Impact of Task-evoked Mental Workloads on Oculo-motor Indices during a Manipulation Task

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Abstract: Oculo-motor metrics which included metrics of microsaccades were analysed in response to the level of cognitive mental workload during a manipulation task. While some oculo-motor metrics correlate with the estimated scores of the mental workload, these metrics mutually correlate with each other. A model of causal relationship was created using all metrics, including subjective measurements. Metrics of microsaccades perform the function of intermediating behaviour between participant's subjective assessments and conventional ocular measurements, such as saccades and pupil responses.

1 INTRODUCTION

The design of an operational interface helps users to be able to manipulate the underlying system using peripheral devices, in order to develop better controls. Eye tracking techniques have been introduced to evaluate human mental workloads in order to improve the manipulation interfaces and address environmental issues, as some studies using eye movements have already been conducted in the field of aviation (Ziv, 2016; Peiß et al., 2018). While oculo-motor indices have been employed to evaluate system usability for operational interfaces (Nakayama and Katsukura, 2011), metrics of microsaccades (MSs) have often been used recently, as they reflect the level of task difficulty or a higher order cognitive process (Dalmaso et al., 2017; Kohama et al., 2017; Krejtz et al., 2018). Therefore, various indices of eye movements and pupil responses can be applied to evaluate mental workloads, and these indices also have some relationships between themselves, because the responses are based on a common system. The potential for assessment using MSs is recognised, and the details of the behaviour of MS have been studied using various approaches.

A mechanism for stimulating the appearance of MSs was discussed in a previous study (Engbert, 2006), and the mutual relationships between the metrics of oculo-motors were also discussed (Nakayama and Hayakawa, 2019). A detailed analysis of these mutual relationships during a manipulation task should be conducted carefully. In this paper, all metrics are re-analysed and their contributions to each other considered in comparison with the previous report (Nakayama and Hayakawa, 2019). In particular, detailed features of MSs have been introduced, and the contributions of these are additionally analysed.

For this purpose, the following topics are addressed.

1. The relationships between recognised mental workloads and metrics of eye activity, such as microsaccades, saccades, and pupil reactions are examined.
2. The causal relationships between recognised mental workloads and metrics of eye activity are analysed.

2 METHOD

2.1 Experiment Overview

2.1.1 Experimental Tasks

In order to control the level of cognitive workload during a task, a black box interface (Furuta et al., 1993) for the manipulation of an object on a PC monitor was developed, as shown in Figure 1.

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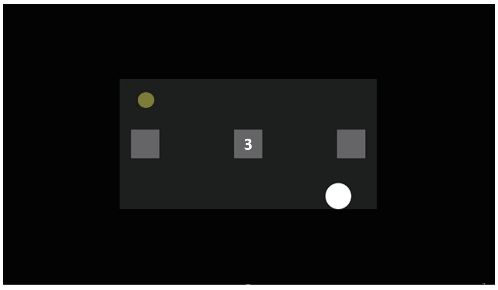


Figure 1: A screen-shot of the manipulation task.

The task is to move a disc (the small yellow disc) to the goal (the white circle) as fast as possible, using the four arrow keys of a keyboard. Task difficulty consisted of three cube obstacles, which were located in the centre of the display, along the path between the initial position and the goal position, as shown in Figure 1. As a penalty, the disc returned to its starting position whenever it touched an obstacle while being moved.

2.1.2 Manipulation Conditions

The 5 conditions that the black box interface modifies are manipulations of keys, as follows:

1. Output 1: The disc moved smoothly at a speed people felt comfortable with, which was determined during the preparation experiments (Normal condition).
2. Output 2: The key response speed was reduced to 1/4 of the speed in Output 1.
3. Output 3: The key response speed was increased to 4 times the speed in Output 1.
4. Output 4: The direction of the key manipulation was rotated 45 degrees.
5. Output 5: Key assignments and direction of movement were randomised.

For each condition, the task duration was 10 seconds, and two sets of trials using the 5 randomised conditions were conducted as a repeated-measure experiment design. The mean durations of the manipulation tasks were below 10 seconds, although the “Output 1” condition required around 5 seconds.

2.1.3 Participants

Participants were 10 male university students aged 21-25 years old who had sufficient visual acuity. Before the experiment, participants gave their informed written consent after a short description of the aims of the experiment.

Figure 2: Factor scores for experimental conditions.

