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Influence of Task-evoked Mental Workloads on Oculo-motor indices and their connections

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Abstract

The frequency of microsaccades is often used as a measurement of eye movement in order to estimate the level of effort required, because some indices of oculo-motors suggest the level of mental activity. In an experiment involving several task-manipulation levels, ocular information including microsaccades, saccades and pupil diameters were measured and compared in order to estimate workload levels during problem solving. While some oculo-motor metrics correlate with the estimated scores of the mental workload, these metrics mutually correlate with each other. A causal relationship model 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.

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1. Introduction

The design of an operational interface helps users manipulate its underlying system using peripheral devices, in order to better utilise the system. Overall assessment of the user experience is often discussed as usability, and it is conducted using various methodologies [1]. One of the methodologies employs an eye tracking technique [2]. In addition to this research, the possibility of assessing usability and observing mental workloads during manipulation tasks using ocular-motor measurements as an objective evaluation has also been discussed [3, 4]. Therefore, eye tracking techniques have been introduced to evaluate human mental workloads in order to improve manipulation interfaces and address environmental issues. Some studies using eye movement have already been conducted in the field of aviation [5, 6]. While oculo-motor indices have been employed to evaluate the system usability of operational interfaces [7], the metrics of microsaccades (MSs) and pupil responses have been used more often recently, as they react well to the level of task difficulty and to higher order cognitive processes [8–10].

In particular, microsaccades are often used as an index of high level information processing, such as an indicator of covert orienting attention and emotional responses [11, 12]. Microsaccades appear during fixation, and the possibility of detecting them during smooth pursuit has also been suggested [13].

A mechanism for stimulating the appearance of MSs was discussed in a previous study [14], and the mutual relationships between the metrics of oculo-motors were also discussed [15]. A detailed analysis of these mutual relationships during a manipulation task should be conducted carefully. In particular, further analysis of MSs and their contributions is required, as the information may affect various responses. Because most indices of oculo-motor reactions are based on an aspect of cognitive load, common factors such as MS activity may be the cause of the observable metrics such as eye movement and pupillary dilation. In regards to the hypothesis, the activity of ocular-motor responses and its contributions mutually to each other are considered

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in comparison with the results of previous reports [15, 16]. This original approach may help determine which ocular responses can be used to monitor a cognitive workload situation of the experiment's participants.

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.

The remainder of the paper is structured as follows. Section 2 introduces experimental methodologies and analytical procedures used to extract covert activity during computer operation by the experiment's participants. Section 3 presents the results of analysis of behavioural responses and changes of oculo-motor indices during the operational experiment. A detailed analysis which extracts the latent relationships between measured metrics and their contributions is conducted, and a discussion of possible interpretation is summarised in Section 4. The overall results of this paper are summarised in Section 5.

2. Method

2.1. Experimental tasks

In order to control the level of cognitive workload during tasks, a black box interface [17] was developed to facilitate manipulation of an object shown on a PC monitor. The black box interface was designed for an object manipulation task, where changes in subjective impressions were observed and user's oculo-motor measurements during the task were recorded.

The experimental stimulus, which consists of a moving disc, a goal circle and three grey cubes serving as obstacles, is illustrated in Figure 1. The task is to move the disc (a small yellow disc) to the goal (a white circle) as fast as possible, using the keyboard arrow keys. As a means of controlling task difficulty, there were 5 levels of movement for the moving disc. Each level changed the speed and rate of directional change of the moving disc. As a penalty, the disc returned to its starting position whenever it touched an obstacle during the experiment.

The duration of each trial was 10 seconds, and a new trial began even if the disc was not successfully moved to the goal in the given time. If the task was completed within 10 seconds, the next task was presented.

The key inputs were modified using a black box software interface between the manipulation task controller and the PC keyboard [17].

