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Multiple levels of mental attentional demand modulate peak saccade velocity and blink rate

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ABSTRACT

Every day we mentally process new information that needs to be attended, encoded and retrieved. Processing demands depend on the amount of information and the mental attentional capacity of the individual. Research shows that eye movement indices such as peak saccade velocity and blink rate are related to processes of attentional control, however it is still unclear how eye movements are affected by graded changes in task demand. We examine for the first time relations of eye movements to mental attentional tasks with six levels of task demand and two interference conditions. We report data on 57 adults who completed two versions of the color matching task and provided subjective self rating for each mental attentional demand level. Results show that peak saccade velocity and blink rate decrease as a function of mental attentional demand and correlate negatively with self rating of mental effort. Theoretically, new findings related to mental attentional demand and eye movements inform models of visual processing and cognition. Practically, results point to directions for further research to better understand complex relations among eye movements and mental attentional demand in pediatric populations and individuals with cognitive deficits.

1. Introduction

Attention is a way we dispose of our consciousness, and how many things we can mobilize with attention can change how we problem solve. Mental attention is the effortful application of cognitive resources in the service of problem solving (Pascual-Leone, 1970; Pascual-Leone and Johnson, 2021). Eye movements have been shown to be closely related to attentional processes (Duchowski, 2003). Most eye-tracking studies examine eye movements associated with perceptual attention or perceptual processes (e.g., automatic bottom-up attention, orienting, vigilance; see Mackworth et al., 1964; Oken et al., 2006 for a review). Fewer eye-tracking studies examine attentional focus associated with tasks of executive attention or working memory (Patt et al., 2014; Martin et al., 2017; Tremblay et al., 2006; Theeuwes et al., 2005; Lawrence et al., 2004; Postle et al., 2006). Mental attention is similar to executive attention and working memory in that it is effortful and requires high levels of top down control. In fact, the theory of constructive operators frames mental attention as nested within working memory (Pascual-Leone, 1970; Pascual-Leone & Johnson, 2005, 2021). Importantly, this theory allows for the quantification of mental attentional capacity by way of especially constructed measures that manipulate mental attentional demand of a task. Although extensive research shows behavioral basis of mental attentional capacity (e.g., Arsalidou and Im-Bolter, 2017 for review), little is known about effects of mental attentional demand on eye movements. This is the first study to date to examine eye movements during tasks of mental-attentional capacity. The current study investigates eye-movements as a function of six levels of mental attentional demand, two levels of interference and explores relations among eye movements, behavioural performance, and subjective self ratings of mental effort.

Within the Theory of Constructive Operators, working memory is considered as the field of currently activated perceptual and cognitive schemes (Pascual-Leone, 1970, 1987; Pascual-Leone and Johnson, 2005, 2011). These are schemes that are not otherwise facilitated by the situation. In a nested, flashlight model, mental attention allows one to effortfully select and maintain relevant schemes within working memory, which are within the field of activated schemes. In other words, mental attention mimics a beam of light energy. This ‘energy’ is limited, changes with age and corresponds to the number of schemes (i.e., operative and figurative), that can be maintained and processed (Pascual-Leone, 1970,

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1987; Pascual-Leone and Johnson, 2005, 2011, 2017). This formulation of mental attention is similar to a recent conceptualization on the nature of limits within working memory in the brain (Ma et al., 2014). Using meta-subjective task analyses, mental attentional demand of a task is qualitatively described as the type of schemes needed and quantitatively defined as the number of schemes that need to be coordinated for a successful task solution (e.g., Pascual-Leone and Johnson, 2005). Importantly, both theory and empirical evidence support the inclusion of misleading cues in tasks measuring mental attentional capacity (Arsalidou et al., 2010) and working memory (Engle and Kane, 2004). Engle and Kane (2004) claimed that individual differences in working memory capacity are not only about storage space but about executive control in maintaining goal-relevant information in a highly active, accessible state under conditions of interference, and argued that simple span tasks show little correlation with other cognitive abilities (reading, mathematical cognition; Conway et al., 2005; Redick et al., 2019). Arsalidou et al. (2010) provided evidence in support of using tasks with misleading context to measure mental attentional capacity, comparing results of two matched tasks with low and high levels of interference in several age groups.

Measures of mental attentional capacity that ensure linear increase in mental attentional demand across multiple levels without variation in the rules of the task (i.e., increase in need for executive control) have been developed specifically for use in developmental science within the framework of the Theory of Constructive Operators (Pascual-Leone, 1970; Pascual-Leone and Johnson, 2005, 2011, 2021). Parametric measures such as the Colour Matching Task have six levels of difficulty and two interference versions (Balloons/Clowns; Figure 1; Arsalidou et al., 2010). These task characteristics satisfy several important requirements: parametric levels of difficulty (i.e., one additional colour for every difficulty change), unchanging executive goal across difficulty levels (i.e., the goal to match colors remains the same) and culture fairness (e.g., use of color; simple visual-spatial stimuli; Arsalidou and Im-Bolter, 2017). In both versions of the task the goal of the player is to compare the colours they see in the picture to the colours they saw in the previous picture and press a button to indicate whether the relevant colours are the same or different as quickly and as accurately as possible, disregarding the position of the colours. The levels of difficulty correspond to the number of relevant colours to hold in mind and compare. Mental attentional demand of the task is calculated as the number of relevant colors plus constant for operative schemes: (a) needed in each version of the task for maintaining with the rule to identify and match colors and effortfully, and (b) extract colors by inhibiting distracting features needed for the high interferences version (i.e., Balloons: $n + 1$ and Clowns: $n + 2$, where n is the number of relevant colours; see Arsalidou et al., 2010 for task analyses). Two colours (green and blue) are irrelevant and participants are instructed to ignore them. In the first version of the task colorful balloons appear in the picture. In the second version participants are presented with an image of a clown dressed in brightly coloured clothes. The Clown version of the task with n colours is thus proposed to be more difficult than the Balloons version with n colors due to higher interference caused by increased complexity of the stimuli (i.e. participants need to additionally ignore the information about which item of clothing the colours were associated with).