2.2 Subjective Assessment of the Task

Participant’s overall impressions of their manipulating the directional keys during the 5 conditions were measured using the 5-point scale of an assessment inventory which consisted of seven questions that rated aspects such as “difficulty”, “being in a hurry”, “unpleasant”, “unusable”, “fulfilment”, “irritating” and “mental workload” (Mizushina et al., 2011).

Two factors such as “Mental workload” (Factor 1) and “Fulfilment” (Factor 2) have been extracted using factor analysis (Nakayama and Hayakawa, 2019), and the mean factor scores are summarised in Figure 2. Since factor scores for “Mental workload” increase with the levels of difficulty of the five experimental conditions, participants recognised the difficulty of the tasks (Nakayama and Hayakawa, 2019). The other factor scores for “Fulfilment” almost always decreases as the difficulty of the experimental condition increases, and the two factor scores negatively correlate with each other.

2.3 Oculo-motor Measurement

The stimulus was presented on a 27 inch LCD monitor which was 40cm from the viewer. Both eye movements and pupil diameters were measured at 400Hz (Arrington Research: Viewpoint EyeTracker USB400).

In response to manipulation tasks, the following metrics were re-analysed (Nakayama and Hayakawa, 2019).

- Microsaccades (MSs) were extracted using a piece of microsaccade detection software (Microsaccade Toolbox 0.9 (Engbert et al., 2015)), and frequency, peak velocities, amplitudes and durations of MSs were compared.
- Saccade frequencies and amplitudes were extracted from eye fixations using a threshold of

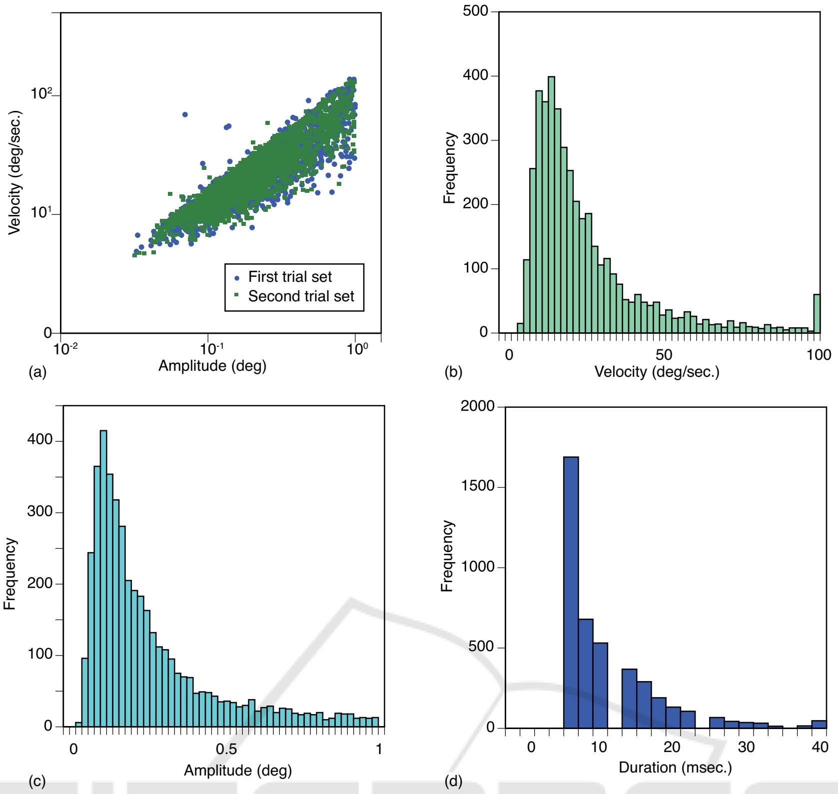


Figure 3: Characteristics of observed microsaccades: (a) relationship between amplitudes and velocities, histograms for (b) peak velocity, (c) amplitude, and (d) duration.

40deg/s (Ebisawa and Sugiura, 1998; Andersson et al., 2017).

- Mean pupil size and power spectral of density (PSD) for pupillary oscillations were also calculated (Nakayama and Shimizu, 2004; Nakayama and Katsukura, 2011).

3 RESULTS

3.1 Oculo-motor Indices

3.1.1 MS Characteristics

Features of MSs during manipulation tasks are summarised in Figure 3, using the same format as in the previous study (Engbert, 2006). As the overall tendency is similar to the reported results, the appropriate MSs may be extracted. In Figure 3 (a), the data in the two sets of trials are illustrated similarly, and the repetition of the measure may not influence the behaviours of MS.

