SELF-PROCESSING IN HANDWRITTEN CHARACTERS

Title:

Processing of self-related kinematic information embedded in static
handwritten characters

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Abstract

Handwritten characters are generated by our own motor actions, and previous studies have shown that the manner in which such characters are perceived and generated is related. However, the temporal course of the neural activation involved in the processing of self-related kinematic information embedded in static handwritten characters remains to be identified. We applied event-related potential (ERP) recording while participants judged whether handwritten characters were self- or non-self-generated. To test the effects of the self-related kinematic characteristics of static handwritten characters, we conducted two experiments in which the styles or familiarity of characters were manipulated. The ERP results indicated differences in brain activation between self- and non-self-written characters for the P250 component (250–350 ms after stimulus onset) in right posterior regions and for the late positive component (LPC; 350–500 ms after stimulus onset) in anterior midline regions; this was the case even when the handwritten characters were not generated in their usual form or were written for the first time. Therefore, our data indicate that self-information embedded in

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handwritten characters involves both right-lateralized brain activation associated with bodily self-processing and anterior midline brain activation related to self-referential processing.

Keywords: event-related potential; handwritten character; bodily self-processing; self-referential processing

1. Introduction

Handwritten characters are generated by human motor actions (i.e., writing), and even the same character may differ among individuals in terms of kinematic characteristics, such as the shape of trajectories, stroke order, speed, and pressure. Moreover, individualized self-related kinematic information embedded in static handwritten characters enables us to easily discriminate our own writing from that of others.

Previous studies have indicated that such kinematic information contributes to the perception of handwritten characters. Behavioral studies have found a qualitative difference between the recognition of handwritten versus printed characters (Williams, 1984) and have demonstrated that individuals can extract kinematic information from static handwritten characters (Babcock and Freyd, 1988). Neuroimaging studies have also shown differences in the visual processing of handwritten and printed characters; the processing of handwritten characters is associated with the primary motor cortex (Longcamp et al., 2011) and right ventral occipito-temporal cortex (Barton et al., 2010; Qiao et al., 2010). These studies have indicated that the manner in which

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static characters are produced modulates their subsequent visual processing.

An increasing number of studies have demonstrated that visual processing of the bodily self, including the face and body, preferentially involves the right hemisphere. Behavioral studies have shown a left-hand advantage in response to the self-face (Keenan et al., 1999; Keenan et al., 2000; Platek et al., 2004a; Platek et al., 2004b). These results support the notion of right hemispheric dominance during self-face processing, which is in accordance with contralateral motor control. Furthermore, neuroimaging studies have shown that the major regions involved in self-face processing (Kaplan et al., 2008; Ma and Han, 2012; Uddin et al., 2005; however, see Sugiura, 2015) and self-body processing (Hodzic et al., 2009; Myers and Sowden, 2008) are the right frontal and parietal areas. Moreover, in addition to the self-body, the products of self-generated motor actions may also induce right-lateralized brain activation. For example, behavioral and neuroimaging studies indicate preferential involvement of the right hemisphere during the processing of one's own voice (Kaplan et al., 2008; Nakamura et al., 2001; Rosa et al.,

2008).

Electrophysiological studies, which allow for high time-resolution measurements, have provided information on the temporal features involved in bodily self-processing. Several event-related potential (ERP) components exhibit differences with respect to the processing of self- versus non-self bodily stimuli. First, for the N170 component, a study found that negative deflections occurring around 170 ms after stimulus onset at posterior regions, reflecting structural encoding processing (Bentin and Deouell, 2000), were greater for self-face than for non-self-faces (Keyes et al., 2010). However, several studies did not find differences in N170 amplitude between self- and non-self-faces (Caharel et al., 2002; Caharel et al., 2005), rendering the sensitivity of the N170 component to self-processing ambiguous. Second, for the P250 component, positive deflections occurring around 250–350 ms post-stimulus at posterior sites, which are associated with the activation of stored structural representations in memory, were found to be smaller for self-face compared with non-self-faces (Caharel et al., 2002). The results were interpreted as demonstrating that self-faces demand a smaller

1 perceptual load than non-self-faces with respect to retrieval from and
2 access to stored structural representations, whereas non-self faces require
3 a more extensive memory search (Caharel et al., 2002; Caharel et al.,
4 2005), which is consistent with the hypotheses that long-term experience
5 of faces enhances their representation in memory and that their visual
6 processing demands fewer attentional resources (Tong and Nakayama,
7 1999). Third, the late positive potential after 350–500 ms (late positive
8 component; LPC) in anterior midline regions is greater for self- versus
9 non-self-related stimuli. A previous study reported a greater LPC for
10 one's own hands than those of others (Su et al., 2010). Similarly, several
11 studies have shown that psychological self-processing modulates LPC
12 amplitude (e.g., self-appraisal: Luo et al., 2010). Therefore, the LPC in
13 anterior midline regions appears not only to relate to bodily
14 self-processing but also to reflect the self-referential processing involved
15 in the judgment of whether stimuli are self- or non-self-relevant (i.e.,
16 authorship judgment).

17 Several recent electrophysiological studies regarding the
18 self-processing of static handwritten characters have revealed the

temporal features of brain activation. Wamain et al. (2012) demonstrated differences between self- and non-self-written characters in the ERPs in right posterior regions that peak approximately 300 ms after stimulus onset. This suggests that the processing of self-generated handwritten characters is related to right-lateralized bodily self-processing. Moreover, Chen et al. (2008) reported differences in positive deflections in anterior midline regions at a time window of 360–440 ms in response to the recognition of self- versus non-self-written characters, suggesting that this component reflects self-referential processing during authorship judgments. Taken together, these data indicate that visual processing of the self-related information embedded in self-generated handwritten characters may modulate the P250 component in right posterior regions in addition to the LPC in anterior midline regions.