Considering only the number of relevant colors, both the balloons and clown versions have six levels of difficulty. Colors correspond to figurative schemes as they represent features on the pictures. Operative schemes however correspond to mental actions that need to be considered for successful problem solving. Thus, despite the number of colors being the same in task versions (i.e., Balloons and Clowns), because of operative schemes, mental attentional demand levels range from 2-7 for the Balloons (i.e., $n + 1$) and 3–8 for the Clowns (i.e., $n + 2$, where n is the number of relevant colors). Distinguishing qualitative (i.e., operative vs figurative) and quantitative (i.e., number) properties of schemes allows for controlling for effects imposed by interference. For example, trials with two relevant colors in the Balloon task will have a mental attentional demand of three, whereas a mental demand of three is required to solve a trial with one relevant color in the Clown task. Behaviorally, adults are expected to focus on and manage about seven units of information (Miller, 1956; Pascual-Leone, 1970). Critically, little is known about how eye movements relate to such tasks.

Common sense tells us that what we look at corresponds to what we are mentally focused on. Although this is not always true, eye-tracking is still very useful for studying attention and related cognitive processes (Richardson et al., 2007). Eye-tracking has been shown to reveal information about mental processes, that may not be easily accessible through other measures, such as decision-making and problem-solving strategies (for a comprehensive review on eye-movements in decision making see Orquin and Mueller Loose, 2013, for spatial attention see Kiefer et al., 2017). Another strong advantage of eye-tracking methods is that this technique is non-invasive and can be easily accessible. Further, many eye-tracking indices, such as saccades, fixations, blink and pupil dilation, are well studied in relation to some aspects of cognition. A notable example is cognitive load or what we refer to as mental attentional demand in the current study.

Spontaneous blink rate has been found to be robustly affected by cognitive load in complex visual tasks (Recarte et al., 2008; Faure et al., 2016; Ahlstrom and Friedman-Berg, 2006; Maffei and Angrilli, 2018; Chen et al., 2011). Early studies found that spontaneous blink rate decreased with increase in visual demand of the task (Poulton and Gregory, 1952). Since then studies have shown that spontaneous blink rate decreases as a function of increasing difficulty and cognitive effort in both visual and non-visual tasks, including mental arithmetic and digit span tasks (Holland and Tarlow, 1972). Decrease in spontaneous blink rate was observed with an introduction of a visual search second task to a non-visual cognitive task (Recarte et al., 2008), with increasing task

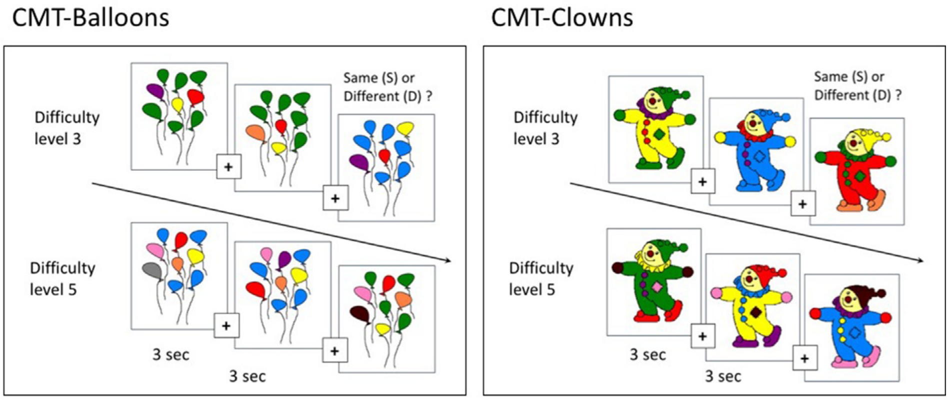

Figure 1. Example of stimuli and procedure for CMT.

complexity (Faure et al., 2016) and with increase in working memory load (Chen et al., 2011). Increase in attentional load in a vigilance task was also associated with a decrease in spontaneous blink rate (Maffei and Angrilli, 2018). The suggested explanation for this effect is top-down inhibition of blinks that interfere with sensory and possibly cognitive processes.

Another eye-tracking measure used as a measure of mental workload in neuro-ergonomic approaches is peak saccade velocity (Di Stasi et al., 2010; Savage et al., 2020; App and Debus, 1998). It is widely accepted that peak saccade velocity increases with amplitude. This relation, known as the 'main sequence', was first proposed by Bahill et al. (1975), and has since then been repeatedly replicated (e.g., Gibaldi and Sabatini, 2020 for review). Notably, recent studies have shown that there may be more flexibility in what drives the main sequence than was previously assumed, and peak saccade velocity may vary as a function of cognitive load independently of saccadic amplitude (Muhammed et al., 2020). Peak saccadic velocity was first suggested as a valid measure of workload in the field of ergonomics by App and Debus (1998), who found that it decreases as the time of experiment increases, which was interpreted as a measure of fatigue. In more ecologically valid tasks peak saccade velocity has been found to decrease with increases in mental workload after correcting for effect of amplitude with a binning procedure (Di Stasi et al., 2010). Peak saccade velocity has also been shown to be affected by introduction of a distracting second task (i.e. avoiding a hazard during driving) (Savage et al., 2020). Due to the visual nature of our task we selected spontaneous blink rate and peak saccade velocity as indicators of changes in mental attentional demand. Importantly, all aforementioned studies have only three levels of demand (i.e. low, high and medium). Demand is varied either by including a secondary task or by increasing the number of relevant elements or the overall perceptual density of the task. The color matching tasks have six levels of mental attentional demand as estimated using a-priori tasks analyses (Arsalidou et al., 2010). Although a-priori evaluations of task difficulty are fundamental, subjective estimates of mental effort exerted during problem solving can also be useful in interpreting findings and verifying task demand.