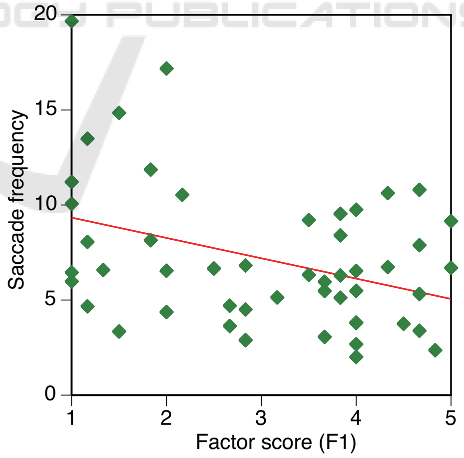


Figure 4: Relationship between factor score as subjective evaluation (Factor1) and saccade frequency ($r = -0.37$).

3.1.2 Relationship between Oculo-motor Indices

To evaluate the effect of the experimental conditions, all metrics of every trial are summarised (N=50: 10 subject × 5 conditions).

The influence of the manipulation of the condi-

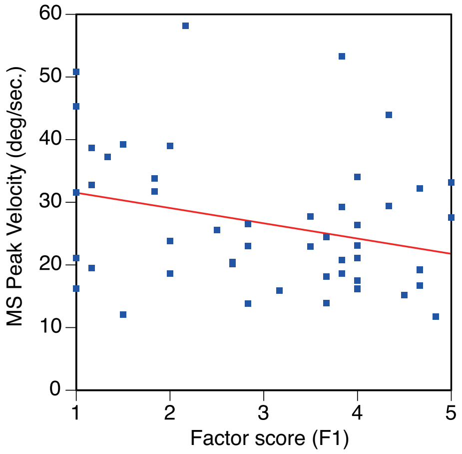


Figure 5: Relationship between factor score as subjective evaluation (Factor1) and peak velocity of micro saccade ($r = -0.29$).

tions on oculo-motors were examined using One-way ANOVA . However, the contributions of the conditions to the metrics are few, including to the saccades and pupil responses. On the other hand, some metrics correlate with the factor scores for "Mental workload". Figure 4 represents a scattergram between the factor scores and saccade frequency ($r = -0.37$, $p < 0.01$), and Figure 5 represents the relationship between the factor scores and the peak velocity of MS ($r = -0.29$, $p < 0.05$). Also, the deviations in pupil diameters correlate with the factor scores.

The above results suggest that oculo-motor indices correlate with the factor scores for "Mental workload", though the manipulation of the conditions showed few contributions. As participants rated scales based on their individual impressions in response to their own oculo-motor reactions, the relationships emphasised these associations.

3.2 Causal Analysis between Observed Metrics

In the above analyses, the impact of the experimental conditions and the subjective assessments of mental workloads on ocular indices were examined. The observed metrics are definitely correlated with each other. For example, there is a relationship between the saccade amplitude and the amplitude of the MS, as shown in Figure 6. There is a significant correlation ($r = -0.73$, $p < 0.01$). During the trial session, the saccade amplitude negatively correlated with the frequency of saccades ($r = -0.71$, $p < 0.01$), and the saccade metrics significantly correlated with peak velocities and amplitudes of MSs, while both peak velocities and amplitudes of MSs correlated with each other.

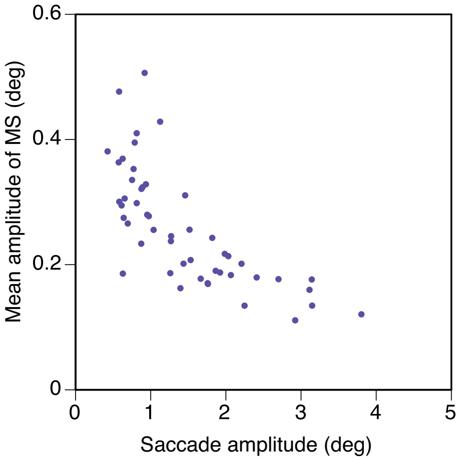
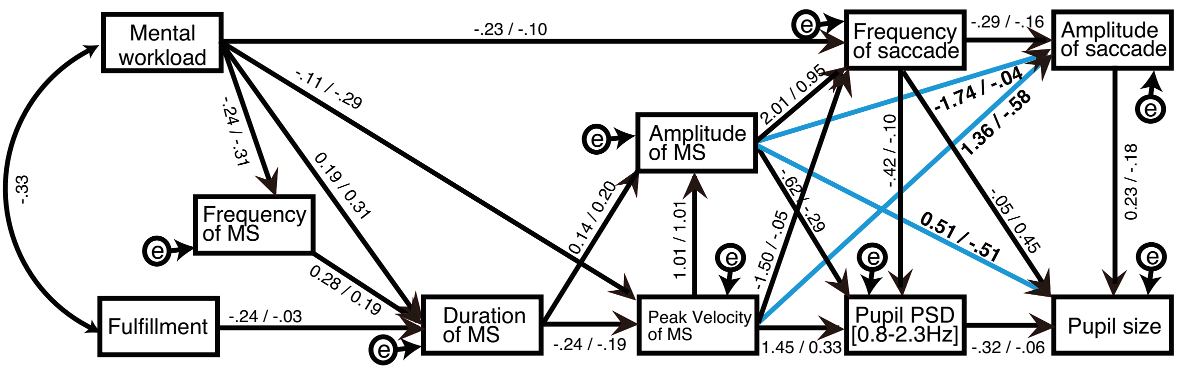