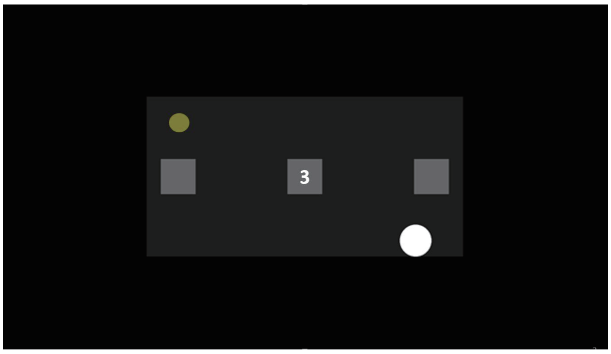

Figure 1. A screen-shot of the manipulation task

Manipulation conditions. The 5 conditions that the black box interface modifies are key manipulations, 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 of Output 1.

3. Output 3: The key response speed was increased to 4 times the speed of 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 task only required around 5 seconds.

Participants of the study. Participants were 10 male university students aged 21-25 years old, who had sufficient visual acuity. All were paid participants, Faculty of Engineering students, and thus familiar with simple mouse and keyboard computer interfaces. They were unaware of the experimental task and conditions, however. Before the experiment, participants gave their informed written consent after a short description of the aims of the experiment.

2.2. Subjective assessment of the task

The experimental conditions may control participant's responses, their own impression and subjective assessments can also be evidence of the effectiveness of the experiment. Participant's overall impressions of the

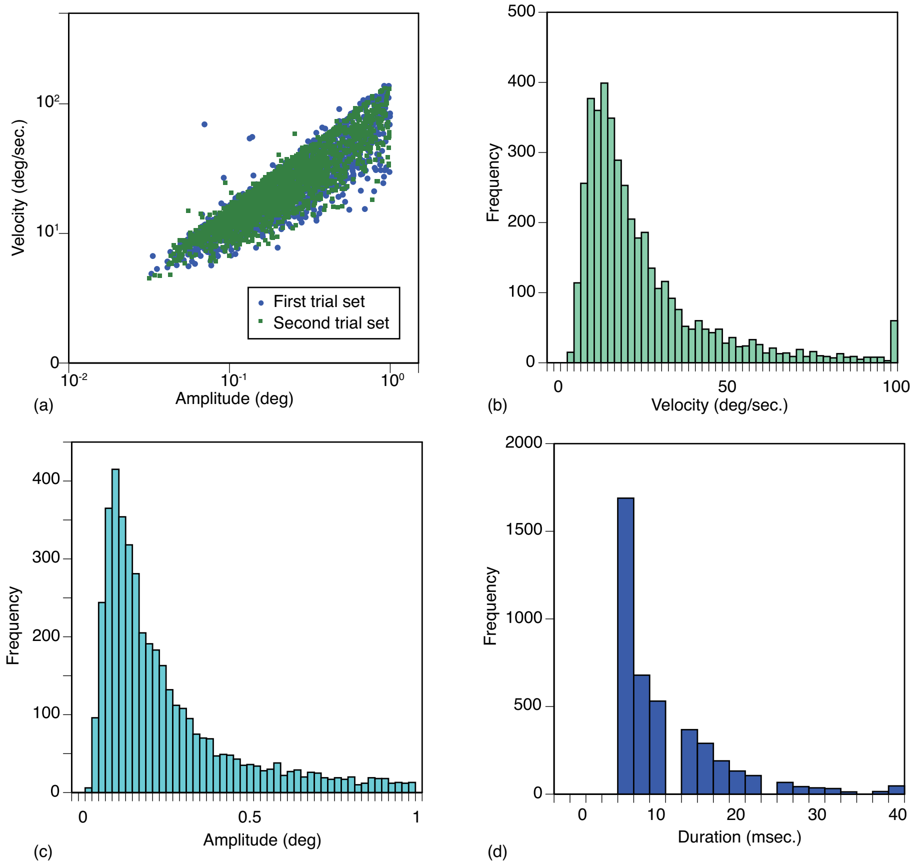

Figure 2. Characteristics of observed microsaccades: (a) relationship between amplitudes and velocities, histograms for (b) peak velocity, (c) amplitude, and (d) duration

manipulation of the directional keys during each of the 5 conditions of the task were measured using a 5-point inventory assessment scale consisting of seven questions which rated aspects such as "Difficulty", "Being in a hurry", "Unpleasant", "Unusable", "Fulfilment", "Irritating" and "Mental workload" [4].