A traditional method to measure subjective effort is through self-report (Ayres, 2018). One of the most widely used techniques is to use subjective rating scales, either at different points during the task or at the end of the experimental session. Typically, the participant is asked to assess either subjective mental effort or perceived task difficulty on a Likert scale (Schmeck et al., 2015). While this method has been criticized as potentially unreliable (Brunken et al., 2003), a comprehensive review on cognitive load measurement theory concludes that it shows surprising sensitivity to changes in task load (Sweller et al., 2011) and this is supported by more recent studies (Haji et al., 2015; Joseph, 2013). Due to their sensitivity and economicity, subjective rating scales of mental effort were included in our study as an additional control measure.

This will be the first study to examine effects of multiple graded levels of mental attentional demand on eye-movements as well as relations between eye movements and self-reported effort. Specifically, we hypothesised that increases in mental attentional demand will be associated with decreases in spontaneous blink rate and peak saccade velocity. Importantly, because level of mental attentional demand is estimated a priori to account operative and figurative scheme (i.e., control for n + 1 and n + 2 associated with the balloons and clowns, respectively) we expected to find no main effect of task condition. Subjective ratings of mental effort were expected to be positively related to mental attentional demand and negatively related to peak saccade velocity and blink rate.

2. Methods

2.1. Participants

Sixty-five participants with normal or corrected vision with contact lenses and no prior self-reported head trauma or cognitive impairments were recruited through advertisement for research participants on the university campus and through the universities mailing list. After preprocessing, data from 5 participants were removed due to technical errors during recording and from 3 participants due to incomplete data. Statistical analyses were performed on data from 57 participants (mean age = 23.30 ± 3.93, 24 male). All participants provided written consent, and materials and procedures were approved by the Higher School of Economics (HSE) University Committee on Interuniversity Surveys and Ethical Assessment of Empirical Research. (code #22.08).

2.2. Materials

2.2.1. Colour matching task (CMT)

Parametric measures developed by Arsalidou et al. (2010), the Colour Matching Task with six levels of difficulty and two versions (Balloons/Clowns, Figure 1) were used for mental attentional capacity assessment. Each task version contains 6 difficulty levels presented in 4 blocks (32s duration). Each block contains eight stimuli of a specific difficulty level, and seven trials that they need to respond to. With seven trials in four blocks for each of the six difficulty levels, the total number of trials where participants need to respond to equals 168 per task version. Difficulty levels are presented in a pseudo-random order. To evaluate subjective ratings of mental effort, every task block is followed by a screen with a question that asks participants to rate the mental effort they exerted on a scale from 1 to 5 (1 being not effortful at all, 5 being very effortful). After the mental effort rating screen, a baseline trial that requires no response is presented and serves as an indicator of a change in difficulty level. Baseline trial consists of the same image as the rest of the task, with the difference that it contains no relevant colors (i.e. only irrelevant colors: green and blue). Each task stimulus is presented for three seconds, during which the participant needs to make a response (same/different) by pressing one of two keys: '.' for 'same' and '/' for 'different'. Every trial is followed by a one inter-stimulus cross in the center of the screen. Task stimuli occupy the centre of the screen with width equaling 488 and height equaling 494 screen pixels (on a 1366 × 768 screen, the stimuli taking up approximately 13 × 14 cm). Reaction time and accuracy are recorded. Mental attentional demand of the task is indexed by the difficulty level (n = number of relevant colours) plus executive demand of the task that includes processing of interference effects, which are considered in calculation of individual mental attention (M-)scores of participants. To account for mental attentional demand posed by operations needed in each task version, 1 is added to the final score for the balloons and 2 for the clowns. Because relevant colors are contextually embedded (integral features) in the clown figure, participants must actively extract one by one the relevant colors to check for a possible match with colors of the previous clown. This extraction process is not automatized, and therefore, it adds a second operative unit to the mental attentional demand for CMT-Clown, making it one unit higher than that of CMT-Balloon (Arsalidou et al., 2010 for task analyses). For example, a balloon trial with two relevant colours has a mental attentional demand of (n+1; n is the number of relevant colours +1 operation) three, whereas a clown trial with two relevant colours has a mental attentional demand (n+2; n is the number of relevant colours +2 operations) four. A difficulty level is considered to be passed reliably when accuracy, estimated using the percentage of correct responses, was 70% or more. Subjective mental effort exerted is estimated by averaging all blocks associated with each level of mental attentional demand.

2.3. Procedure

Participants were invited to complete a series of trials in the experimental tasks after a detailed scripted, verbal explanation of the task. During the task their eye-movements were recorded with the use of The EyeLink Portable Duo (SR Research) recording at frequency 1000 Hz in remote head-free-to-move mode. All participants performed the task on the same laptop, model HP 15-ba503ur, with screen size 15.6" and screen resolution 1366 × 768. Prior to each experimental task for both versions of CMT, calibration and validation for the pupil was done for nine points. Participants reported no colour-blindness and were able to distinguish all colours associated with the task.

Importantly, as blink rate has been shown to be affected by several confounding factors, including caffeine (Holmqvist et al., 2011) and the position of stimuli on the screen (Cruz et al., 2011), we followed the methodological recommendations provided by Eckstein et al. (2017). Specifically, in order to control for those factors we advised participants to get a good night's sleep and refrain from drinking coffee before the experiment and the stimuli were located centrally on the screen.

2.4. Data analysis

2.4.1. Data preprocessing

Data preprocessing and extraction of eye movement events was conducted with the use of Data Viewer software (SR Research, version 3.1.1). We first selected an interest period, which consisted of the three seconds during which the participant had to view the stimuli and make a response. Saccades and fixations were identified with the use of the saccade detection algorithm developed by SR Research within the Data Viewer. To detect a saccade, for each data sample, the parser computes instantaneous velocity and acceleration and compares these to the velocity and acceleration thresholds. If either is above threshold, a saccade signal is generated. The parser checks that the saccade signal is on or off for a critical time before deciding that a saccade has begun or ended. Saccades were identified by deflections in eye position in excess of 0.1°, with a minimum velocity of 30° z s21 and a minimum acceleration of 8000° z s22, maintained for at least 4 ms. Blinks were defined as a period of saccade-detector activity with the pupil data missing for three or more samples in a sequence. High recording frequency of The EyeLink Portable Duo eye-tracker (1000 Hz) was used in order to ensure accurate detection of blink events (for a discussion of the importance of sampling speed on blink detection see Pedrotti et al., 2011 and Schmidt et al., 2018).