People generally have more opportunities to observe their own handwritten characters than those of others, suggesting that extensive experience of observing one's own handwritten characters results in the representation of self-related information associated with handwritten characters. On the other hand, in the domain of dynamic handwriting

1 perception, previous studies have shown that people can distinguish their
2 own handwriting from the handwriting of others when the shapes are both
3 familiar and unfamiliar (Knoblich and Prinz, 2001). This suggests that it
4 is the experience of the action of self-generated writing, and not the
5 specific shape of the trajectories, that is involved in the construction of
6 self-kinematic representations in memory. Thus, it remains unclear
7 whether the ERP responses to self-generated handwritten characters found
8 in previous studies (Chen et al., 2008; Wamain et al., 2012) depended on
9 stored representations developed through the experience of observing the
10 particular shapes of self-handwritten characters, or whether the ERP
11 responses were induced by stored representations developed through
12 self-related kinematic characteristics (i.e., the writing action itself).

13 In the present study, we conducted ERP experiments in which
14 participants judged whether a presented character was self-generated or
15 non-self-generated, with the aim of investigating the temporal features of
16 the neural correlates underlying the processing of self-generated visual
17 patterns. Two approaches were adopted to delineate the effects of visual
18 experience and self-kinematic information on ERP responses to

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1 handwritten characters. In the first approach (experiment 1), the degree of
2 stylization of characters was manipulated. There were two conditions: the
3 freestyle condition, in which participants wrote characters in their
4 habitual style, and the stylized condition, in which they wrote characters
5 in strict adherence to a specific model. Under the freestyle condition,
6 responses to self- and non-self-generated handwritten characters differed
7 with respect to both the degree of experience in observing the handwritten
8 characters and the availability of self-related kinematic information. In
9 contrast, under the stylized condition, participants had had little
10 opportunity to observe their own handwritten characters, and the shapes
11 of the trajectories of the self- and non-self-written characters were almost
12 the same. Thus, the stylized condition equalized (at least to an
13 approximate degree) the experience of observing self- and
14 non-self-written characters, while maintaining a contrast in the
15 availability of kinematic information between self- and non-self-written
16 characters. If the differences in ERP responses shown in previous studies
17 (Chen et al., 2008; Wamain et al., 2012) originated from self-related
18 kinematic information *per se*, rather than from greater experience with

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1 observing self-specific character shapes relative to non-self-written
2 characters, then self-related ERP modulations for stylized characters as
3 well as for freely-written ones should be evident.

4 In the second approach (experiment 2), the familiarity of characters
5 was manipulated across two conditions, the familiar and unfamiliar
6 conditions. Under the familiar condition, stimuli were chosen from among
7 characters that participants used frequently in their daily lives. In
8 contrast, under the unfamiliar condition, stimuli were characters that they
9 had never used before. Thus, with respect to the unknown characters,
10 participants had virtually equal amounts of experience (i.e., none) in
11 observing their own handwritten characters and those generated by
12 someone else. If self-related kinematic representations are developed
13 through the writing action itself, rather than through experience of
14 observing the characters, ERP differences between self-written characters
15 and those generated by someone else should be found under both the
16 familiar and unfamiliar conditions.

17 In accordance with the aforementioned ERP studies (e.g., Caharel
18 et al., 2002; Chen et al., 2008; Wamain et al., 2012), we analyzed ERPs

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1 between 140–210 ms (N170) and 250–350 ms (P250) in posterior regions
2 and those after 350–500 ms (LPC) in anterior midline regions to clarify
3 the self-related processing of static handwritten characters. Additionally,
4 ERPs of 100–140 ms (P100) at occipital sites were also analyzed to assess
5 the effect of the perceptual aspects of stimuli, such as their size,
6 brightness, and contrast (Allison et al., 1999); we expected that
7 self-related processing would not be associated with these basic visual
8 features. We predicted that (1) self-processing of static handwritten
9 characters would enhance the right-lateral posterior activity of the P250
10 component related to bodily self-processing; (2) correct judgments for
11 self- versus non-self-stimuli would enhance the anterior midline
12 activities of the LPC related to self-referential processing; and, assuming
13 that the modulation of the P250 component and LPC observed in the
14 previous studies was not dependent on the experience of observing
15 self-generated characters but was due, instead, to self-related kinematic
16 information developed as a result of the experience of writing actions, (3)
17 these self-related effects would be observed even when the characters
18 were stylized or the characters were written for the first time.

2. Results

2.1. Experiment 1

Experiment 1 manipulated the degree to which handwritten characters were stylized (i.e., freestyle and stylized forms) (Fig. 1A). Behavioral and ERP data were obtained when participants judged whether the presented stimuli were examples of their own handwritten characters or those generated by someone else.

Figure 1

2.1.1. Behavioral data

The mean ($\pm SE$) accuracy and reaction time (RT) under each condition are shown in Table 1. The accuracy was above chance (50%) under all conditions ($t(12) > 2.57, p < .05$). The two-way repeated measures analysis of variance (ANOVA) with identity (self and non-self) and style (freestyle and stylized) as factors revealed no significant main effect or

interaction ($F(1, 12) < 3.72, p > .05$). The results showed that participants judged self- and non-self-written characters accurately above the level of chance under both freestyle and stylized conditions.

In terms of RTs, the two-way ANOVA with identity and style as factors revealed no significant main effect or interactions ($F(1, 12) < 2.77, p > .10$). There was no significant difference between self- and non-self-written characters in terms of judgment speed under either the freestyle or stylized conditions.