After their session, an assessment asked each subject to rate each trial using the items listed above.

2.3. Measurement procedure

The stimulus was presented on a 27 inch LCD monitor which was 40cm from the viewer. Both eye movement and pupil diameters were measured at 400Hz (Arrington Research: Viewpoint EyeTracker USB400), and a chin rest was employed. The measured data such as two-dimensional eye position of viewing is recorded as time series data in pixels on the screen. The data can be converted into visual angles. The periods of blinks were detected using the aspect ratios of the pupil diameters, and were then removed during the processing which followed.

In response to manipulation tasks, the following metrics were extracted [15].

- Microsaccades (MSs) were extracted using a piece of microsaccade detection software (Microsaccade Toolbox 0.9 [18]) which included the recorded two-dimensional data of the tracked eyes, and provided the following metrics: frequency, peak velocity, amplitude and duration of MSs to be compared.

- Saccade frequencies and amplitudes were extracted from eye fixations using a threshold of 40deg/s [19, 20].

- Mean pupil sizes and power spectral densities (PSDs) of pupillary oscillations were also calculated [7, 21]. Since individual differences were observed, pupil sizes were standardised using the overall means of pupil diameters (=1) of all tasks for each subject.

Also, frequency power spectral densities (PSDs) for pupil responses and cross power spectral densities (CSDs) were extracted using a frequency analysis technique with Hanning window, in order to evaluate both types of eye activity [7, 21]. These metrics were calculated using MATLAB functions.

Table 1. Factor loading matrix for subjective evaluation with Promax rotation

Question item	Factor1	Factor2
Difficulty	**1.00**	0.19
Unusable	**0.96**	0.07
Mental workload	**0.90**	-.08
Unpleasant	**0.86**	-.09
Irritating	**0.81**	-.08
Being in a hurry	**0.58**	-.34
Fulfilment	0.14	**1.06**
Contribution ratio	0.64	0.18
Correlation	r=0.48	

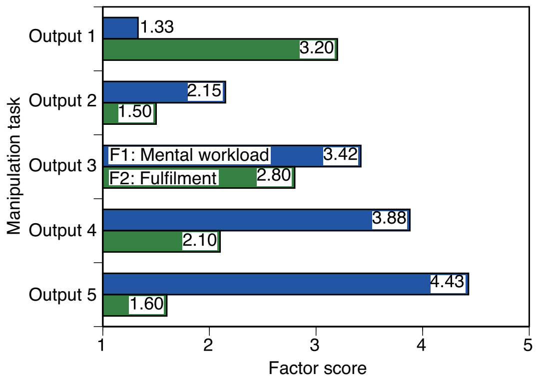

Figure 3. Factor scores for experimental conditions

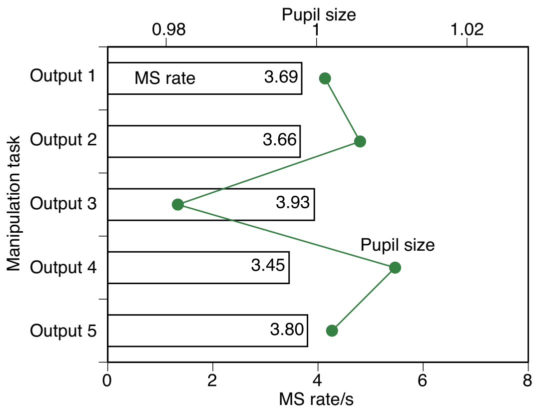

Figure 4. Microsaccade rates and pupil sizes for experimental conditions

2.4. Causal modelling analysis

In regards to the relationships between the observed metrics, overall relationships such as causal relationships were considered step by step, on trial and error basis. To construct a hypothesised model, a matrix of correlation coefficients between all metrics were calculated. In addition to these relationships, participant's physiological aspects were also considered. In order to illustrate these mutual relationships, a structural equation modeling technique was introduced [22]. All parameters were estimated using AMOS packages [22], and the model of fitness was evaluated using a GFI (goodness of fit index).