Then saccade amplitude (i.e., amplitude of the current saccade in degrees of visual angle), saccade peak velocity (i.e., peak value of gaze velocity measure in visual degrees per second of the current saccade) and information on whether a blink happened during the current saccade was extracted for each saccade. Accuracy and reaction time for each trial was also extracted. At this stage data of five participants were classified as corrupt and excluded from the analyses along with the data from one participant with only the Clown condition completed yielding a total of 57 participants. From the resulting dataset trials where blink duration equaled trial duration (7% of total observations) and saccades with amplitude above 15° (2% of total observations) were identified as outliers.

All further analyses were conducted with the use of statistical packages of R programming language. Descriptive results of task version (n = 2) and levels of mental attentional demand (n = 6) were calculated. We conducted five repeated measures two-way ANOVA to test the effect of mental attentional demand (n = 5, shared by both task versions levels 3–7; mental attentional demand level 2 is not present in CMT-clowns, and mental attentional demand 8 is not present in CMT-balloons) and interference (CMT-balloons and CMT-clown) on accuracy (i.e., percent of correct responses), reaction time, peak saccade velocity and spontaneous blink rate. In order to ensure that effects of mental attentional demand on peak saccade velocity were not caused by changes in amplitude, we conducted additional repeated measures ANOVA for saccadic amplitude. To correct for violation of sphericity we applied Greenhouse Geisser correction on p-values, as all models violated sphericity assumptions. An α level of 0.05 was used for all statistical tests. Bonnferoni correction was used for all post-hoc t-tests. Pearson correlations were used to examine relations among subjective ratings of mental effort, theoretically defined mental attentional demand, eye-tracking indices and behavioral scores (i.e., percentage correct and reaction time).

3. Results

The average M-score of our sample was 5.80 ± 1.15 for CMT-balloons and 5.83 ± 1.18 for CMT-clown. As a function of mental attentional demand, mean accuracy scores decrease (Figure 2, Table 1), reaction time increases (Figure 2, Table 1) and subjective mental effort ratings increase (Table 1). Peak saccade velocity decreased by 10–23°/*s* per level of mental attentional demand (Figure 2, Table 2), and spontaneous blink rate decreased by 0.04 blinks/second every other level (Figure 2, Table 2).

3.1. Effect of mental attentional demand and interference condition on accuracy and reaction time

Repeated measures two-way (mental attentional demand x interference) ANOVA showed a significant interaction effect of mental attentional demand and interference condition for reaction times (F (4,224) = 7.35, p = 3.16e-06, $\eta^2 = 0.01$) but not for accuracy (F (4, 224) = 1.97, p = .09, $\eta^2 = 0.005$). Significant main effects of mental attentional demand on accuracy (F (4,224) = 175.80, p = 3.01e-37, $\eta^2 = 0.48$) and reaction time (F (4,224) = 219.96, p = 3.52e-46, $\eta^2 = 0.45$) were also observed. Main effects of interference were not significant for either accuracy (F (1, 56) = 0.50, p = .40, $\eta^2 = 0.0006$) or reaction time (F (1, 56) = 1.79, p = .25, $\eta^2 = 0.001$). To further explore the results, we conducted post-hoc pairwise t-tests with Bonferroni correction; differences among all levels were significant both for accuracy and reaction time. Post-hoc results with all p-values, as well as Cohen's d effect sizes are presented in Table 3.

3.2. Effect of mental attentional demand and interference condition on eye-tracking indices

Repeated measures two-way (mental attentional demand x interference) ANOVA showed no significant interaction effect for peak saccade velocity (F (4, 224) = 0.88, p = .48, $\eta^2 = 0.001$) and spontaneous blink rate (F (4, 224) = 0.89, p = .80, $\eta = 0.0008$). We found main effects of mental attentional demand on peak saccade velocity (F (4,224) = 18.38, p = 2.04e-08, $\eta^2 = 0.037$) and blink rate (F (4, 224) = 19.02, p = 1.67e-09, $\eta^2 = 0.028$). Main effects of interference were not significant for either peak saccade velocity (F (1, 56) = 1.76, p = .18, $\eta^2 = 0.002$) or blink rate (F (1, 56) = 0.14, p = .70, $\eta^2 = 0.0004$). To further explore significant main effects, we conducted post-hoc pairwise t-tests with Bonferroni correction (Table 4). For peak saccade velocity differences among all levels were significant with the exception of two pairs of levels: level 4 vs 5 comparison and level 6 vs 7 comparison. For spontaneous blink rate statistically significant differences were observed for all comparisons except levels 6 vs 7 and 3 vs 4, and levels 5 vs 4. All p-values, as well as Cohen's d are presented in Table 4. Importantly, while ANOVA did show a main effect of demand on amplitude (F (2,224) = 4.10, p = .01, $\eta^2 = 0.007$), post-hoc tests revealed that significant differences were present only for comparisons 7 vs 3 and 6 vs 7 (p-values and Cohen's d are presented in Table 4) and the direction of effect is the opposite (i.e. amplitude appears to increase slightly with increase in task demand). Therefore, we believe that the effect of task demand on peak saccade velocity cannot be solely attributed to changes in saccadic amplitude in our analysis.