Table 1

2.1.2. P100 of occipital regions

A three-way ANOVA with identity (self and non-self), style (freestyle and stylized), and electrode (O1/O2) as factors was conducted. Although there was an interaction between electrode and style ($F(1, 12) = 7.11, p < .05$), a simple effects test failed to reveal a significant difference in P100 amplitudes between freestyle and stylized characters

($F(1, 24) < 2.05, p > .17$). No other significant main effect or interaction was found ($p > .05$). The results revealed no differences in P100 amplitudes between self- and non-self-written characters or between freestyle and stylized characters.

2.1.3. ERP components of lateral posterior regions

The grand-averaged waveforms at posterior region electrodes are shown in Figure 2A. The mean amplitudes at 140–210 ms and 250–350 ms were analyzed.

Figure 2

N170 (140–210 ms). The mean amplitudes under each condition at the electrodes in the left and right hemisphere are shown in Figure 2B. A four-way ANOVA with identity (self and non-self), style (freestyle and stylized), electrode (TP7/TP8, P7/P8, P3/P4, and O1/O2), and laterality (left and right) as factors revealed a significant main effect of electrode ($F(3, 36) = 4.75, p < .05$) and significant two-way interactions between

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identity and laterality ($F(1, 12) = 6.31, p < .05$), and between style and laterality ($F(1, 12) = 10.55, p < .01$). There was no other significant main effect or interaction ($p > .05$). Although multiple comparisons for the main effect of electrode were performed, no difference in N170 amplitudes was observed among electrodes (absolute $t(36) < 2.62, p > .13$).

A simple effects test for the interaction between identity and laterality revealed no significant difference between self- and non-self-handwritten characters in either hemisphere ($F(1, 24) < 3.80, p > .07$) or between the left and right hemispheres with regard to self- or non-self-written characters ($F(1, 24) < 0.93, p > .35$). Although the significant interaction between identity and laterality implies a difference between the left and right hemispheres with respect to the relationship between the N170 amplitude and self-relevance, the results indicate that the N170 amplitude did not exhibit a robust difference between self- and non-self-written characters.

A simple effects test for the interaction between style and laterality revealed a smaller N170 for freestyle characters than for stylized

characters in the left hemisphere ($F(1, 24) = 4.67, p = .05$), but no difference was observed in the right hemisphere ($F(1, 24) = 0.06, p > .80$). The test did not reveal any difference between left and right hemispheres under either the freestyle or the stylized conditions ($F(1, 24) < 2.24, p > .10$).

P250 (250–350 ms). The mean amplitudes under each condition at electrodes in the left and right hemispheres are shown in Figure 2C. An ANOVA with identity, style, electrode, and laterality as factors revealed a significant main effect of electrode ($F(3, 36) = 30.82, p < .001$) and significant two-way interactions between identity and laterality ($F(1, 12) = 16.19, p < .01$) and between style and laterality ($F(1, 12) = 11.66, p < .01$). There was no other significant main effect or interaction ($p > .05$). For the main effect of electrode, multiple comparisons indicated that the amplitudes of P250 were larger at the P3/P4 electrodes than at the other electrodes ($t(36) > 4.26, p < .01$).

A simple effects test for the interaction between identity and laterality indicated reduced P250 for self-written, compared with non-self-written, characters in the right hemisphere ($F(1, 24) = 8.47, p$

< .05), but no difference was observed in the left hemisphere ($F(1, 24) = 0.05, p > .10$). The test showed no laterality difference for either self- or non-self-written characters ($F(1, 24) < 2.28, p > .10$).

A simple effects test for the interaction between style and laterality showed a larger P250 for freestyle characters than for stylized characters in the left hemisphere ($F(1, 24) = 8.16, p < .05$), but no such difference was observed in the right hemisphere ($F(1, 24) = 1.64, p > .10$). This test did not reveal a significant difference between left and right hemispheres for either freestyle or stylized characters ($F(1, 24) < 3.72, p > .07$).

2.1.4. *LPC of anterior midline regions*

The grand-averaged waveforms at electrodes in anterior midline regions are shown in Figure 3A. The mean amplitudes at 350–500 ms were analyzed.

Figure 3

The mean amplitudes under each condition are shown in Figure 3B.

A three-way ANOVA with identity (self and non-self), style (freestyle and stylized), and electrode (Fz, FCz, and Cz) as factors revealed significant main effects of identity ($F(1, 12) = 5.04, p < .05$) and electrode ($F(1, 12) = 23.92, p < .001$). The main effect of identity indicated that self-written characters enhanced LPC in anterior midline regions compared with non-self-written characters. For the main effect of electrode, multiple comparisons revealed that positive deflections were higher at the Cz electrode than at the other electrodes ($t(24) > 5.09, p < .001$). There was no other significant main effect or interaction ($p > .10$).

2.1.5. Summary

We measured ERPs while participants made authorship judgments of static handwritten characters in freestyle and stylized forms. The ERP data differed in accordance with self-processing of static handwritten characters, while there was no difference in accuracy or RTs between self- and non-self-judgments. First, the right-lateralized posterior P250 amplitude was reduced in response to self-written characters relative to non-self-written characters. Second, self-written characters were

1 associated with enhanced anterior midline LPC activity relative to
2 non-self-written characters. Importantly, these self-related effects on ERP
3 components were obtained even when the degree of stylization of the
4 handwritten characters was manipulated.

5 In contrast to the effects of self-processing, the stylized characters,
6 when compared against the freestyle characters, resulted in enhanced
7 activity in the N170 component and reduced activity in the P250
8 component, but only in the left hemisphere. This suggests that processing
9 of self-related kinematic information embedded in handwritten characters
10 elicits neural activation that is dissociable from that induced by the style
11 of the characters.

