



Evaluation of handwriting task difficulty based on detrended fluctuation analysis

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Abstract

The control of voluntary movements is a dual structure consisting of cognitive and physical controls; cognitive control involves attentional resources, unlike physical control. Various voluntary movements can be performed by combining cognitive and physical controls. Body movements depending on attentional resources are performed using cognitive control; these movements fluctuate with white noise and their fluctuations gradually become the one-over- f fluctuation as the dependence on the attentional resources decreases. The handwriting process of characters is a voluntary movement. This study focused on the relationship between the repetitive handwriting process and the attentional resources allocated to it. The attention resources allocated to the handwriting process depend on the difficulty of the handwriting task. Moreover, the difficulty of a handwriting task is determined by the complexity of the shape of the handwritten characters, and the stroke counts is one indicator of this. Therefore, we focused on five Chinese kanji characters with different stroke counts. We investigated fluctuations in the temporal and spatial handwriting elements (twelve handwriting elements in all) defined within the handwriting process of each Chinese kanji character. The detrended fluctuation analysis was applied to the fluctuation analysis of the handwriting elements. In this paper, we discussed the relationship between the handwriting task difficulties and handwriting elements using local scaling indices based on the detrended fluctuation analysis.

Keywords Handwriting task · Fluctuation · One-over- f fluctuation · White noise · Detrended fluctuation analysis

1 Introduction

The control of voluntary movements is a dual structure consisting of cognitive and physical controls; cognitive control involves attentional resources, unlike physical control. Various voluntary movements can be performed by combining cognitive and physical controls. The separation of these controls could enable us to predict the level of physical skills acquisition from the expenditure of attentional resources. The relationship between repetitive body movements and attentional resources has been investigated via synchronous tapping tasks [1, 2]. Body movements depending on

attentional resources are performed using cognitive control; these movements fluctuate with white noise and their fluctuations gradually become an one-over- f fluctuation as the dependence on the attentional resources decreases.

Handwriting is a voluntary movement. Maleki et al focused on the repetitive handwriting task of Chinese kanji characters and developed an experimental system to clarify the relationship between fluctuations and voluntary movements, that is, a dual-task method that combines synchronous tapping tasks and handwriting tasks [3, 4]. The specific method consisted of repeating and alternating one character handwriting and one tapping in synchronization with auditory stimuli presented at regular time intervals. In their experiment, six types of partial motion times were defined within the single-character handwriting task, which were called handwriting temporal elements (HTE), and the time series of the six HTEs were measured by repeating the single-character handwriting process. Fluctuation analysis was applied to each of the six measured HTE time series to examine the relationship between the partial motion elements corresponding to each HTE and the attentional resources

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allocated to it. Differences in the number of strokes between the three focused Chinese kanji characters were associated with differences in the difficulty of the handwriting task, and the relationship between the difficulty of the handwriting task and the allocation of attentional resources corresponding to each HTE was discussed.

The level of difficulty of a handwriting task is determined by the complexity of the shape of the handwritten characters, and the stroke counts is one indicator of this. The complexity of the character shape might affect the attention resources consumed in handwriting process the character. Probably, the arrangement state (the distribution) of attention resources is not uniform in one-character shape, and the arrangement state of attention resources varies from trial to trial even within an individual, and it may not be uniform. Furthermore, the authors believe that if you want to handwrite a character beautifully, it is important to pay attention to the appropriate part of the character shape. That is, if the arrangement state of attention resources in the handwriting process of the character is quantitatively evaluated, it will give a learning guideline in handwriting learning. In addition, it may be applicable to handwriting proficiency evaluation from the increase and decrease of attention resource consumption.

By the way, fluctuations that can be measured in the handwriting process are not limited to temporal factors. Since the nib moves on the surface of the paper and the pen tablet, the position of the nib can also be measured. Therefore, in this