3.3. Subjective mental effort rating and mental attentional demand

In order to test the validity of our theoretical assessment of mental attentional demand, we used Pearson's correlation analysis to examine whether a-priori assignment of mental attentional demand for the levels of the task (Arsalidou et al., 2010) correlates with participants' subjective mental effort ratings. We extracted effort ratings for every block of the two conditions and conducted the analysis on values averaged by block. The results are illustrated in Figure 3. Strong significant correlations demonstrating the validity of our original assessment of mental

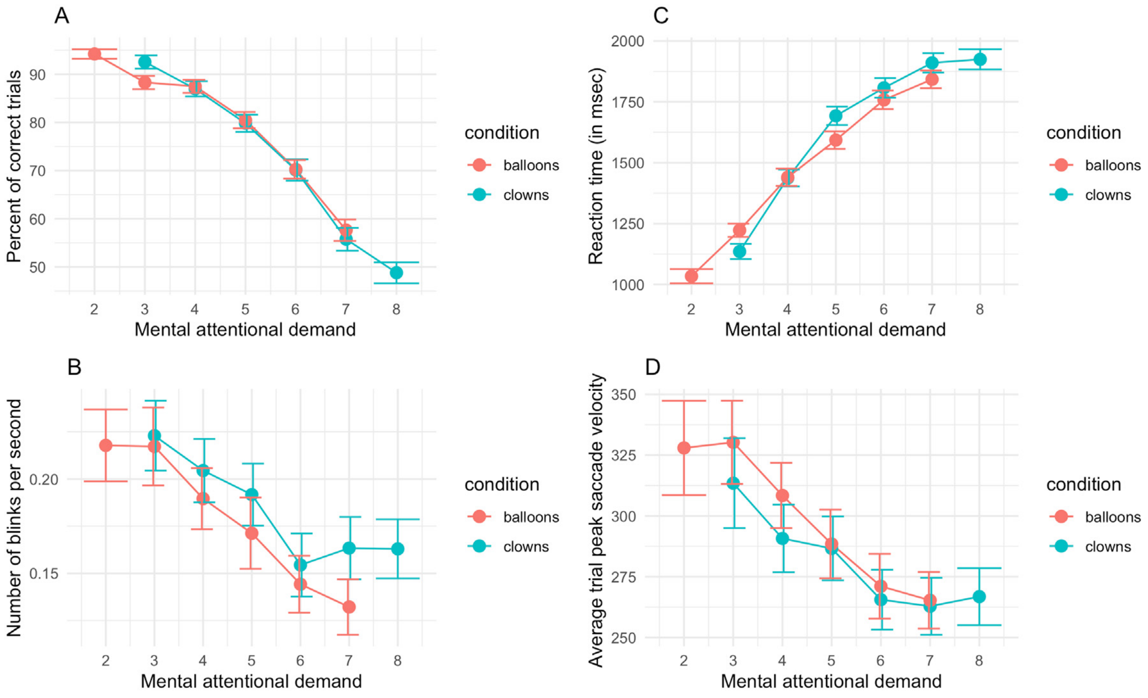

Figure 2. Accuracy, reaction time, blink rate and peak saccade velocity as a function of mental attentional demand in CMT-balloons and CMT-clowns (means and standard error). A. Accuracy and mental attentional demand; B. Blink rate and mental attentional demand; C. Reaction time and mental attentional demand; D. Peak saccade velocity and mental attentional demand.

Table 1. Accuracy, reaction time and effort self-rating as a function of mental attentional demand.

Mental attentional demand	CMT-Balloons			CMT-Clowns		
	Accuracy	Reaction time	Effort self-rating	Accuracy	Reaction time	Effort self-rating
2	94.21 ± 7.74	1034.13 ± 225.56	2.15 ± 1.37	-	-	
3	88.30 ± 10.78	1222.82 ± 213.62	2.39 ± 1.17	92.54 ± 10.74	1135.35 ± 243.46	2.31 ± 1.26
4	87.50 ± 10.65	1440.28 ± 278.70	2.69 ± 1.15	86.97 ± 12.36	1437.07 ± 271.67	2.62 ± 1.11
5	80.48 ± 13.18	1593.06 ± 280.28	2.92 ± 1.05	79.82 ± 13.95	1692.58 ± 298.00	2.95 ± 1.09
6	70.26 ± 15.11	1758.19 ± 296.12	3.23 ± 0.92	70.11 ± 17.37	1807.40 ± 316.14	3.16 ± 1.07
7	57.64 ± 17.31	1842.38 ± 285.40	3.56 ± 0.86	55.76 ± 18.47	1910.23 ± 312.07	3.48 ± 0.94
8	-	-		48.81 ± 17.03	1924. 46 ± 326.37	3.59 ± 1.08

Note: Mean ± Standard Deviation. Accuracy is calculated as percent of correct responses; Reaction time is presented in msec, Mental attentional demand equals to number of relevant color +1 for balloons and +2 for clowns.

Table 2. Peak saccade velocity, amplitude and blink rate as a function of mental attentional demand.

Mental attentional demand	CMT-Balloons			CMT-Clowns		
	Peak saccade velocity	Amplitude	Blink rate	Peak saccade velocity	Amplitude	Blink rate
2	327.96 ± 151.46	2.56 ± 0.58	0.22 ± 0.18	-	-	
3	330.26 ± 133.76	3.20 ± 0.66	0.22 ± 0.20	313.46 ± 144.29	2.86 ± 0.64	0.22 ± 0.18
4	308.40 ± 104.76	3.12 ± 0.60	0.19 ± 0.16	290.74 ± 108.54	3.15 ± 0.71	0.20 ± 0.16
5	288.45 ± 110.54	3.06 ± 0.69	0.17 ± 0.18	286.63 ± 102.66	3.31 ± 0.72	0.19 ± 0.16
6	271.08 ± 104.25	3.03 ± 0.63	0.14 ± 0.15	265.59 ± 96.28	3.20 ± 0.76	0.15 ± 0.16
7	265.32 ± 90.85	3.16 ± 0.73	0.13 ± 0.14	262.86 ± 91.31	3.24 ± 0.70	0.16 ± 0.16
8	-	-		266.83 ± 91.32	3.25 ± 0.69	0.16 ± 0.15

Note: Mean ± Standard Deviation. Peak velocity is measured in °/s, amplitude is measured in °, spontaneous blink rate is calculated as the number of blinks per second. Mental attentional demand equals to number of relevant color +1 for balloons and +2 for clowns.

attentional demand, were found for both tasks: for CMT-clowns ($p = 3.54e-16$, Pearson $r(21) = 0.98$) and for CMT-balloons ($p < 2.2e-16$, Pearson $r(21) = 0.994$).

