell between 100-2,000 milliseconds (ms) after a star appeared or disappeared. A response was considered a miss if no response occurred during the 100-2,000 ms interval. A response following a hit or miss when a stimulus had not occurred was coded as a false positive (see Figure 2) (Rizzo & Robin, 1996). To ensure data accuracy, response times that extended beyond 8,000 ms have been eliminated from the analyses. These responses were deemed potentially influenced by the participant's unintentional act of leaving their finger on the keyboard's space bar. Additionally, the data was refined to encompass solely data pertaining to "hits".

Figure 2. The schema for Starry Night response windows.



Design and Analysis

This study is a retrospective analysis of a repeated measures design that uses a mixed model to investigate the effect of Group (TBI versus control), Task Complexity, and their interaction on the response variable of the Complexity Estimate (an index of reaction time variability). The model used Group, Task Complexity, and the interaction of Group and Task complexity as fixed effects. Study Subject was a random effect. A first-order autoregressive (AR(1)) covariance structure was used. The model was run in JMP Pro version 16.1.0. Pairwise comparisons were performed post-hoc with a Tukey HSD test. Level of significance was set at *p-value*=<.05.

The complexity estimate (Batista et al., 2014) is a measure of the overall complexity of a time series; it measures the magnitude of the fluctuations in a system from one event to the next, in this case RT. The complexity estimate for each time series was calculated using a standardized approach. Prior to calculating the complexity estimate, the algorithm applied a standardization formula as shown in Figure 3 to each time series. To elaborate, for each subject's time series (x) at a particular task complexity level, the mean (μ) of all reaction time (i.e., all the points in the time series) was computed. Next, each time point in the time series was standardized by subtracting the mean and dividing by the standard deviation (σ). The rationale behind standardizing the time series was to bring all the data to the same scale and enable more meaningful comparisons. As a result of the standardization process, each time series had a mean of zero and a standard deviation of one. In doing so, the fluctuations of reaction times were measured based on the standardized mean and standard deviation, rather than the raw values.

$$z = \frac{x - \mu}{\sigma}$$

Figure 3. Equation for standardizing time series.

The complexity estimate (Batista et al., 2014) is a measure of the overall complexity of a time series; it measures the magnitude of the fluctuations in a system from one event to the next, in this case RT. To calculate the complexity estimate associated with RT, we used the following formula (Batista et al., 2014) (Figure 4). RT in ms was recorded when a participant correctly identified an appearing or disappearing star (i.e., an "event"). Each participant's trial resulted in a time series of RTs. Time series length varied from 251 events to 914 events per person.

$$\sqrt{\sum_{i=1}^{n-1}(x_i - x_{i-1})^2}$$

Figure 3. The formula to calculate the complexity estimate associated with RT.

Where *x* is the RT at event *i* and *n* is the total number of events in the time series.

III. RESULTS

Mean RT complexity, categorized by task complexity (i.e., 50, 250, and 1,000 stars) and group (TBI vs. control), along with standard error bars, is shown in Figure 4.