12 13 2.2. *Experiment 2*

14 Experiment 2 manipulated the familiarity of handwritten characters (i.e.,
15 familiar and unfamiliar characters) (Fig. 1B). Behavioral and ERP data
16 were collected when participants judged whether characters were
17 self-written.

2.2.1. Behavioral data

The mean ($\pm SE$) of accuracy and RTs under each condition are shown in Table 2. The accuracy was above chance (50%) under all conditions ($t(14) > 2.73$, $p < .05$). A two-way ANOVA with identity (self and non-self) and familiarity (familiar and unfamiliar) as factors revealed no significant main effect or interaction ($F(1, 14) < 3.06$, $p > .10$). Participants judged self- and non-self-written characters at an accuracy rate above the level of chance, and no difference was observed between the familiar and unfamiliar character conditions.

Table 2

In terms of RTs, the two-way ANOVA revealed no significant main effect or interaction ($F(1, 14) < 4.21$, $p > .05$). Hence, the speed of participants' responses to self- and non-self-written characters did not differ under either the familiar or unfamiliar conditions.

2.2.2. P100 of occipital regions

A three-way ANOVA with identity (self and non-self), familiarity (familiar and unfamiliar), and electrode (O1/O2) as factors revealed no significant effect or interaction ($F(1, 14) < 1.52, p > .23$). The results indicate no differences in P100 amplitudes between self- and non-self-written characters or between familiar and unfamiliar characters.

2.2.3. ERP components of lateral posterior regions

The grand-averaged waveforms at the posterior region electrodes are shown in Figure 4A. The mean amplitude data at 140–210 ms and 250–350 ms were analyzed.

Figure 4

N170 (140–210 ms). The mean amplitudes under each condition at electrodes in the left and right hemispheres are shown in Figure 4B. A four-way ANOVA with factors of identity (self and non-self), familiarity (familiar and unfamiliar), electrode (TP7/TP8, P7/P8, P3/P4, and O1/O2), and laterality (left and right) revealed no significant main effect or

1 interaction ($p > .05$). These results indicate that the N170 component did
2 not differ between self- and non-self-written characters or between
3 familiar and unfamiliar characters in the posterior regions.

4 *P250 (250–350 ms)*. The mean amplitudes under each condition at
5 electrodes in the left and right hemispheres are shown in Figure 4C. An
6 ANOVA revealed significant main effects of identity ($F(1, 14) = 13.02, p$
7 $< .005$), familiarity ($F(1, 14) = 12.76, p < .005$), and electrode ($F(3, 42) =$
8 $17.84, p < .001$), and a significant two-way interaction between identity
9 and laterality ($F(1, 14) = 6.45, p < .05$). There was no other significant
10 main effect or interaction ($p > .05$). The main effect of familiarity was
11 associated with a larger P250 component for unfamiliar versus familiar
12 characters in both the left and right posterior regions. Multiple
13 comparisons for the main effect of electrode indicated that the P250
14 component was larger at P3/P4 than at the other electrodes ($t(42) > 3.77,$
15 $p < .05$).

16 A simple effects test for the interaction between identity and
17 laterality demonstrated that self-written characters decreased P250
18 amplitudes compared with non-self-written characters in the right

hemisphere ($F(1, 28) = 18.17, p < .005$), but there was no difference between self- and non-self-written characters in the left hemisphere ($F(1, 28) = 0.31, p > .10$). Additionally, no significant difference in P250 activity between left and right hemispheres was observed for either self- or non-self-written characters ($F(1, 28) < 3.03, p > .10$).

2.2.4. *LPC of anterior midline regions*

The grand-averaged waveforms of anterior region electrodes are shown in Figure 5A. The mean amplitude data at 350–500 ms were analyzed.

Figure 5

The mean amplitudes under each condition are shown in Figure 5B.

A three-way ANOVA with identity (self and non-self), familiarity (familiar and unfamiliar), and electrode (Fz, FCz, and Cz) as factors revealed significant main effects of identity ($F(1, 14) = 5.62, p < .05$) and electrode ($F(1, 14) = 18.62, p < .001$). In terms of the main effect of identity, self-written characters enhanced LPC in anterior midline regions

relative to non-self-written characters. With respect to the main effect of electrode, multiple comparisons indicated that positive deflections were higher at the Cz electrode than at the other electrodes ($t(28) > 4.76$, $p < .005$). There was no other significant main effect or interaction ($p > .05$).

2.2.5. Summary

In experiment 2, we performed ERP measurements during authorship judgments of familiar and unfamiliar handwritten characters. The ERP data replicated the two main results of experiment 1, which pertained to the self-processing of handwritten characters. First, self-written characters reduced the amplitude of the right-lateralized posterior P250 component compared with non-self-written characters. Second, self-written characters enhanced the anterior midline LPC amplitude relative to non-self-written characters. These results were obtained for both familiar (i.e., used in daily life) and unfamiliar (i.e., never written previously) characters.

Additionally, we observed differences between the familiar and

unfamiliar character conditions in the amplitude of the P250 component in bilateral posterior regions. In contrast, self-processing affected the amplitude of the right-lateralized P250 component. Therefore, it appears likely that the familiarity of characters exerted an effect that was, at least in part, independent from that of the self-processing of handwritten characters.