Additionally, we ran a two-factor repeated measures ANOVA on means of self-rating of mental effort for every participant by task demand with task condition and level of demand as within-group factors, which

Table 3. Significant pairwise t-tests and effect sizes for accuracy and reaction time.

Mental attentional demand levels		Accuracy		Reaction time	
		Cohen's d	p-value	Cohen's d	p-value
3	4	0.26	0.0005	-0.97	1.08e-28
3	5	0.79	1.47e-15	-1.72	5.37e-41
3	6	1.40	3.14e-28	-2.22	3.25e-44
3	7	2.29	1.51e-41	-2.61	5.33e-47
4	5	0.54	3.94e-10	-0.72	2.24e-20
4	6	1.17	9.40e-27	-1.20	2.73e-28
4	7	2.06	5.106e-39	-1.55	3.53e-31
5	6	0.64	7.81e-13	-0.48	7.95e-11
5	7	1.51	3.48e-29	-0.81	5.97e-17
6	7	0.83	2.84e-18	-0.31	8.16e-05

Note: Cohen proposed that d = 0.2, d = 0.5 and d = 0.8 are considered a small, medium and large effect sizes, respectively. Bonferroni corrections for multiple comparisons performed for all tests.

Table 4. Pairwise t-tests and effect sizes for peak saccade velocity.

Mental attentional demand levels		Peak saccade velocity		Blink rate		Saccade amplitude	
		Cohen's d	p-value	Cohen's d	p-value	Cohen's d	p-value
3	4	0.16	.015*	0.12	.07	-0.15	.17
3	5	0.26	3.61e-04*	0.21	.003*	-0.21	.05
3	6	0.41	4.49e-08*	0.40	1.56e-08*	-0.12	1
3	7	0.45	1.28e-07*	0.41	8.45e-08*	-0.24	.04*
4	5	0.11	.64	0.09	.75	-0.06	1
4	6	0.30	1.40e-05*	0.31	1.91e-07*	-0.05	1
4	7	0.35	4.67e-06*	0.32	3.55e-07*	-0.09	1
5	6	0.18	.02*	0.20	.004*	0.10	.27
5	7	0.23	.001*	0.21	5.62e-04*	-0.03	1
6	7	0.04	1	0.01	1	-0.13	.008*

Note: * = significant test; Cohen proposed that d = 0.2, d = 0.5 and d = 0.8 are considered a small, medium and large effect sizes, respectively. Bonferroni corrections for multiple comparisons performed for all tests.

revealed a strong significant effect of demand (F (56) = 53.99, p = 9.204507e-10, generalized eta squared (ges) = 0.41), a small significant effect of task condition (F (56) = 13.18, p = 6.129260e-04, ges = 0.05) and no interaction effect (F (56) = 0.89, p = 3.470129e-01, ges = 0.0009). A linear increase in self-rating by mental attentional demand level is illustrated in Figure 3B.

3.4. Subjective ratings of mental effort and eye-tracking indices

The relation between participants' ratings of mental effort and their eye movement indices was analyzed. We found significant negative correlations between blink rate and ratings of mental effort for both balloons (p = .03, Pearson r (50) = -0.31) and clowns (p = .04, Pearson r (52) = -0.27). However, when relations between peak saccade velocity and effort rating were analyzed for the two task versions, we found no significant correlations for balloons (p = .14, Pearson r (50) = -0.20) and clowns (p = .17, Pearson r (52) = -0.19) (see Figure 4).

4. Discussion

We examine the effect of multiple levels of mental attentional demand on eye movements and their relations to behavioural performance and self ratings of mental effort. The study has three main findings: 1) Incremental changes in mental attentional demand affect peak saccade velocity and spontaneous blink rate. Peak saccade velocity decreased by 10–22 °/*s* by one level of mental attentional demand, and spontaneous blink rate decreased by 0.04 blinks/second every other level, providing target values for predicting scaled increases in task difficulty. 2) Interference (i.e., balloons vs clowns) had no effect on eye movements, once executive demand of inhibiting interference was accounted for in calculating mental attentional demand, confirming construct validity in terms of task analyses. 3) Subjective ratings of mental effort correlated significantly with spontaneous blink rate, which decreased as subjective mental effort scores increased. Results are discussed in terms of practical implications and theories of cognition.

We found that the level of mental attentional demand in a parametric task linearly modulates eye movement activity. Specifically, peak saccade velocity as a measure is sensitive enough to distinguish among all levels of mental attentional demand with the exception of the highest two levels, which were generally either at or above the limit of participant's mental attentional capacity. The direction of the relation between mental attentional demand and eye movements is consistent with some past studies (Di Stasi et al., 2010; Savage et al., 2020) but not others (Bodala et al., 2014). Specifically, Di Stasi et al. (2010) and Savage et al. (2020) found that peak saccade velocity decreases with increase in task complexity and increase in mental workload with the introduction of a second task to a virtual driving task (Di Stasi et al., 2010). Some studies have found the opposite effect of increased mental workload on peak saccade velocity. Specifically, increase in the noisiness in visual stimuli, associated with an increase in subjective mental workload was associated with an increase in peak saccade velocity (Bodala et al., 2014). Differences among studies may depend on the type of schemes and operations that contributed to subjective ratings of cognitive workload. Alternatively, evidence from pharmacological studies that connect peak saccade velocity to arousal and studies in tasks with higher ecological validity may provide a possible explanation for this discrepancy. Di Stazi and colleagues proposed that tasks with high mental demand may elicit decreased peak saccade velocity by decreasing arousal due to fatigue (Di Stasi et al., 2013). Increase in peak velocity would also be expected if increase in task difficulty was not sufficient for eliciting significant mental fatigue but instead resulted in increased arousal during the task. More subtle experimental manipulations are required to test this claim and dissociate these effects.