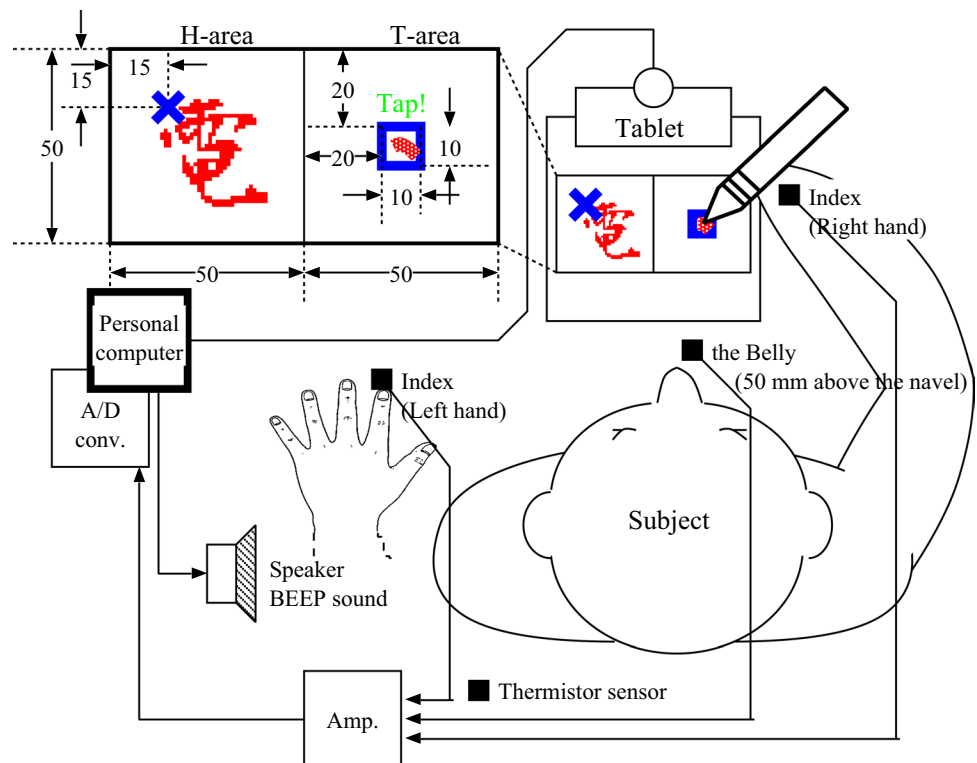
study, we defined the handwriting spatial element (HSE) as the two-dimensional positional coordinate components of the start and endpoints of the handwriting and the tapping point of the tapping in the handwriting task of Chinese kanji characters. We focused on five kanji characters with different stroke counts; den, tsu, ki, dai, and ichi, and the fluctuation analysis was performed on twelve handwriting element time series with new HSEs added to the conventional HTEs. In this study, the correct stationarity of the HTEs and the HSEs was hard to ensure; therefore, we performed the detrended fluctuation analysis (DFA) following conventional study [5–7]. In particular, following a previous study by Uchida et al. [9–11], we investigated the features of these elements by using scaling indices that qualitatively evaluate their fluctuations locally on a timescale. We investigated the relationship between the six HTEs and the six HSEs by assessing the relationship between local scaling indices on a timescale and the difficulty of handwriting tasks. As a result, it was suggested that the arrangement of attention resources in a character shape may not be uniform.

2 Experiment

Figure 1 illustrates the configuration of our experimental system.

The stroke motion was measured with a pen tablet (PTH-860, WACOM Corp.); the coordinate positions of the pen

Fig. 1 Experimental system



on the pen tablet were recorded on the computer at 200 Hz. Moreover, a trigger signal indicating whether the pen tip is attached to or detached from the tablet was output via a digital-to-analog converter (USB-3105, Measurement Computing Corp.) and recorded at 1 kHz via an analog-to-digital converter (AIO-60/4/1B-USC, Y2 Corp.). The handwriting field on the pen tablet comprised a square area with a side 50-mm side on the left (H-area) and a square area with a 10-mm side on the right (T-area). An “x” mark was drawn in the H-area to be used by the subject as the starting point to handwriting the designated kanji character.

The computer output a voltage rectangular waveform with a 20-ms width for emitting auditory stimuli from the speaker. Following a previous study by Maleki et al. [3, 4], we measured body temperature to easily assess the activation of the autonomic nervous system during the experiment. The body temperature was measured by three contact thermometers (thermistor sensor SZL-64, high-accuracy temperature converter E471-0, Tateyama Kagaku Kogyo); the peripheral skin temperature was measured by attaching a thermometer to the tip of both hands so as to not impede their movement and another was placed on the abdomen (50-mm above the navel) to monitor the temperature. First, the subjects answered two types of psychological questionnaires; the profile of mood states (POMS) and the state-trait anxiety inventory (STAI) [12, 13]. Then, they were instructed to close their eyes and rest for 150 s. Next, they repeated the character writing and tapping tasks for 250 times in synchronization with the auditory stimuli, followed by another resting with closed eyes for 150 s. Finally, the POMS and STAI questionnaires were conducted again. The experiment took 6 days for about 3 h per day. The POMS and STAI and the body temperature recordings were set up to monitor the subjects’ well-being during the experiment. As a result, no cases of suspected influence on the experimental results were identified in any of the subjects.