3. Discussion

Our primary purpose was to investigate the effect of self-generated kinematic information on the visual processing of static self-written characters. To investigate this issue, we conducted two ERP experiments involving authorship judgments of handwritten characters while controlling the degree of stylization (experiment 1) and the familiarity of characters (experiment 2), which allow us to delineate the degree of experience in observing and availability of self-related kinematic information. Both experiments consistently demonstrated the modulatory effects of self-related information in handwritten characters on two ERP components. First, self-generated characters modulated right lateralized

1 posterior brain activation at 250–350 ms after stimulus onset (i.e., P250)
2 compared with non-self-generated characters. In terms of temporal
3 features, our results are consistent with a previous study of handwritten
4 characters, which showed ERP differences between self- and
5 non-self-written or printed characters after approximately 300 ms
6 (Wamain et al., 2012). The results are also consistent with previous
7 studies of faces that showed smaller P250 amplitudes in response to
8 self-face compared with non-self-face (Caharel et al., 2002; Caharel et al.,
9 2005). P250 reflects the activation of stored representations in memory
10 (Caharel et al., 2002) that were developed as a result of long-term
11 experience (Tong and Nakayama, 1999). Therefore, our data suggest that
12 self-written characters, relative to non-self-written characters, impose a
13 lower perceptual load when it comes to matching visual inputs with stored
14 representations.

15 Concerning the laterality of brain activation, differences in the
16 amplitudes of the P250 component between self- and non-self-written
17 characters were observed at only the right posterior sites. This is
18 consistent with a previous ERP study showing ERP differences between

self- and non-self-written characters in right-lateralized posterior regions (Wamain et al., 2012). Our result is also in line with previous studies demonstrating the strong involvement of visual regions of the right hemisphere with respect to the motor content of stimulus letters (Barton et al., 2010; Qiao et al., 2010). Moreover, the data accord with previous neuroimaging studies showing that the processing of the bodily self, including the face (Kaplan et al., 2008; Ma and Han, 2012; Uddin et al., 2005), other body parts (e.g., Myers & Sowden, 2008), and the voice (e.g., Nakamura et al., 2001), involves right-lateralized brain activation. Our results indicate that the self-processing of handwritten characters involves right-lateralized bodily self-processing related to kinematic information.

Second, self-written characters enhanced anterior midline activation at 350–500 ms after stimulus onset (i.e., LPC) relative to non-self-written characters. This component is considered to be related to self-referential processing (Chen et al., 2008; Su et al., 2010). Our results are also consistent with a previous study in which freehand self-written words enhanced brain activity in the same regions after 200–500 ms

(Chen et al., 2008) and with another study in which the self-processing of body parts enhanced positive components in the same regions after 350–500 ms (Su et al., 2010). Our data suggest that the self-related information embedded in static handwritten characters elicits self-referential processing during authorship judgments.

More importantly, the present study elaborated on previous findings (e.g., Chen et al., 2008; Wamain et al., 2012) by manipulating the degree of stylization and the familiarity of characters. The results of experiment 1 showed that ERP differences between self- and non-self-written characters in the right posterior P250 component and anterior midline LPC were present both when the characters were written in the participants' habitual manner and when they were generated as stylized forms. These results indicate that subtle traces of residual self-related information were sufficient to induce self-processing even when the written characters were highly stylized. The results of experiment 2 indicate that the ERP differences between self- and non-self-handwritten characters persisted under both the familiar and unfamiliar character conditions. In other words, ERPs related to self-processing were obtained

1 not only when participants had considerable experience of writing out a
2 character but also when they wrote a particular character for the first time.
3 Thus, we observed no significant effects of either the style or the
4 familiarity of characters on the modulatory effects of self-relevance on
5 ERP responses. This result suggests that a stored representation of one's
6 own kinematic characteristics of handwritten characters, which
7 presumably forms during past self-motor experiences, can be generatively
8 projected on to non-habitual or novel characters and that this is not
9 limited to certain forms or shapes. It has been demonstrated that there is a
10 link between authorship in handwriting and experience involving writing
11 actions (Knoblich and Prinz, 2001; Knoblich et al., 2002; see Knoblich
12 and Flach, 2003, for a review). The researchers have proposed that,
13 although biological motor actions are generally non-constant even within
14 an individual, representations of general patterns of self-generated motor
15 actions are stored in the neural system and influence the observation of
16 products generated by one's own motor actions. Taken together, our
17 results suggest that accumulated experience with self-writing actions may
18 result in a representation of the characteristics of an individual's own

1 kinematic patterns, and observing traces of self-generated handwriting
2 effectively activates these representations.

3 The lack of interaction effects between self-relevance and degrees
4 of stylization or familiarity of characters in both the behavioral and ERP
5 results seems counterintuitive. As briefly mentioned above, Tong and
6 Nakayama (1999) argued that structural representations of certain types
7 of self-related information are formed through accumulated visual
8 experience. If this is the case, why does the processing of self-relevant
9 information in handwritten characters seem insensitive to visual
10 experience? With regard to this point, we offer a few tentative
11 explanations. First, the residual self-related information contained in
12 stylized handwritten characters (experiment 1) and in unfamiliar
13 characters (experiment 2) may be sufficient to trigger neural activation
14 associated with self-processing. In other words, a ceiling effect may have
15 masked any interaction between self-relevance and visual experience.
16 Second, the representation of self-related kinematic characteristics in
17 handwritten characters may not be visual in nature and, thus, behavioral
18 and ERP responses may be independent of visual experience. The

1 recognition of authorship in dynamic handwriting is considered to be
2 inherently linked to self-motor experience (Knoblich and Flach, 2003). If
3 that is the case, an interesting possibility arises, which is that the
4 self-related kinematic characteristics of handwritten characters are
5 represented not in terms of pure visual processing, but in terms of
6 motor-related processing, such as that involved in biological motion
7 perception (Jokisch et al., 2005). This hypothesis is in accordance with
8 the proposition that authorship recognition is due to self-kinematic motor
9 information embedded in self-handwritten characters.