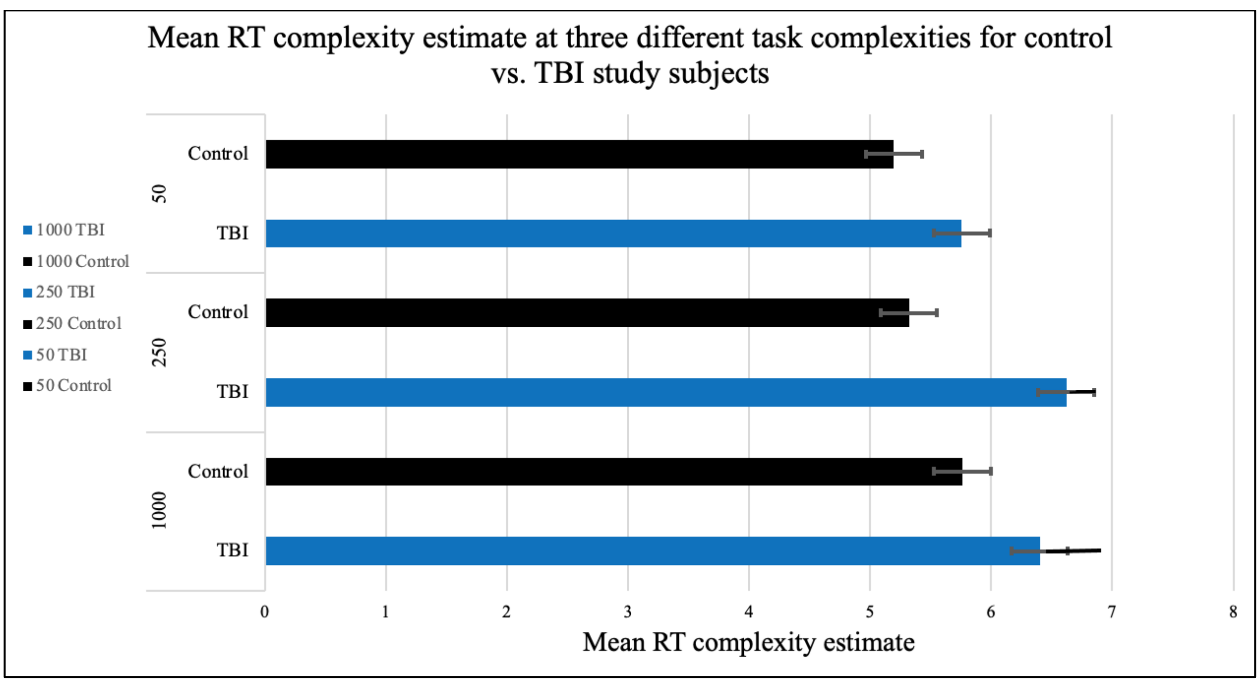


Figure 4: Mean RT complexity estimate at three different task complexities for control vs. TBI study subjects.

Task Complexity and Group were both found to be significant predictors of Reaction Time Complexity (Table 2). Additionally, there was a significant interaction between Task Complexity and Group (F Ratio = 4.28, *p*-value=0.0167), indicating that the effect of Group on Reaction Time Complexity depends on the level of the Task Complexity, and the reverse. This implies that reaction time complexity is influenced by both the participant's group and the complexity of the task they are performing. It was observed that there was no statistically significant difference in RT complexity for the control group, however in the TBI group, there was a statistically significant difference in reaction time based on the task's complexity.

Fixed Effects Test					
Source	**Nparm**	**DFNum**	**DFDen**	**F Ratio**	**Prob > F**
Complexity	2	2	91.7	9.6824904	0.0002*
Group	1	1	129.9	5.8685799	0.0168*
Complexity*Group	2	2	91.7	4.2775524	0.0167*

Table 2: Summary of fixed effects test of reaction time complexity between task complexity and group.

A post-hoc Tukey HSD test was conducted to examine pairwise comparisons (Table 3). Significant differences in reaction time variability were found between the TBI and control groups at 250- and 1,000-stars, but not at 50-stars. Within the control group, no significant differences were detected when comparing 50-, 250-, and 1,000-star densities. Within the TBI group, there were differences between 50- and 250-star densities and 50- and 1,000-star densities, but not between 250- and 1,000-star densities.