Interestingly, our results demonstrate that peak saccade velocity decreases by 10–22°/s, for mental attentional demand levels that were successfully attained (i.e., within the participant's mental attentional capacity). Past studies show a difference of 13°/s between high and low demand levels (Di Stasi et al., 2010) and 30°/s between single and dual-task conditions (Savage et al., 2020). Our results not only replicate findings of previous research in this area, providing supporting evidence for the flexibility of the main sequence, but also show that peak saccade velocity is indeed affected by mental attentional demand. This effect is observed even for consecutive levels of mental attentional demand (i.e., when the difference between difficulty levels is just one added unit of relevant information, one figurative scheme). Further, our study is the first to demonstrate consistent decrease for multiple levels of mental attentional demand. This conceptualization of difficulty, exemplified by decreases in peak saccade velocity may contribute to theoretical frameworks that elaborate on limits of mental attention and working memory, as eye-tracking may be considered as an additional mode of measurement. This novel finding can also serve as a target for changes in task difficulty level in research investigating effects of cognitive load.

Similar to peak saccade velocity, spontaneous blink rate is also sensitive to changes in mental attentional demand, however less so, with effects reflecting broad differences between high- and low-levels of demand. Changes in spontaneous blink rate is consistent with the findings of prior studies (Recarte et al., 2008; Faure et al., 2016; Ahlstrom and Friedman-Berg, 2006; Maffei and Angrilli, 2018; Chen et al., 2011; Eckstein et al., 2017). Studies show that blink rate decreases with

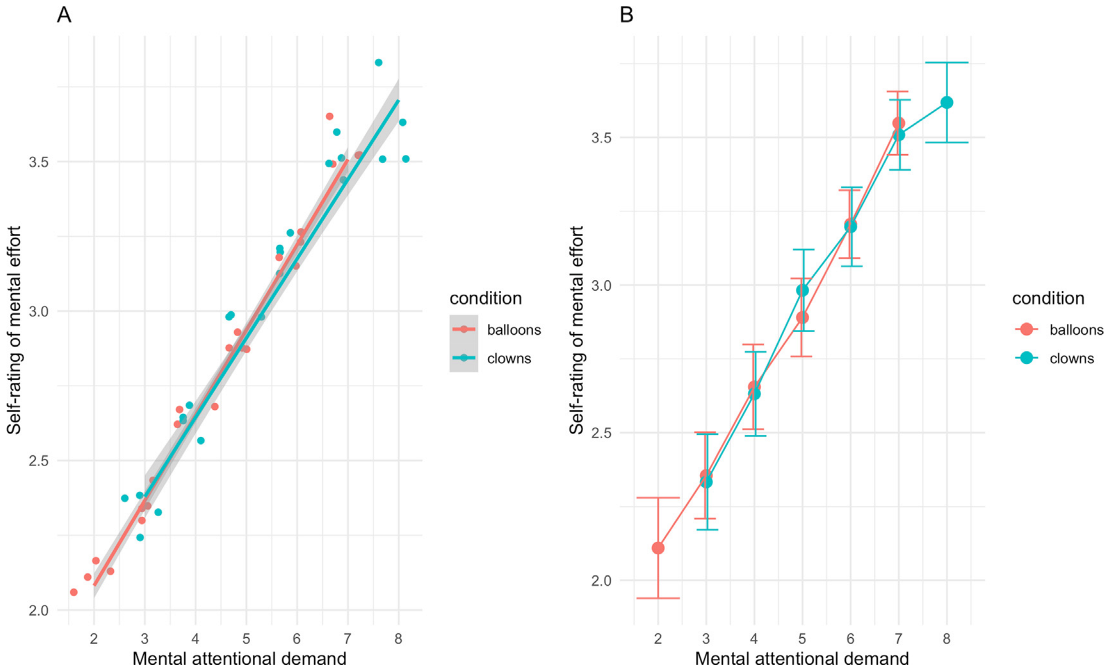

Figure 3. A. Scatterplot of subjective ratings of mental effort and a-priori defined mental attentional task demand (each point represents average rating of all participants for every block of the task); B. Means of subjective ratings of mental effort by a-priori defined mental attentional task demand with standard error.