10 We observed no difference between self- and non-self-written
11 characters in the amplitude of the N170 component. Although several
12 studies have demonstrated a larger N170 component for the self- versus
13 non-self-face (Keyes et al., 2010), others have reported no such
14 difference (Caharel et al., 2002; Caharel et al., 2005). Our results support
15 the latter view (i.e., that self-related information does not robustly reflect
16 the ERP components within this latency range).

17 Additionally, we found no difference between self- and
18 non-self-written characters in the P100 component in the occipital

regions. Moreover, there was no difference in the P100 amplitude either between freestyle and stylized or between familiar and unfamiliar characters. Because P100 is reported to be sensitive to basic perceptual aspects of stimuli such as size, brightness, and contrast (Allison et al., 1999), the results indicate that the processing of information related to self-relevance, degree of stylization, or familiarity of handwritten characters was not associated with that of basic perceptual factors.

Concerning the effects of the style and familiarity of characters, we observed different patterns of brain activation during self-processing. First, the results of experiment 1 showed that the stylization effects were observed in the N170 and P250 components at left posterior regions, indicating that differences in style were processed during the structural encoding stages which begin prior to self-processing. Moreover, previous studies have indicated that the left hemisphere is more involved in the visual processing of printed words compared with that of handwritten words (Hellige and Adamson, 2007). Therefore, it appears that stylized characters enhance brain activity in the left hemisphere to a greater degree than do freehand characters, because stylized characters appear

1 similar to printed typefaces. Second, experiment 2 demonstrated an effect
2 of familiarity of characters on P250 component in bilateral posterior
3 regions, which is consistent with previous studies in which unfamiliar
4 faces enhanced the amplitude of P250 component (Caharel et al., 2002;
5 Caharel et al., 2005). In contrast to the familiarity effect of the characters,
6 we observed self-related effects on the amplitude of P250 component only
7 in the right hemisphere. Thus, the results suggest that the processing of
8 self-related kinematic information can be dissociated from processing
9 related to the degree of stylization or familiarity of characters.

10 We found that the accuracy of self- or non-self-judgments was
11 above chance under all conditions, indicating that participants identified
12 self- and non-self-written characters even when characters did not appear
13 in their habitual style or when they were written for the first time.
14 However, accuracy was relatively low compared with a previous study
15 (Chen et al., 2008). Methodological differences might explain this
16 discrepancy. Written verse pairs were used in the previous study (Chen et
17 al., 2008), whereas single characters were presented in this study. Such
18 differences in stimulus scripts might have led to relatively low rates of

1 accurate authorship judgments in this study, because single characters
2 provide less identifying information relative to short sentences.

3 This study had some limitations. First, we presented the stimuli in a
4 block form under the character-related condition (e.g., the freestyle and
5 stylized conditions in experiment 1). We consider that this improved the
6 accuracy of authorship judgment by removing character-related
7 distracters. However, further work using randomized stimulus
8 presentation is needed to confirm the present results. Second, although
9 the time windows of ERP components (100–500 ms) differed from the
10 time of reaction execution (800–1200 ms), we were unable to clearly
11 discriminate between visual processing and response processing. Future
12 studies using passive observation may provide data on the spontaneous
13 visual processing of self-related kinematic information. Fourth, we
14 presented the same stimuli four times throughout the experiment; it is
15 possible that habituation to repeated patterns influenced the results.

16 Because of the small number of trials, we could not compare the
17 repetition effect on ERP components related to self-processing. The
18 repetition effect on the brain activation should be assessed using a greater

number of stimulus presentations or a higher frequency of repetition. Finally, although self-processing of handwritten characters was not modulated by specific character shapes, we did not manipulate the manner of producing the actions. The variables that contribute to an individual's manner of writing, such as stroke order, speed, and pressure, affect the recognition of characters (e.g., Babcock and Freyd, 1988). Moreover, it is known that the motor content of character generation, whether in writing or typing, modulates the visual processing of characters (e.g., Wamain et al., 2010). Further studies controlling writing actions or motor content are needed to assess the effects of individual manners of writing on the self-processing of handwritten characters.

In summary, the present study found that self-related kinematic information embedded in handwritten characters reduced right posterior brain activation at 250–350 ms and enhanced anterior midline brain activation at 350–500 ms compared with non-self-information. Additionally, information related to the style or familiarity of characters was processed differently from self-related information: the style of characters modulated left posterior brain activation at 140–210 ms and

250–350 ms, whereas the familiarity of characters modulated bilateral posterior brain activation at 140–210 ms and 250–350 ms. These results suggest that self-processing of static handwritten characters involves both bodily self-processing and self-referential processing even in cases where characters are in a stylized form or are written for the first time.

6. Experimental Procedure

6.1. Experiment 1

6.1.1. Participants

Thirteen Japanese volunteers (five females; mean $\pm$ *SD* age: 27.62 ± 5.74 years), all of whom provided written informed consent, participated in this experiment, which was approved by the Ethics Committee of the Primate Research Institute, Kyoto University. All participants were right handed as assessed by the H. N. Handedness Inventory (Hatta and Nakatsuka, 1975) and had normal or corrected-to-normal vision.

6.1.2. Stimuli

Examples of handwritten stimuli are presented in Figure 1A. All stimuli

were Japanese syllabary characters (Hiragana) that were familiar to all participants.

Writing. Fourteen characters were randomly selected from a total of 48 characters. Under both the freestyle- and stylized-character conditions, participants wrote each character five times. They produced each character within a 5-cm square (with gridlines) using a no-lead pencil on pressure-sensitive paper (Figure 6A); this prevented participants from observing the stimuli prior to the commencement of the ERP experiments. Under the freestyle condition, participants were asked to write characters that were read aloud by the experimenter (Figure 6B). Under the stylized condition, participants were presented with visual examples of each character that they were then required to produce (Figure 6C).