Tukey HSD All Pairwise Comparisons

Quantile = 2.91088, Adjusted DF = 91.7, Adjustment = Tukey-Kramer

Complexity	Group	-Complexity	-Group	Difference	Std Error	t Ratio	Prob> [t]	Lower 95%	Upper 95%
50	TBI	50	Control	0.56504	0.2332437	2.42	0.1594	-0.11391	1.24398
50	TBI	250	TBI	-0.85327	0.1938929	-4.40	0.0004*	-1.41767	-0.28887
50	TBI	250	Control	0.44469	0.2305101	1.93	0.3914	-0.22630	1.11567
50	TBI	1000	TBI	-0.63419	0.1938929	-3.27	0.0183*	-1.19859	-0.06979
50	TBI	1000	Control	0.00414	0.2305101	0.02	1.0000	-0.66684	0.67513
50	Control	250	TBI	-1.41831	0.2177345	-6.51	<.0001*	-2.05210	-0.78451
50	Control	250	Control	-0.12035	0.2086266	-0.58	0.9923	-0.72763	0.48694
50	Control	1000	TBI	-1.19923	0.2177345	-5.51	<.0001*	-1.83303	-0.56543
50	Control	1000	Control	-0.56089	0.2086266	-2.69	0.0874	-1.16818	0.04639
250	TBI	250	Control	1.29796	0.2148036	6.04	<.0001*	0.67269	1.92322
250	TBI	1000	TBI	0.21908	0.1749290	1.25	0.8096	-0.29012	0.72827
250	TBI	1000	Control	0.85741	0.2148036	3.99	0.0018*	0.23215	1.48268
250	Control	1000	TBI	-1.07888	0.2148036	-5.02	<.0001*	-1.70415	-0.45361
250	Control	1000	Control	-0.44054	0.2055659	-2.14	0.2749	-1.03892	0.15783
1000	TBI	1000	Control	0.63834	0.2148036	2.97	0.0426*	0.01307	1.26360

Table 3. Summary of Tukey-Kramer HSD all Pairwise Comparisons

When adjusting for task complexity, the mean reaction time complexity in the TBI group was 0.283 higher than in the Control group (Table 4). When adjusting for group, the mean reaction time complexity at the task complexity level of 250 was 0.487 higher than at level 50, and reaction time complexity at level 1,000 was not significantly higher than at level 250.

Cohen's *d* which is a standardized effect size was used to measure the difference between the TBI and control groups. Effect sizes of *d*=0.2, *d*=0.5, and *d*=0.8 are considered small, medium, and large, respectively. The study found large effect sizes between the TBI and control groups at 250- and 50-stars (*d*=3.42), at 1,000- and 250-stars (*d*=0.82), and at 1,000- and 50-stars (*d*=4.2). Furthermore, large effects sizes were found within the TBI group across all complexities (*d*=2.42), between 250- and 50-stars (*d*=2.57), and between 250- and 1,000-stars (*d*=2.44). However, a small effect size was found within the TBI group between 1,000- and 50-stars (*d*=0.26).

Fixed Effects Parameter Estimate			
Term	**Estimate**	**Std Error**	**Cohen's *d***
Complexity[250-50]	0.4868086	0.142407	3.418422
Complexity[1000-250]	0.1107336	0.134961	0.820488
Complexity[1000-50]	0.597542	0.142407	4.196004
Group[TBI]	0.2825182	0.116622	2.422516
Complexity[250-50]*Group[TBI]	0.3664603	0.142407	2.573323
Complexity[250-1000]*Group[TBI]	0.329811	0.134961	2.443757
Complexity[1000-50]*Group[TBI]	0.03665	0.142407	0.25736

Table 4: Summary of fixed effects parameter estimate adjusted for task complexity between the TBI and control group.

IV. DISCUSSION

The present study was designed to investigate time series complexity as quantified by the complexity estimate (CE) in individuals with TBI during the Starry Night Test of Sustained Attention. Two hypotheses were tested in this study. The primary hypothesis was that individuals with TBI would exhibit a higher CE of RT data than individuals with no brain injury. The secondary hypothesis postulated that increases in task complexity (star density) would be associated with increases in CE suggesting that as task complexity increases, the stability of performance becomes more entropic. Thus, we aimed to examine the association between CE and the presence of a TBI as well as its association with task difficulty, hypothesizing that the level of entropy would rise concomitant with the increase in complexity, with individuals with TBI disproportionally affected by this increase. The results generally supported these predictions in paired comparisons. The CE was significantly higher in individuals with TBI compared to neurologically healthy individuals, confirming the primary hypothesis. Furthermore, the secondary hypothesis was also supported, a significant CE difference was observed in the TBI, but not the neurologically healthy participant group between 50- and 250-star densities, as well and between 50- and 1,000-star densities in the TBI group. These findings extend those reported by Robin et al., (1999), which indicated that individuals with TBI demonstrated lower accuracy and longer response times in the 250-star density condition. The current research expands on this by highlighting that task difficulty (star density) had a significant impact on TBI group performance, with lower accuracy and longer response times observed across varying star densities.