3. Results

In regards to task observation, the mean duration of the manipulation task was almost 10 seconds, except for the "Output 1" condition, which required around 5 seconds. Responses of participants were analysed as follows.

3.1. Subjective assessment

After each session, subjective assessments using 7 question items were conducted. In order to extract common scales from the subjective assessments, factor analysis with Promax rotation was conducted. As a result, two factors were extracted, as shown in Table 1. The labels of the factors are "Mental workload" (Factor 1) and "Fulfilment" (Factor 2).

Mean factor scores for each condition are summarised in Figure 3. The factor scores for "Mental workload" as a mean of the 6 responses increased as the experimental condition changed from "Output 1" to "Output 5", while the scores for "Fulfilment" decreased gradually, with the exception of "Output 2". The results show that the experimental condition controlled the participant's impression of the level of mental workload. Since the response during "Output 2" condition was very slow, the scores for "Fulfilment" are the lowest.

3.2. Oculo-motor indices

Metrics of eye responses. Conventional metrics of eye responses, such as saccade frequency, saccade length and pupil sizes were summarised for each condition and each participant.

MS characteristics. Features of MSs during manipulation tasks are summarised in Figure 2, using the same format as in the previous study [14]. All metrics are generated using a piece of MS detection software [18]. As the overall tendency is similar to the reported results, the appropriate MSs could be extracted. In Figure 2 (a), the data in the two sets of trials is illustrated similarly, and the repetition of the measurements may not influence the behaviours of MS.

Comparison of ocular indices by manipulation condition. As both microsaccade rates and pupil sizes react to the mental workload, they are summarised for each condition, and presented in Figure 4. The horizontal axis represents the frequency of both microsaccades and pupil sizes.

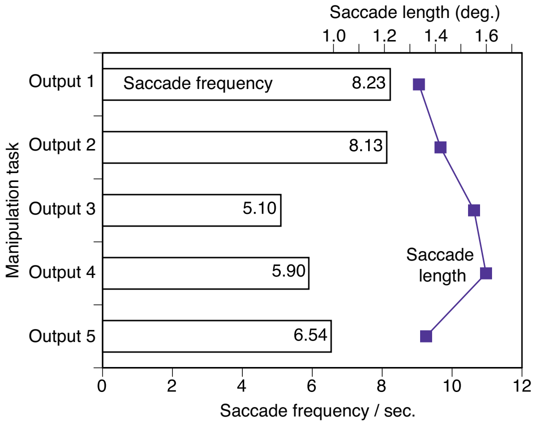

Figure 5. Mean saccade frequencies and mean saccade lengths for experimental conditions

As the figure shows, both metrics increase gradually in regards to the level of task difficulty, with some exceptions. In general, the microsaccade rates decrease with the level of the mental workload and the high level of information processing required, while pupil sizes increase with the level of mental workload. Though there are no significant differences in both of the measurements between conditions, the measurements between microsaccade rates and pupil sizes corresponded partially. This detailed relationship will be discussed later.

Features of eye movements, such as saccade frequency and saccade length, are summarised in Figure 5. As mean saccade frequencies per second were between 5 and 8 degrees, saccades occurred very frequently during the manipulation task. Under some conditions, saccades may be suppressed, though mean saccade lengths are relatively long. These indices may be influenced by the mental workload.

3.3. Frequency analysis of eye metrics

During the experimental tasks, both eye movements and pupil diameters changed, and the deviations were analysed using a frequency analysis technique. Since lower frequency components of biological signals react to this kind of activity, pupil diameters of less than 6Hz and eye movements of less than 15Hz were analysed. Factor analysis was applied to frequency components in order to extract the frequency ranges [7]. Two ranges for pupil responses in power spectral density (PSD) 1.5~3.1Hz (Fact-P1) and 3.9~5.4Hz (Fact-P2) in Table 2, and three ranges for eye movements in cross spectral density (CSD) 5.4~11.7Hz (Fact-C1), 1.5~4.6Hz (Fact-C2), and 11.7~14.8Hz (Fact-C3) were extracted in Table 3.