Figures 6

Scanning and preparing stimuli. The handwritten characters created by each participant were scanned (ES-700, Epson Corporation) and converted into image data. Each character was cropped to a 5-cm

1 square. The size of the characters was determined so as to retain
2 information present in the original handwritten characters; differences in
3 the size of handwritten characters modulate the motor actions of writing
4 and may change the kinematic information associated with handwritten
5 characters (Van Drempt et al., 2011). The visual angle of the square was
6 approximately 4.4° in both the width and height dimensions. Stimuli for
7 each participant were selected from among all the handwritten samples;
8 six characters were randomly selected from 14 characters, and three
9 versions were selected from five versions of the same characters.
10 Therefore, 36 characters ($6 \text{ characters} \times 3 \text{ versions} \times 2 \text{ styles}$) were
11 prepared for each of the self- and non-self-stimulus conditions. Although
12 we used 36 characters as stimuli, participants were instructed to write a
13 larger number of characters (70 characters for each style condition) in the
14 preceding writing session to mitigate the possibility that participants
15 might have paid attention to or memorized the visual patterns of their
16 handwritten characters. Characters written by a given participant were
17 used as “self” stimuli; those created by another participant, randomly
18 chosen for each participant, were used as the “non-self” stimuli. There

was no significant difference in mean luminance across stimulus conditions as assessed by one-way ANOVA ($F(3.36) = 2.33, p > .09$).

6.1.3. Procedure

The experiments were conducted at least two weeks after the participants had created the stimuli. During the experiment, participants were seated 65 cm from a 19-inch display monitor (Prolite E481S, Iiyama Corporation) in a dimly lit room. The presentation of the stimuli was controlled using Visual Basic .NET software (Microsoft Corporation) implemented on a Windows computer (Lenovo ThinkPad R52, IBM Corporation).

The experiment comprised four blocks with short breaks between blocks. The first two blocks were under the stylized conditions and the last two were under the freestyle conditions. This was done so that participants' responses to stylized characters would not be influenced by the similarities of visual characteristics of the freestyle characters. Each block consisted of 72 trials, half of which were self-written characters. In total, there were 72 trials under each stimulus condition (self/freestyle,

non-self/freestyle, self/stylized, and non-self/stylized). The order of stimulus presentation was randomized within a block. Each trial began with the presentation of a fixation cross in the center of the screen for 1500 ms, followed by the presentation of the handwritten character for 2000 ms (Fig. 1C). Participants were asked to maintain their gaze on the fixation cross and to indicate whether the characters were self- or non-self-written by pressing one of two assigned buttons as quickly and accurately as possible. The correspondence between answers and buttons was counterbalanced across participants. No feedback was provided to participants concerning the accuracy of their responses.

6.1.4. EEG data recording

Continuous electroencephalography (EEG) was recorded from 30 scalp sites (Fp1, Fp2, F7, F8, F3, F4, Fz, FT7, FT8, FC3, FC4, FCz, T7, T8, C3, C4, Cz, TP7, TP8, CP3, CP4, CPz, P7, P8, P3, P4, Pz, O1, O2, and Oz) located according to the international 10–20 system, using Ag–AgCl electrodes mounted in an elastic cap. Electrooculogram (EOG) activity was monitored at the electrodes on the bilateral canthi and above and

below the left eye. Reference electrodes placed on the earlobes and the middle of the forehead served as ground. Electrode impedance was maintained below 20 k Ω . The sampling rate was set at 1 kHz using the NeuroScan NuAmps System (Compumedics NeuroScan Inc.), and data were stored on a hard disk.

6.1.5. Data analysis

All statistical tests were performed using SPSS software (ver. 22; IBM Corporation), and a p value of $< .05$ indicated statistical significance.

Behavioral data. The mean accuracy and RTs of correct responses were calculated for each condition. Trials measuring beyond ± 3 SD from the mean RTs were excluded (mean $\pm SD$: 0.63 $\pm$ 0.86 trials). The data were then subjected to a two-way repeated-measures ANOVA with identity (self and non-self) and style (freestyle and stylized) as the within-subject factors. A simple effects test was performed to examine the significant interactions. When higher-order interactions were significant, the main effects or lower-order interactions were not interpreted (Kirk, 2013).

1 *ERP data.* ERPs were calculated using the EEGLAB (Delorme and
2 Makeig, 2004; <http://www.sccn.ucsd.edu/eeglab>) via Matlab software (ver.
3 R2011b; MathWorks). Trials with correct responses were analyzed. Data
4 were filtered offline through a band-pass of 0.1–30 Hz. EEG data were
5 segmented to obtain epochs starting 100 ms before stimulus onset and
6 continuing for 600 ms post-stimulus. Pre-stimulus data, collected while
7 the fixation cross was presented, served as a baseline. Grand-averaged
8 waveforms were calculated after trials with ocular movements and
9 artifacts ($> 75 \mu\text{V}$) had been rejected. The artifact-contaminated trials
10 (mean $\pm$ SD: 8.46 ± 9.34 trials) did not differ across conditions ($F(3.36) =$
11 1.56, $p > .22$).

12 The mean amplitudes of the N170 (140–210 ms) and P250 (250–350
13 ms) components at lateral posterior electrodes were subjected to a
14 four-way ANOVA with identity (self and non-self), style (freestyle and
15 stylized), electrode (TP7/TP8, P7/P8, P3/P4, and O1/O2), and laterality
16 (left and right) as within-subject variables. The mean amplitudes of LPC
17 (350–500 ms) at anterior midline electrodes were subjected to a three-way
18 ANOVA with identity (self and non-self), style (freestyle and stylized),

and electrode (Fz, FCz, and Cz) as within-subject variables. Additionally, the mean amplitudes of the P100 (100–140 ms) components at lateral occipital electrodes were subjected to a three-way ANOVA with identity (self and non-self), style (freestyle and stylized), and electrode (O1 and O2) as within-subject variables. The electrode sites are shown in Figure 7. The main effect of electrodes was analyzed using multiple comparisons with Bonferroni corrections. A simple effects test was conducted to examine the significant interactions. When higher-order interactions were significant, main effects or lower-order interactions were not interpreted (Kirk, 2013).