Figures 2 and 3 show the HTEs and HSEs measured in this experiment. Each HTE, analyzed conventionally, was composed of SLs; it is the time from an auditory stimulus to the start of writing one character, SLe; it is the time from an auditory stimulus to the end of writing one character, LsT; it is the time from the start of writing one character to tapping, LsLe; it is the time from the start to the end of writing one character, LeT; it is the time from the end of writing one character to tapping, and ST; it is the time from an auditory stimulus to tapping. The HSEs, which were newly analyzed in this study, consisted of l_{sx}; it is *x* coordinate of a start point of writing one character, l_{sy}; it is *y* coordinate of a start point of writing one character, l_{ex}; it is *x* coordinate of an endpoint of writing one character, l_{ey}; it is *y* coordinate of an endpoint of writing one character, t_x; it is *x* coordinate of tapping, and t_y; it is *y* coordinate of tapping. Thus, six HTEs and six HSEs were extracted from each trial. The

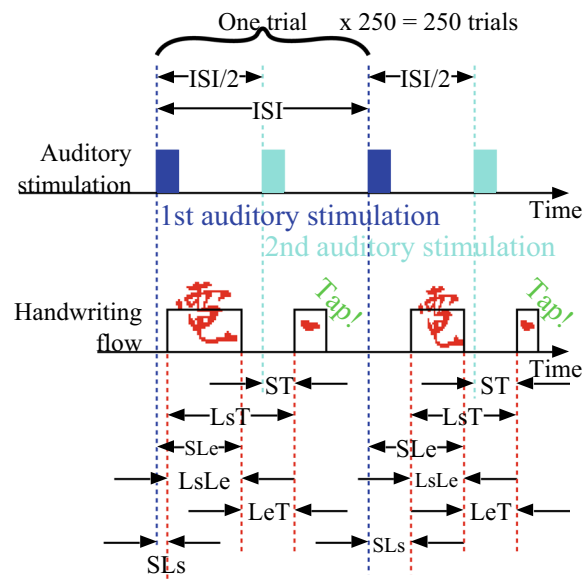


Fig. 2 Handwriting temporal elements

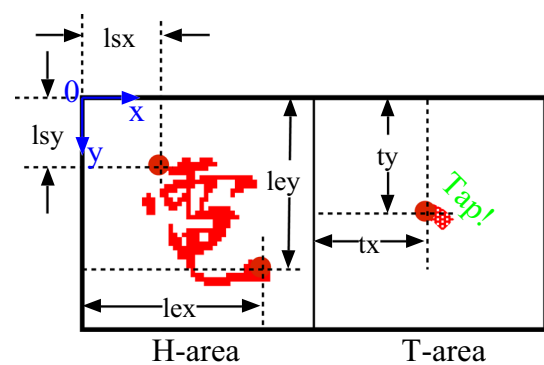


Fig. 3 Handwriting spatial elements

measurement elements; that is, the HTEs and the HSEs, that can be relatively easily referred and extracted from a single character are limited to six temporal and six spatial elements that are characterized by either the beginning and the end of a single character drawing sequence and by an auditory stimulus or a tap.

Table 1 summarizes the five characters selected for the handwriting task. They differ in the numbers of strokes and, thus, also in the handwriting ease. There are various possible indicators of the handwriting difficulty. However, in this study, the handwriting difficulty level is not important, but rather the differences in the handwriting difficulty between the five characters used in this experiment. The five characters used in this experiment are ranked by the number of strokes. In many cases, the handwriting of characters with a high stroke count tends to be more tedious than handwriting of characters with a low stroke count. The subjects were

Table 1 Chinese kanji characters selected for the handwriting task

Pronunciation	Character shape	Stroke count
den	電	13
tsu	通	9
ki	気	6
dai	大	3
ichi	一	1

11 healthy males (21–25 years old) They were all college students with Japanese as their native language.