Mean PSDs of pupillary changes are summarised in Figure 6. Though mean PSDs for "Output 1" are

Table 2. Factor loading matrix for Frequency power spectrum of Pupillary change with Promax rotation

Frequency	Factor1	Factor2
0.78	0.00	-.18
1.56	**1.06**	-.13
2.34	**0.98**	0.02
3.13	**0.64**	0.42
3.91	0.10	**0.91**
4.69	-.07	**1.04**
5.47	0.44	**0.63**
Contribution ratio	0.26	0.17
Correlation	r=0.64	

Table 3. Factor loading matrix for cross spectrum of eye movement with Promax rotation

Frequency	Factor1	Factor2	Factor3
0.78	0.04	0.17	0.04
1.56	-.10	**0.77**	0.33
2.34	0.07	**0.88**	0.11
3.13	0.12	**0.87**	0.08
3.91	0.32	**0.73**	0.04
4.69	0.48	**0.67**	-.07
5.47	**0.65**	0.50	-.07
6.25	**0.76**	0.36	-.05
7.03	**0.85**	0.26	-.07
7.81	**0.89**	0.12	0.04
8.59	**0.90**	0.09	0.05
9.38	**0.91**	0.04	0.09
10.16	**0.85**	-.04	0.26
10.94	**0.79**	-.05	0.34
11.72	**0.57**	-.12	**0.62**
12.50	0.29	-.04	**0.82**
13.28	0.03	0.14	**0.89**
14.06	-.08	0.28	**0.87**
14.84	0.02	0.50	**0.58**
Contribution ratio	0.18	0.12	0.11
Correlation	-	0.62	0.57
coefficients(r)	-	-	0.53

the lowest, and mean PSDs increase gradually as the manipulation condition becomes harder, though the mean for "Output 5" is not the highest. As an overall assessment for PSD changes of pupillary oscillation, this metric may react to the level of mental activity. Also, the means of CSDs for eye movement using the first factor (Fact-C1) decreased gradually according to the experimental condition became more difficult, except for "Output 3" (Figure 7).

Therefore, the influence of mental workload on changes in both means may not be much, since there are no significant correlational relationships between them.

To evaluate the effect of the experimental conditions, all metrics of all trials are summarised (N=50: 10 subject × 5 conditions). The influence of the manipulation