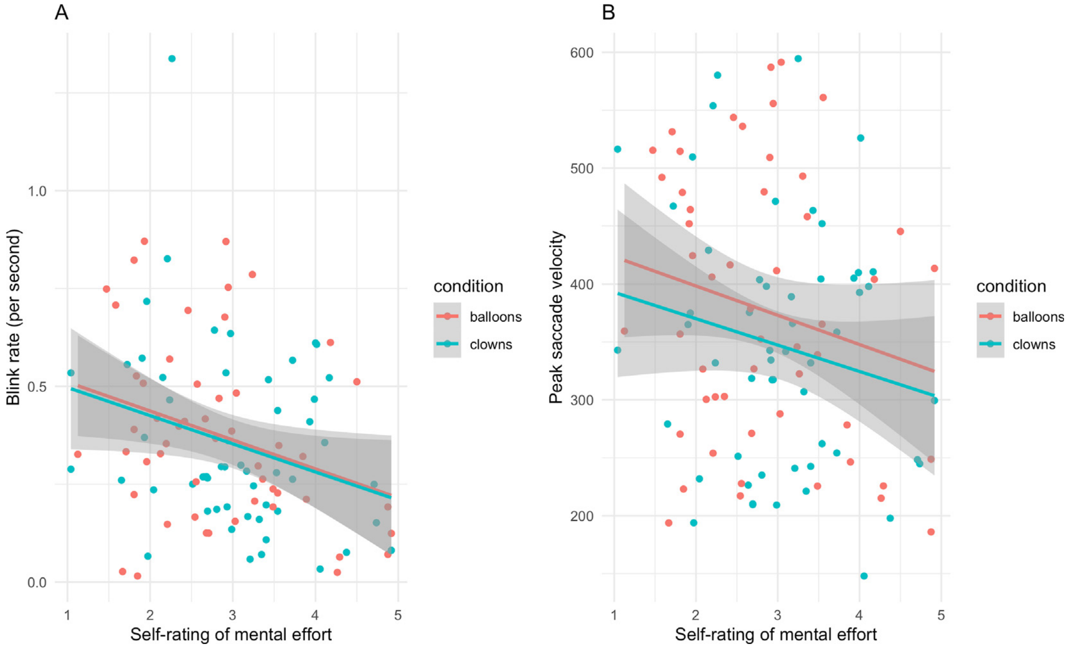

Figure 4. A. Scatterplot of subjective ratings mental effort and blink rate (blinks per second); B. Scatterplot of subjective ratings mental effort and peak saccade velocity.

increase in cognitive load in an attentional task, working memory tasks, and tasks high in ecological validity (Recarte et al., 2008; Faure et al., 2016; Maffei and Angrilli, 2018; Chen et al., 2011). A potential explanation for this relation is that spontaneous blinking interferes with sensory processing and cognitive processing relies on sensory imagery (i.e. mental arithmetic) and thus successful performance in visual tasks requires inhibition of blinks. Additional support for this interpretation is offered by Irwin (2014) study, where participants were instructed to perform blinks during the task performed worse in a short-term memory task than those who were asked to inhibit blinking activity. Similarly, a number of studies found that increases in blink rate during tasks requiring updating in working memory predicts worse performance (Zhang et al., 2015; Tharp and Pickering, 2011). Notably, when the task does not require efficient updating of visual information, the number of blinks may increase with difficulty as a function of activation of the dopaminergic system (see Eckstein et al., 2017 for a review of blink rate and dopamine function). In this study we show the effects of graded levels of theoretically defined mental attentional demand on eye movements in a visual-spatial task. Our results replicate effects observed in studies with visual paradigms and extend this knowledge by showing additionally that significant differences in blink rate can be reliably detected when the difference between levels of demand constitutes two or more figurative schemes. Quantification by blink rate may also serve as a mode of measurement for theoretical formulations for cognitive limits and future directions of study.

Task analysis estimated that additional interference included in the CMT-clown as compared with CMT-balloons would increase the mental attentional demand by one unit (Arsalidou et al., 2010). As expected, our results show that when we account for this one unit in our analyses no significant difference between conditions is observed for both behavioural and eye movements indices. This result provides support to the quantification of schemes and the method of meta subjective task analyses proposed by the theoretical framework of constructive operators that is useful for a-priori hypothesis testing (e.g., Pascual-Leone and Johnson, 2005) and shows that eye movements indices are sensitive not only to perceptual (i.e. visual), but also to executive demands of the task.

A robust relation between objective (a-priori) level of mental attentional demand as assessed by task analysis and self-ratings of mental effort provides face validity (i.e., does the content of the test suitable to measure what it aims) and construct validity (i.e., does the test measure what is intended to measure) for the graded levels of difficulty in the task. Further, we found that spontaneous blink rate correlates significantly with self-ratings of mental effort. These results are consistent with prior studies (Ayres, 2018; Schmeck et al., 2015; Sweller et al., 2011; Haji et al., 2015) and show that subjective rating of mental effort can be used as a sensitive measure of mental demand of the task. Additionally, the correlation between eye movements and self rating is consistent with studies with the use of other psychophysiological measures. Larmuseau et al. (2019) find no effect of task difficulty manipulation on physiological data (such as skin temperature and electrodermal activity) but report a correlation between rating of mental effort and electrodermal activity for individual differences. Fewer studies, however, investigated correlations between eye movement indices and self rating of mental effort. We find that participants performed less blinks when their self-rating of mental effort increased. It is possible that eye-movements and other physiological data, which we did not assess, contribute to the interoceptive evaluation of mental effort we asked the participants to perform. An embodied evaluation of mental effort relates to the somatic marker hypothesis that refers to conscious or nonconscious body-state regulations that affect decision making (Damasio, 1996). The current finding offers additional support for the use of subjective effort rating as a measure of mental effort. As time of day (e.g., Barbato et al., 2000) and pharmacological interventions (Yolton et al., 1994) affect blink rate, future studies may consider evaluating such interactions with mental demand and mental effort. Studies with developmental samples would also shed light on eye-movement metrics related to the trade off between mental attentional demand of the task and mental attentional demand of the individual.

5. Conclusion

We examined the effect of parametric increase in mental attentional demand on eye movements and explored relations among individual behavioural performance, self rating of mental effort and eye movements. Following our predictions both blink rate and peak saccade velocity are sensitive to changes in mental attentional demand, albeit peak saccade velocity has higher sensitivity, with blink rate distinguishing only between high, medium and low demand. Further, we document significant relations among eye movements and self rating of mental effort: a decrease in the frequency of blinks associated with an increase in self rating of effort. Furthermore, we identify a steady rate decrease (10–22°/s) in peak saccade velocity as a function of difficulty. Together these findings suggest that eye movements can be reliably used as an index of increase in mental attentional demand and reflect individual differences depending on mental attentional capacity of participants. Theoretically, new findings related to mental attentional demand and eye movements inform models of visual processing and cognition, providing additional evidence that non-voluntary eye movements reflect not only perceptual, but also cognitive demand in healthy participants. Practically, results point to directions for further research to better understand complex relations among eye movements and mental attentional demand in pediatric populations and individuals with neurodevelopmental disorders and offer possibilities of using eye movement metrics as an objective measure of mental attentional demand in cognitive performance when self-rating of effort and other measures are difficult or impossible to use.

Declarations

Author contribution statement

Valentina Bachurina: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

Marie Arsalidou: Conceived and designed the experiments; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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The authors do not have permission to share data.

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The authors declare no conflict of interest.

Additional information

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