Interpretation Based on Kahneman's Limited Capacity Model of Attention

The results of the present study demonstrated that individuals with TBI show a higher CE than neurologically healthy individuals. These data are consistent with Kahneman's model of attention which focuses on capacity limitations in relation to task complexity. As individuals reach their capacity limit, the ability to allocate attentional resources diminishes and results in greater performance variability and ultimately incorrect performance on a given task. Results suggest that individuals with TBI exhibit greater variability on the Starry Night task compared to their neurologically healthy counterparts. Specifically, the heightened demands on attention and mental effort in TBI appears to be associated with a diminished ability to allocate attentional resources efficiently. These data suggest that as entropy (noise) increases, the ability to allocate attentional resources decreases, leading to difficulty in accurately assigning priority to upcoming tasks.

Kahneman's model of attention (Figure 1) characterizes the supply of effort as a function of demands on a primary task and provides a useful framework for explaining the results of this study. Specifically, how humans respond to demands on effort. The model can shed light on the relationship between task difficulty, allocation of attentional resources, and performance on the Starry Night task. To clarify, the x-axis of the model represents the capacity demanded by the primary task, which in this study is equivalent to the level of task difficulty, as reflected by the star density. As the demands of the primary task increase, the capacity required to complete the task also increase, resulting in a decrease in the available resources for other tasks.

Based on the model, decreases in capacity can lead to poorer performance and slower reaction times, as observed in previous research (Robin et al., 1999). The model has the amount of resources in relation to task complexity, focusing on how individuals strategically allocate their attentional resources. In the context of this study, resources are supplied in order to be available to complete different task difficulties (as indicated by star densities) in the Starry Night task. During the completion of the primary task in the Starry Night task, which involves detecting the appearance or disappearance of a star, individuals must direct their attentional resources away from other visual distractors in the environment (i.e., greater star densities). As a result, the amount of attentional resources available decreases. Therefore, as task difficulty increases, the capacity limit is reached more quickly, leading to reduced performance and slower reaction times. In Figure 2 on the straight dotted line labeled “supply=demand”, demand” can be interpreted as the point at which an individual reaches their capacity limit, the supply of attentional resources cannot meet the demand. Thus, the system has become overloaded, or entropic, and they are unable to supply the right amount of resources onto the primary task and therefore have difficulty assigning priority to which tasks or aspects of a task they need to attend to in order to correctly complete a given task. When this occurs, there is no spare capacity. Specifically, for individuals with TBI, when this occurs, they are unable to do anything else; they have reached their attentional overload. The results of this study support this in the TBI group; as task difficulty increases the ability to allocate attentional resources decreases. Therefore, the TBI group reaches their capacity limit at a faster rate that neurologically healthy individuals. Specifically, individuals with TBI exhibit greater variability in their responses as the task complexity increases, which indicates that the demands on attention and mental effort increase with greater star density on the Starry Night task.

Similarly, there was no significant difference in performance when the TBI group at 50-stars was compared with the control group at 250-stars. This suggests that both groups exerted similar amounts of effort on different levels of task difficulty. However, as the level of task difficulty increased, significant differences emerged between the TBI group and the control group. These data demonstrate that the TBI group was abnormally sensitive to changes in task difficulty. For instance, the study revealed a noteworthy distinction in the performance between the TBI and control group during the 250-star density condition. The groups demonstrated a disproportionate performance at the same level of task difficulty. The results indicate that with an increase in task difficulty, attentional resources deplete in the TBI group, leading to entropic allocation of attention and effort as evidenced by increases in performance variability observed between the two groups at the same task difficulty level. This finding highlights the impact of TBI on the allocation of attentional resources, particularly when the complexity of the task increases.

Moreover, no significant difference was found in the 250- and 1000-star comparison in the TBI group. This indicates that the TBI group reached its capacity limit. Specifically, the TBI group's performance did not differ between the two difficulty levels because they had reached their capacity limit. As soon as this limit is reached, performance declines as the demands on attention exceed the resources available (Kahneman, 1973). Consequently, it may be inferred that the attentional demands placed on the 250- and 1,000-star density tasks surpassed the TBI group's attentional resources.