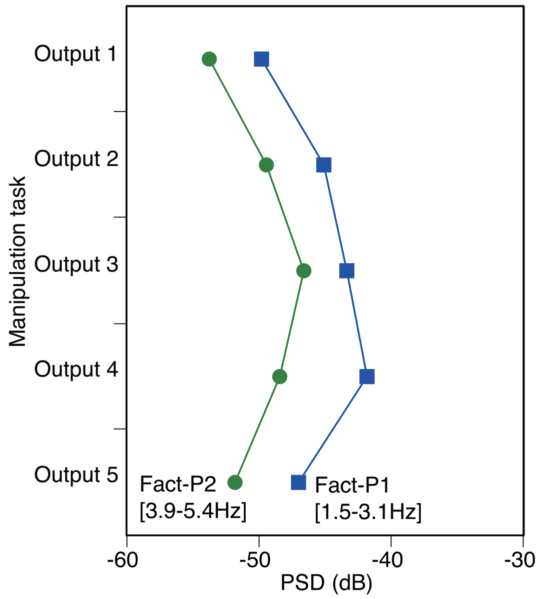

Figure 6. PSDs of pupil reactions for experimental conditions

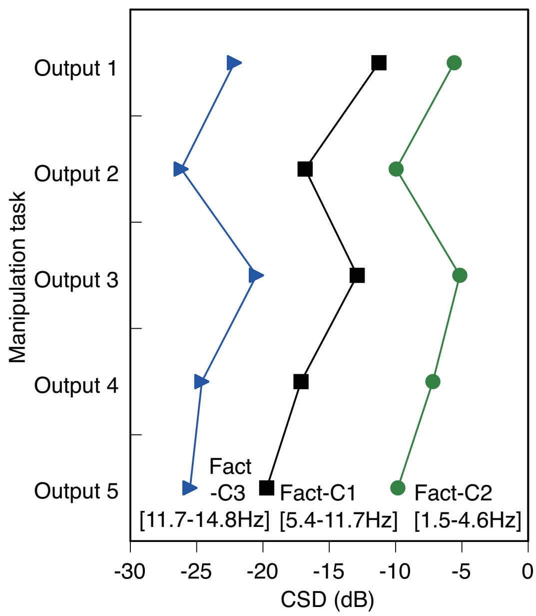

Figure 7. CSDs of eye movements for experimental conditions

conditions on oculo-motors was examined using one-way ANOVA. However, the contributions of the conditions to the metrics are few, including to saccades and pupil responses.

3.4. Relationships between measured metrics

Though the factor scores of mental workload gradually increased as the experimental condition became more difficult, most ocular metrics between conditions did not change. As some results suggest partial

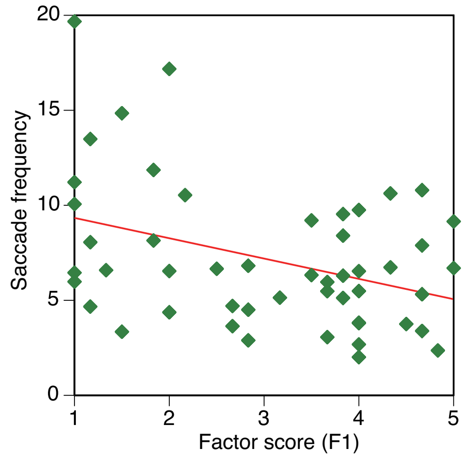

Figure 8. Relationship between factor scores as subjective evaluations (Factor1) and saccade frequency ($r = -0.37$).

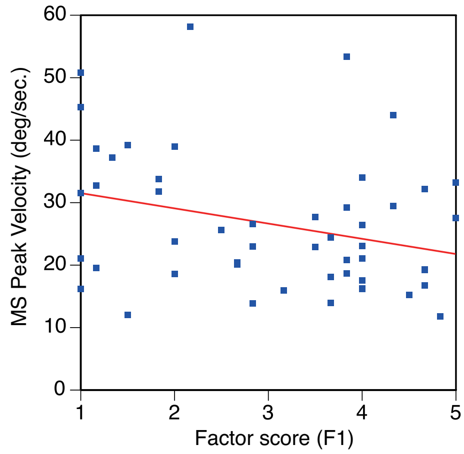

Figure 9. Relationship between factor scores as subjective evaluations (Factor1) and peak velocity of micro saccade ($r = -0.29$).

relationships, the mutual relationships between the surveyed metrics were examined without consideration of the conditions.

Figure 8 represents a scatter gram of the factor scores and saccade frequencies ($r = -0.37$, $p < 0.01$), and Figure 9 represents the relationship between the factor scores and 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 changes in the manipulation condition 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.

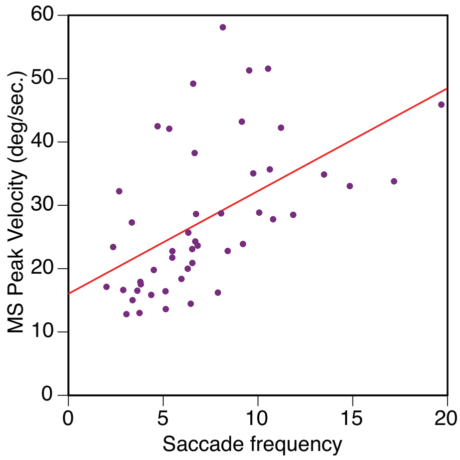

Figure 10. Relationship between saccade frequency and peak velocity of microsaccade ($r = 0.82$).