Figure 6: Relationship between amplitudes of saccades and micro saccades ($r = -0.71$).

In regards to the relationships between the observed metrics, overall relationships such as causal relationships are considered step by step, on trial and error basis. In order to illustrate these mutual relationships, a structural equation modeling technique was introduced (Toyoda, 2007). All parameters were estimated using AMOS packages (Toyoda, 2007), and the model of fitness was evaluated using a GFI (goodness of fit index).

An optimised model, from subjective evaluation to oculo-motor indices, is created using the procedure explained above as shown in Figure 7. Path coefficients are indicated using path arrow lines as path connections between the variables of the first and the second sets of trials. In regards to the results of the optimisation, the GFI is 0.91, thus this path model is an acceptable model (RMSEA: Root Mean Square Error of Approximation < 0.05). In this figure, the differences in path coefficients of the two sets are compared statistically. The coefficients of the three paths between two sets are significantly different ($p < 0.05$). These paths are indicated as blue paths in Figure 7.

The structure of the model suggests that factor scores directly affect the indices of MS and the frequency of saccades, and that indices of MS are mutually related. Finally, subjective impression affects both saccades and pupil responses due to MS behaviours. Relationships between MS indices and the amplitude of saccades and pupil sizes deviated because there are significant differences between the three path coefficients, although the relationships between features of MSs are stable.



GFI=0.91, AGFI=0.79, RMSEA=0.04

Figure 7: Causal relationships between observed variables. The "e" nodes indicate residual term. Path coefficients are indicated for the first and the second sets of trials as shown as the "first/second" format. Blue causal paths indicate that there are significant difference in two path coefficients between two trial sets ($p < 0.05$). The model is validated in regards to the statistical indices of GFI(Goodness of Fit Index), AGFI(Adjusted GFI), and RMSEA(Root Mean Square Error of Approximation) as displayed above.

4 DISCUSSION AND SUMMARY

The conditions in a visual experiment with varying levels of mental workload resulted in behaviour responses which were measured and analysed. Though the participant's subjective assessments are well controlled by the different task manipulation conditions, the eye metrics may reflect the mental states of the participants. Individual differences in these metrics and in the impacts of the experimental conditions may affect the associations in these relationships.

As ocular motor indices, microsaccades and ordinary eye behaviour correlate significantly with mental workload. Therefore, the possibility that oculo-motor metrics can be an index of cognitive mental workload was examined.

A causal connection between these metrics, which are based on mutual relationships, was established using a structural equation modeling technique. A statistically significant model suggests that metrics of MSs between subjective impressions and ordinary eye behaviour, such as saccades and pupil responses, are correlated. Some previous studies have suggested that MSs reflect the internal activity of human information processing (Engbert and Kliegl, 2003; Meyberg et al., 2017). In particular, Engbert has suggested that the superior colliculus (SC) of the human brain, which is concerned with pupil response and eye movement, including saccades, plays a major role in generating MSs during information processing (Engbert, 2006).

As this experiment employed a repeated-measure design, participants might have become familiar with the manipulation tasks. During the causal analysis, path coefficients between two sets of trials were compared. Three coefficients for saccades and pupil size changed significantly, but all coefficients between MS metrics remained comparably similar. This phenomenon may illustrate the stability of metrics of MSs.

The detailed relationships between these metrics should be examined once more. Also, the subjective assessment should employ more robust metrics in order to better evaluate mental workload. These points will be topics of our further study.

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