3 Analysis method

The detrended fluctuation analysis (DFA) was invented by Peng and others in 1994 [7, 8]. The DFA is known to be an effective method for fluctuation analysis for finite length time series. The time series of the HTEs and HSEs is represented by r_i ($i = 1, 2, 3, \dots, N - 1, N$, where N denotes the number of HTE or HSE samples (250)), which is the intended DFA signal. The time series s_k ($k = 1, 2, 3, \dots, N - 1, N$) of the cumulative sum of r_i was computed as follows:

$$s_k = \sum_{i=1}^k (r_i - \bar{r}) \tag{1}$$

where \bar{r} is a mean value of r_i . $s_n^*(k)$ is the regression line of the time series ($s_k, s_{k+1}, s_{k+2}, \dots, s_{k+n-2}, s_{k+n-1}$), where $n = 3, 4, 5, \dots, N - 1, N$ is the timescale. Its slope on the log-log scale field of the $F(n)$ characteristic defined by Eq. (2) is called the scaling index:

$$F(n) = \sqrt{\frac{1}{N} \sum_{k=1}^N (s_k - s_n^*(k))^2} \tag{2}$$

In this study, the general shape of the $F(n)$ characteristics was curved, which is generally identified as a crossover phenomenon. The same linearity is limited to a certain timescale for the crossover phenomenon observed qualitatively. To avoid this crossover problem, we focused on the local trends and defined a new slope parameter $L\beta_m^{knj}$ ($knj = \text{den, tsu, dai, ki, ichi}; m = 4, 5, 6, \dots, N - 1, N$) as a local trend. $L\beta_m^{knj}$ is the slope of the regression line when $F(n)$ is log-log plotted in the timescale interval $[3, m]$. For convenience, we added a subscript el (el = SLs, SLe, ..., ST, lsx, lsy, ..., ty) to the measured $L\beta_m^{knj}$ of the HTEs and HSEs; is described as $L\beta_{m,el}^{knj}, L\beta_{m,SLs}^{knj}, L\beta_{m,SLe}^{knj}, \dots, L\beta_{m,ST}^{knj}, L\beta_{m,lsx}^{knj}, L\beta_{m,lsy}^{knj}, \dots, L\beta_{m,ty}^{knj}$.

We considered $L\beta_{m,el}^{knj}$ as a quantitative measure of the fluctuation characteristics at each timescale. In a previous study by Uchida et al. [10], the relationship of the six $L\beta_{m,el}^{knj}$ of the HTEs at each timescale was evaluated with the maximum, minimum, and standard deviation values. In the present experiment, we investigated the relationship between twelve measured handwriting elements (six HTEs and six HSEs) and the timescale by using $L\beta_{m,el}^{knj}$ and extracted the characteristics of the handwriting fluctuations for the five kanji characters used.

We also measured some biological parameters (i.e., peripheral skin temperature and tympanic temperature) in this experiment. However, we did not know the analytical method to capture the direction of the attentional resources while drawing one kanji character.