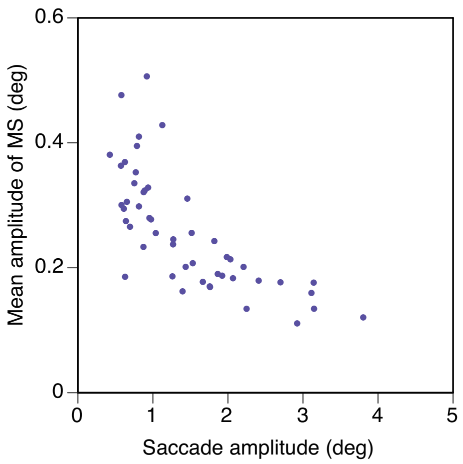

Figure 11. Relationship between amplitudes of saccades and microsaccades ($r = -0.73$).

Relationship between oculo-motor indices. In the above analyses, the impact of the experimental condition and the subjective assessment 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 frequency and the peak velocity of the MS, as shown in Figure 10. The correlation is significant ($r = 0.82$, $p < 0.01$). Also, there is a relationship between the saccade amplitude and the amplitude of the MS, as shown in Figure 11 ($r = -0.73$, $p < 0.01$). During the trial session, the saccade amplitude correlated negatively with the frequency of saccades ($r = -0.71$, $p < 0.01$), and the saccade metrics correlated significantly with peak velocities and amplitudes of MSs, while both peak velocities and amplitudes of MSs correlated with each other.

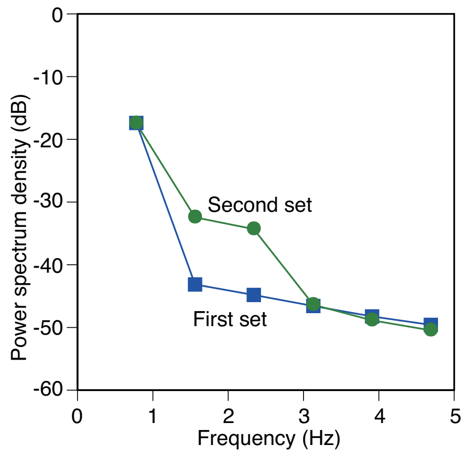

Figure 12. Difference of frequency power spectrum on pupillary responses between 1st and 2nd experimental sets.

3.5. Causal analysis between observed metrics

During the manipulation task, surveyed metrics were mutually related and working collaboratively. An additional factor is the aspect of repeated measure. As mentioned in the experimental procedure, two sets of trials were conducted. The trials may have influenced task difficulty and mental workload. As an example, PSDs of pupil responses between the two trials were compared in Figure 12. The PSDs for the second set in a frequency area which corresponds to Fact-P1 are larger than the ones for the first set. Participants recognised the difficulty of the task in the second trial.

The relationships between variables were considered, in order to create a causal model, and the trial sets are also included in the model. An optimised model, from subjective evaluation to oculo-motor indices, was created using the procedure explained above, and shown in Figure 13. 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 13.

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 impressions affect both saccades and pupil responses due to MS behaviour. Relationships between MS indices and the amplitude of saccades and pupil sizes deviated because there are significant differences between the three