These findings demonstrate that as star density on the Starry Night task became more complex, the demands on attention and mental effort increased as reflected by greater performance variability in the TBI group. By contrast, the neurologically healthy participants did not differ significantly across star densities. Therefore, it can be inferred that neurologically healthy individuals possess intact abilities to allocate attentional resources and accurately assign priority to upcoming tasks. This suggests that neurologically healthy individuals have a greater attentional capacity limit and less entropy compared to individuals with TBI. Interestingly, no statistically significant difference was found between the TBI and control group at 50-star densities. Less complex tasks did not differentiate between the two groups, suggesting that the amount of effort required to complete the task and allocate attentional resources was within their capacity limits. In conclusion, individuals with TBI exhibit greater system entropy during complex tasks, which is reflected in greater performance variability than neurologically healthy individuals. These findings have important implications for individuals with TBI, which should consider the effects of task difficulty on attentional resources and system entropy. Finally, the variance component of the random effect (i.e., Study Subject) was statistically significant. This finding implies the existence of unaccounted factors that could significantly affect the RT and were not included in our model. Such factors could be associated with the duration that elapsed since participants experienced a TBI, the number of TBIs that individuals experienced in their lifetime, or both. Therefore, it is imperative to account for these potential factors in future models.

Clinical Implications

The outcomes of the study shed light on the impact of TBI on attentional control and have significant implications for the development of rehabilitation interventions. The findings suggest that a larger data pool consisting of both neurologically healthy individuals and those with TBI could enhance the potential utility of Starry Night as a clinical tool. If implemented in clinical settings Starry Night could provide valuable insights aimed at improving sustained attention deficits in individuals with TBI. It's important to acknowledge that people with TBI have difficulty predicting how to prioritize and allocate their attention. In light of these findings, it is crucial to consider the development of interventions that focus on this unpredictability to help individuals with TBI overcome this system entropy in order to function better. Understanding the nature of moment-to-moment fluctuation in sustained attention, rather than just the duration of attention, could advance the way clinicians approach interventions for TBI. Overall, these results suggest that Starry Night has promising potential as a clinical tool for rehabilitation interventions in individuals with TBI. Additionally, this study provides insight into how individuals allocate attentional resources and how task demands can affect attentional capacity and performance by utilizing Kahneman's model of attention. These findings have important implications for understanding how individuals with TBI prioritize and allocate their attention in complex environments.

Limitations and Future Directions

This study had several limitations that must be acknowledged. Firstly, the sample size was relatively small, consisting of only 49 participants. Additionally, the distribution of gender was unbalanced across groups, with more females than males in both the TBI and control groups. Secondly, the instrumentation used to provide directions for the Starry Night task was not standardized. As a result, some of the study subjects' data had to be discarded because they held down the space bar key throughout the entire study, rendering the data unusable. Furthermore, the measure of RT complexity utilized in this study is not standardized for the number of time points in the time series. While this limitation did not significantly impact the study findings since there was no significant difference between time points within groups, it is an aspect that should be considered in future studies. Therefore, it is imperative to acknowledge this limitation and be mindful of its potential impact on the results in studies that utilize a measure of RT complexity that is not standardized for the number of time points in the time series. Future research should aim to address these limitations to further enhance the generalizability and validity of findings.

Moving forward, the data from this study could be used to further investigate the relationship between behavioral outcome measures and the Starry Night data. To confirm the findings reported here and explore the link between the Starry Night data and behavioral outcomes, replication studies are necessary. If this link can be established, the Starry Night task may prove to be a useful clinical tool.

In addition, future studies could utilize brain imaging techniques to investigate the neural networks involved in sustained attention while participants complete the Starry Night task. This would provide valuable insight into the cognitive processes underlying sustained attention and how they interact with other cognitive processes that could contribute to cognitive deficits in individuals with TBI. Moreover, establishing a Starry Night data repository with a larger and more diverse data pool could significantly increase the clinical utility of this tool, not only for individuals with TBI but also for those with other disorders. Ultimately, this line of research has the potential to greatly enhance our understanding of the underlying mechanisms of cognitive deficits in TBI and inform the development of more effective intervention.

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