4 Results and discussion

4.1 Relationships between twelve handwriting elements in each timescale slot

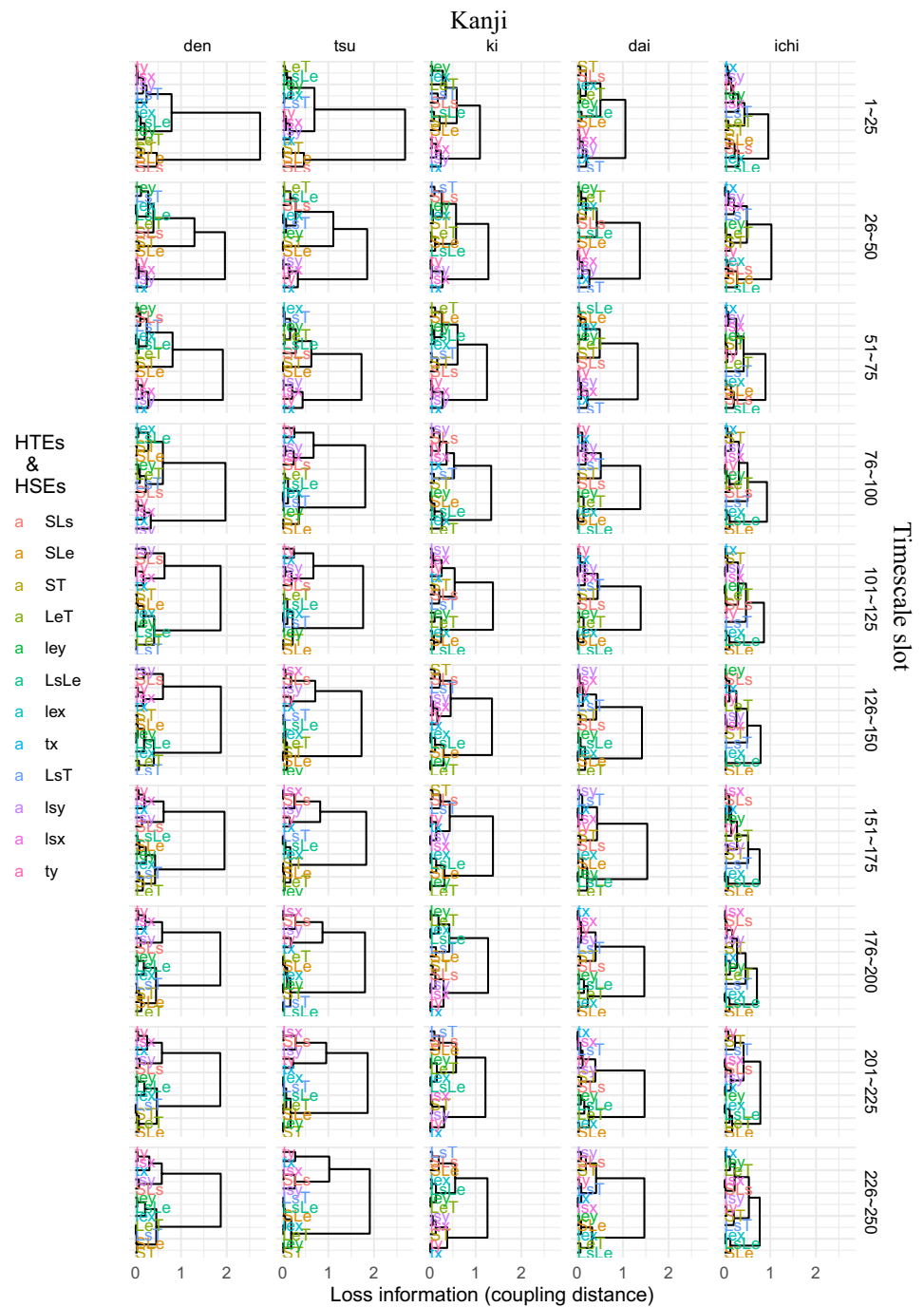
Since analyzing the relationship between twelve handwriting elements for each timescale m would have made the interpretation of the analysis results difficult, we divided the timescales into 10 slots and investigated this relationship for each slot.

For the analysis, we extracted the feature vectors from the $L\beta_{m,el}^{knj}$ time series in each timescale slot. Since the maximum value of m was 250 ($= N$), we divided m into 10 slots and denoted a feature vector as

$$\left[L\beta_{m_1,el}^{knj}, L\beta_{m_2,el}^{knj}, \dots, L\beta_{m_{25},el}^{knj} \right].$$

Since there were 12 el types, 12 feature vectors were extracted from each timescale slot. Figure 4 displays the results of the hierarchical clustering with Ward’s method for these extracted feature vectors. The value of the loss information, also called coupling distance, when multiple feature vectors constitute a cluster was investigated along the dendrogram branches. At a first glance, the components of one cluster seemed to change for each timescale slot and kanji character. It is noteworthy in Fig. 4 that the amount of information loss when twelve handwriting elements are aggregated into a single cluster differs for each character and for each time slot. For example, simple handwriting, such as ichi, is generally low on this amount of lost information. In addition, this amount of lost information is not significantly different between twelve handwriting elements and between time slots. Thus, it suggests that attentional resources were uniformly distributed throughout the series of handwriting motions. On the other hand, den and tsu separated twelve

Fig. 4 Dendrogram array for the kanji characters vs. timescale slots based on the handwriting temporal and spatial elements



handwriting elements into two clusters at high levels of loss information. The difference in the amount of information lost between time slots in den and tsu was also greater than in simple handwriting. In other words, there was a complete separation between the parts of the series of handwriting movements where attentional resources were distributed and those where they were not, and the distribution of attentional resources was not uniform. Thus, the loss information when the 12 feature vectors were divided into two clusters, that is the coupling distance when the 12 feature vectors were

aggregated into a single cluster and the member composition of both clusters was investigated.

