別紙４－１（課程博士（英文））

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Abstract (Doctor)

Title of Thesis	Pupillometry and time perception: Temporal modulation caused by pupillary light reflex to luminance-controlled stimuli

Approx. 800 words

Temporal perception and the ability to precisely ascertain time duration are central to essentially all behaviors. Nevertheless, humans do not have a dedicated receptor that can directly perceive the flow of time and believed that our brain creates a subjective sense of time by integrating various endogenous and sensory inputs. Therefore, our perception of time can be influenced by various non-temporal aspects of the stimulus, known as the "temporal distortion." Interestingly, the pioneering works on temporal perception have consistently found that the subjective duration of a given interval generally correlates positively with the magnitude of the stimulus ("more-is-longer" account). These studies have reported the occurrence of temporal distortion due to non-temporal factors related to the physical aspect of the stimulus, using temporal perception tasks with stimuli associated with different sensory inputs. However, stimulus magnitude can be determined by a complex interaction of the physical intensity, internal representation, and even by pupillary responses of the stimulus. In other words, temporal distortion effect may vary depending on the equiluminant method used. It is important to further clarify the involvement of these factors, especially since the effect of color and luminosity on temporal perception —the most well-known non-temporal aspects that can cause temporal distortion— is still a topic of controversy. In this thesis, we conducted a series of temporal perception experiments to evaluate the effects of different representations of stimulus magnitude on temporal perception, and the role of pupillometry in temporal distortion. Three research questions were addressed in this study.

In the first study, we used color stimuli as the to-be-timed target to answer two research questions: 1) what is the potential effect of color (specifically red versus blue) on temporal perception under different intensity matching conditions, and 2) what is the relationship between pupillary response and temporal perception? Results from previous studies on the perceived duration of red versus blue have been inconsistent since the 1960s, which may be due to difficulties in controlling physical properties such as hue and luminance within and between studies. Therefore, we conducted a two-interval duration-discrimination task to evaluate the perceived duration of color stimuli under different equiluminant conditions: subjective equiluminance and pupillary light reflex (PLR)-based equiluminance. The results, based on psychometric functional analyses and simultaneous pupillary recordings, showed that the perceived duration of red was overestimated compared to blue even when the intensity was

controlled based on subjective equiluminance. However, since blue is known to induce a larger PLR than red despite equiluminance, we conducted a controlled study to differentiate the indirect effect of pupillary response on temporal perception. Interestingly, the effect observed in the first experiment faded when the luminance levels of the two stimuli were matched based on PLR response. These results indicate that duration judgment can be influenced not only by the hue but also by different equiluminance methods.

In the second series of experiments, we adapted an optical illusion named the glare illusion, which enhances the perceived brightness without any actual change in physical intensity, as the to-be-timed target during pupillary recording. This paradigm enabled us to explore two research questions: 1) is subjective magnitude itself sufficient to induce temporal illusions when physical intensity is identical, and again, 2) what is the relationship between pupillary response and temporal perception? This is because it remains unclear how perceptual magnitude, which is assumed to link temporal perception itself directly affects temporal perception. Therefore, we again conducted a duration-discrimination task using glare, halo, and glare-equivalent stimuli. Based on the mean difference in the point of subjective equality derived from a psychometric function and pupil diameter, we found that temporal perception is influenced by the illusory brightness of glare stimuli. Interestingly, the perceived duration of the apparently brighter stimuli (glare stimuli; larger PLR) was shorter than that of control stimuli (halo stimuli; smaller PLR) despite the stimuli remaining physically equiluminant, in contrast with the well-known "more-is-longer" account. Furthermore, this temporal modulation did not occur when the physical luminance of the stimuli was manipulated to match the illusory-induced magnitude. These results indicate that temporal processing depends on the confluence of both external and perceived subjective magnitude, and even illusory brightness is sufficient to affect the sense of duration; which may be explained by the internal magnitude decrease of the glare stimuli due to pupillary constriction decreasing the light entering the eye.

We believe this study not only provides the fact what/which stimuli is perceived subjectively longer but also provides new insights into the importance of what equiluminant methods to use. Furthermore, the fact that PLR amplitude matching resulted in the fading of temporal distortion suggests a new perspective for future studies. While there are currently no physiological models suggesting a differential effect of different PLR amplitudes on temporal perception, our finding of a causal relationship between PLR matching and temporal distortion effects can be explained by neural intensity fluctuations based on the amount of light entering the pupil and the coding efficiency model. Further considerations incorporating psychology, optical, and neuroscience approaches will be required to yield further discussion on theoretical frameworks and the probable mechanism, which should provide an important clue to elucidate the underlying mechanism of temporal perception in humans.