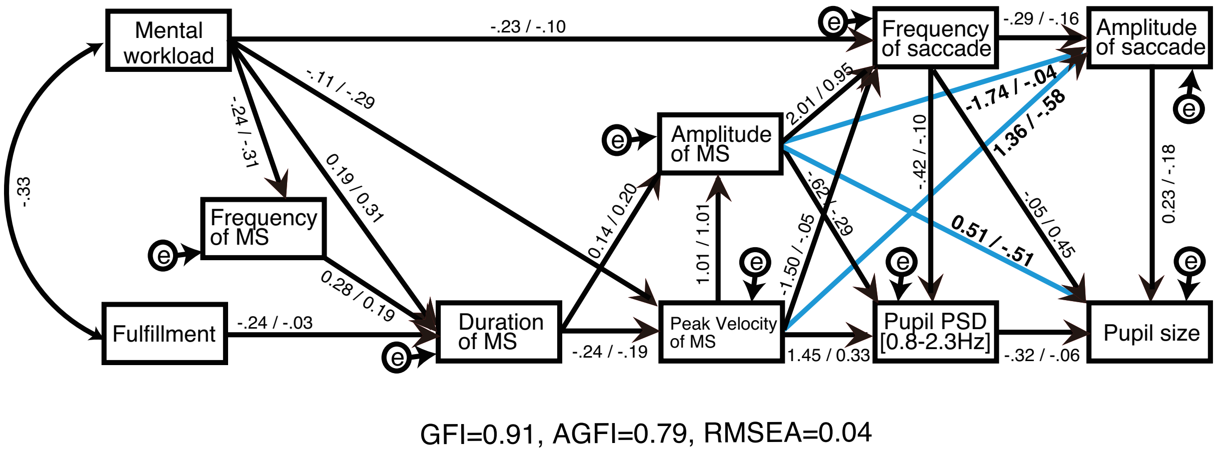

Figure 13. Causal relationships between observed variables. The "e" nodes indicate residual terms. Path coefficients are indicated for the first and the second sets of trials as shown using the "first/second" format. Blue causal paths indicate that there are significant difference in two path coefficients between the 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.

path coefficients, although the relationships between features of MSs are stable.

4. Discussion

A visual experiment with varying levels of mental workload produced behavioural responses which were measured and analysed. Though the participant's subjective assessments were well controlled by the different task manipulation conditions, the mental state of the participant may affect their eye metrics. 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 the level of mental workload. Therefore, the possibility that oculomotor 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 reacts to the internal activity of human information processing [11, 23]. 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 [14].

As this experiment employed a repeated-measure design, participants might have become familiar with the manipulation tasks. During the causal analysis, path coefficients between the 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 above discussion may be limited by the following insufficient aspects. First, the experimental task and conditions should be considered in determining the number of participants and their attitude towards computer operation. In addition, the extraction procedure for MSs at fixation points should be improved so that more accurate detection is provided. An optimisation tool should be considered. Therefore, further experimentation and analysis is required to develop the relationship accurately. These points will be subjects of our further study.

5. Conclusion

This paper presents the relationships between indices of ocular motors during an experiment stimulating task-evoked mental workloads. As metrics of ocular motors, the following information was measured: saccade frequency, saccade length and eye oscillations as features of eye movement, pupil size and pupil oscillations as pupillary changes, and some features of microsaccades (MSs). In particular, the features of MSs are often referred to as an index of high-level information processing for viewers. The role of MSs behaviour was examined.

The following points are revealed in this paper.

1. Levels of viewer's mental workloads were measured using a set of questionnaires. The scores

increased with the level of difficulty of the manipulation task. Though the metrics of the oculo-motors measured did not change with the change in experimental condition, some of the metrics correlated with the scores of mental workloads.

2. Significant correlational relationships between some of the metrics of oculo-motors measured were confirmed during the manipulation tasks. In particular, some of MS features correlated with the features of saccades, although they happened asynchronously. This phenomenon shows the relationships between the metrics that were measured.

3. A possible causal relationship was optimised using surveyed metrics of eye activity. The model suggests that all extracted features of MSs affect the ordinal indices of oculo-motors. This structure shows hierarchical relationships between the metrics, and MS plays a major role regarding oculo-motors.

As many biological measurements are used to observe human behaviour or cognitive loads, the results of this study suggest that some of the metrics examined are mutually correlated and hierarchically related. The results of causal analysis in this study may provide evidence of a possible relationship which illustrate the metrics observed under the experimental conditions. Nevertheless, the detailed relationships between these metrics should be examined in greater detail. Also, the subjective assessments should employ more robust metrics in order to better evaluate the mental workload. Both of these points will be topics of our further study.

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