4.2 Quantitative evaluation in two-cluster composition

Figure 5 illustrates the relationship between the loss information and the timescale slot in the case of the two-cluster composition for each kanji character. The loss information shown might reflect the assumed order of their shape

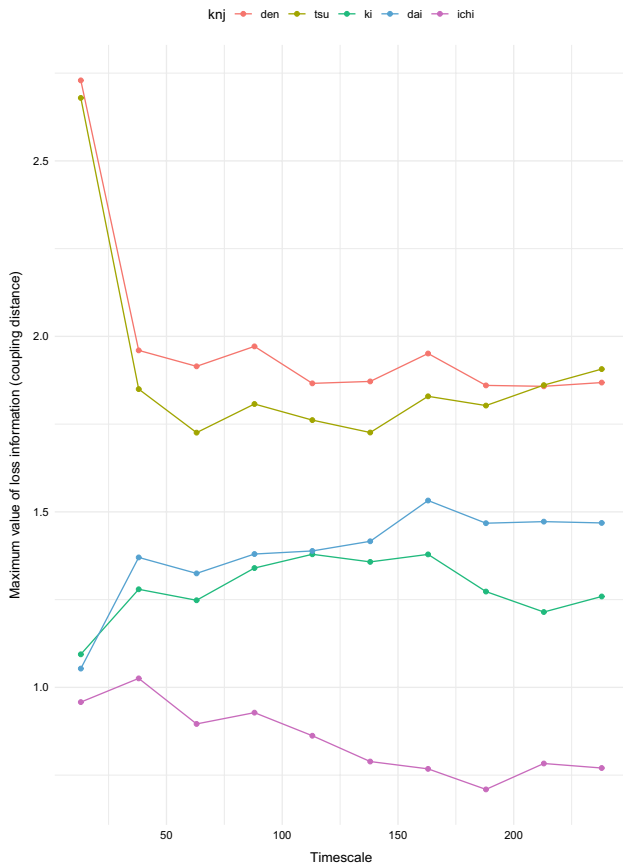


Fig. 5 Relationship between the maximum of loss information and the timescale for the handwriting temporal and spatial elements

complexity, which is den, tsu, ki, dai, and ichi. That is, den is the most complex of the five kanji characters and ichi is the simplest. The loss information levels of den and tsu were always the highest and hardly depended on the timescale except for the shortest slot; in contrast, those of ki and dai tended to increase with the timescale and the ichi one was always low and with a decreasing trend. Figure 6 shows a graph similar to that of Fig. 5, with only one of the HTEs and the HSEs.

The HTEs and HSEs are the components of the temporal and the spatial fluctuation, respectively; the difference between their physical quantities, time and space, must be considered.

4.3 Relationship between twelve handwriting elements

For example, in the case of SLs, out of the total 50 dendrograms in Fig. 4, the number of the dendrograms in which SLs belonged to the same cluster as each of the other eleven handwriting elements (SLe, ST, ..., ty) was (18, 32, 16, 28, 19, 32, 32, 16, 20, 32, 32) in order from SLe. Furthermore,

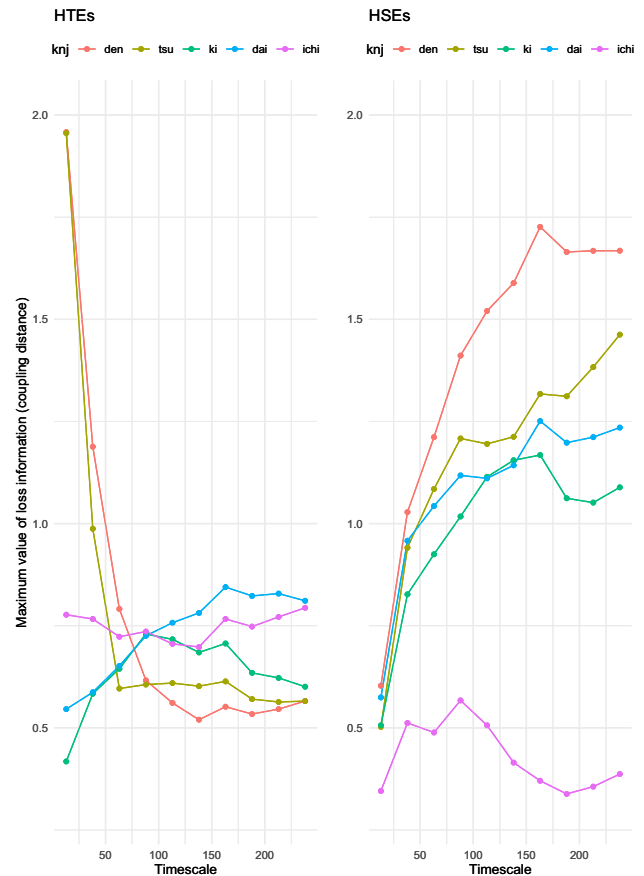


Fig. 6 Relationship between the maximum of loss information and the timescale for the handwriting temporal and spatial elements (HTEs and HSEs, respectively)

since the cluster to which SLs belongs naturally includes SLs itself, the above number in SLs is 50 out of a total of 50. So, we defined the vector

$$v_{SLs} = (50, 18, 32, 16, 28, 19, 32, 32, 16, 20, 32, 32)$$

generated by ordering these numbers in (SLs, SLe, ST, ..., ty) as the feature vector of SLs. Similarly, the feature vector v_{el} ($el = SLs, SLe, \dots, ty$) was determined for each of twelve handwriting elements. Figure 7 shows a dendrogram drawn via the hierarchical clustering of the determined 12 feature vectors; $v_{SLs}, v_{SLe}, \dots, v_{ty}$.

Based on it, we evaluated the similarity between the measured twelve handwriting elements. When describing Fig. 6, we pointed out the difference in the physical quantities of the HTEs and HSEs. However, the blue branch shown in Fig. 7 suggests one cluster consisting of three HTEs (SLe, LsLe, and LeT) and two HSEs (lex and ley). Each of these elements, as indicated by the letter ‘e’ in their name, was associated with an endpoint of the handwriting; this result indicates a commonality between the temporal and spatial

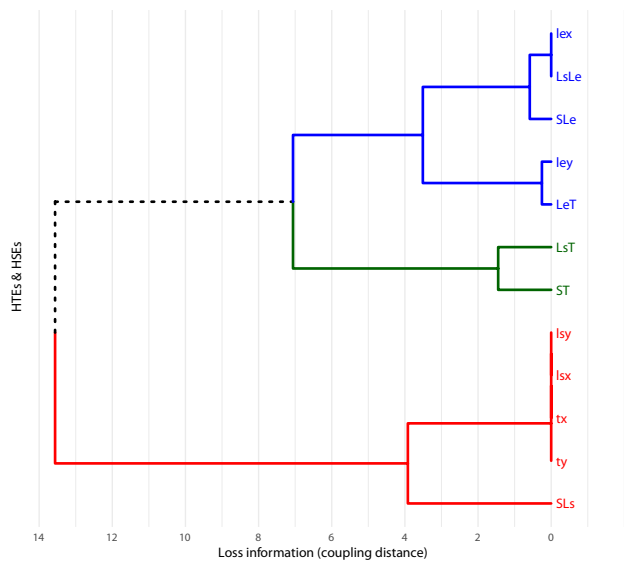


Fig. 7 Dendrogram of the determined 12 feature vectors of the handwriting temporal and spatial elements (HTEs and HSEs, respectively)

fluctuations in endpoint-related handwriting elements. Furthermore, in terms of measuring and analyzing handwriting fluctuations, it also suggests that if two elements capture the same fluctuation characteristics, one of them can be excluded from the measurement target.

5 Conclusion

We investigated the fluctuation characteristics in the handwriting process of five kanji characters. The relationships among six HTEs, six HSEs, five kanji characters, and ten timescale slots were analyzed via hierarchical clustering. We compared the handwriting fluctuation of each kanji character based on the loss information and the composition of both clusters obtained when dividing the twelve handwriting elements into two groups. We used the comparison index $L\beta_{m,el}^{knj}$, which qualitatively evaluated the fluctuations locally on the timescale and included a general scaling index. Based on the results, we suggested the relationship of the HTEs and HSEs with the fluctuations in the kanji character handwriting. Since the experimental system and analysis method examined in this study can be applied to repetitive practice in exercise learning of general physical exercise, it might provide a guideline for exercise learning of its physical exercise.

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