Figure 7

6.2. Experiment 2

6.2.1. Participants

Fifteen right-handed Japanese volunteers (seven females; mean $\pm$ *SD* age: 28.27 ± 7.05 years), all of whom provided written informed consent,

1 participated in this experiment, which was approved by the Ethics
2 Committee of the Primate Research Institute, Kyoto University. Twelve of
3 the participants had taken part in experiment 1; the interval between the
4 two experiments was at least 15 days. All participants were right handed
5 as assessed by the H. N. Handedness Inventory (Hatta and Nakatsuka,
6 1975), and had normal or corrected-to-normal vision.

7 8 6.2.2. *Stimuli*

9 Examples of the handwritten stimuli are displayed in Figure 1B. Seven
10 characters were selected from each of six categories (Hiragana, digits, the
11 English alphabet, Thai script, the Arabic alphabet, and Hindi script). The
12 difference in visual complexity among the six categories of characters
13 was assessed using GIF compression, which has been established as a
14 predictor of perceptual visual complexity (Forsythe et al., 2011), and a
15 one-way ANOVA revealed no differences among the six categories ($F(5,$
16 $36) = 1.89, p > .12$). To examine familiarity with each of the characters,
17 we showed all the examples to participants before writing and asked them
18 to indicate their level of familiarity with each character by answering the

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1 following four questions: (1) Have you ever seen this character before?;
2 (2) Have you ever written this character before?; (3) Are you able to
3 pronounce this character?; and (4) Do you understand the meaning of this
4 character? The characters eliciting affirmative answers to all four
5 questions were defined as familiar stimuli (characters taken from
6 Hiragana, digits, and the English alphabet), and the characters that
7 elicited negative answers to all four questions were defined as unfamiliar
8 stimuli (characters taken from Thai script, the Arabic alphabet, and Hindi
9 script).

10 *Writing.* The stimuli were written in the same manner as described
11 for the stylized condition of experiment 1.

12 *Scanning and preparing stimuli.* Once the stimuli had been scanned
13 and cropped in the same manner as in experiment 1, the stimuli for each
14 participant, were selected from among all the handwritten samples; three
15 characters were selected from among seven characters for each of the six
16 categories, and two versions of each character were randomly selected
17 from the five versions of the same character. Thus, 36 characters (3
18 characters $\times$ 2 versions $\times$ 3 categories for familiar and unfamiliar

characters each) were prepared for each self- and non-self-stimulus condition. Characters produced by a given participant were used as “self” stimuli; those created by another participant, randomly chosen for each participant, were used as the “non-self” stimuli. There was no significant difference in mean luminance among the stimulus conditions ($F(3, 42) = 1.72, p > .19$).

6.2.3. Procedure

The experiment consisted of four blocks; two blocks were the familiar conditions and the two were unfamiliar conditions. The order of conditions was counterbalanced among participants. The experimental procedures governing the presentation of stimuli and the performance of tasks were identical to those described for experiment 1.

6.2.4. EEG data recording

EEG data recording was performed as described for experiment 1.

6.2.5. Data analyses

1 All statistical tests were performed using SPSS software (ver. 22; IBM
2 Corporation), and a p value of $< .05$ was used as the criterion for
3 statistical significance.

4 *Behavioral data.* The mean accuracy and RTs of the correct
5 responses were calculated in an identical manner to that described for
6 experiment 1. Trials ± 3 SD from the mean RTs were excluded (mean $\pm SD$:
7 0.58 ± 0.89 trials). The data were then subjected to a two-way ANOVA
8 with identity (self and non-self) and familiarity (familiar and unfamiliar)
9 as within-subject variables.

10 *ERP data.* EEG data were analyzed in a manner identical to that
11 described for experiment 1. Trials with ocular movements and artifacts ($>$
12 $75 \mu V$) were rejected. The artifact-contaminated trials (mean $\pm SD$: 12.78
13 ± 8.19 trials) did not differ across conditions ($F(3, 42) = 1.24, p > .30$).
14 Data on the mean amplitudes of the N170 (140–210 ms) and P250
15 (250–350 ms) components at posterior electrodes were then subjected to a
16 four-way ANOVA with identity (self and non-self), familiarity (familiar
17 and unfamiliar), electrode (TP7/TP8, P7/P8, P3/P4, and O1/O2), and
18 laterality (left and right) as within-subject factors. The mean amplitudes

1 of LPC (350–500 ms) at midline electrodes were subjected to a three-way
2 ANOVA with identity (self and non-self), familiarity (familiar and
3 unfamiliar), and electrode (Fz, FCz, and Cz) as within-subject factors.
4 The mean amplitudes of the P100 (100–140 ms) component at lateral
5 occipital electrodes were subjected to a three-way ANOVA with identity
6 (self and non-self), familiarity (familiar and unfamiliar), and electrode
7 (O1 and O2) as within-subject variables.

8

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10

1 **Table 1.**

2 *Mean ($\pm$ SE) accuracy and reaction time (RT) in response to self- and*
 3 *non-self-handwritten characters under the freestyle and stylized*
 4 *conditions.*

	Freestyle		Stylized	
	Self	Non-self	Self	Non-Self
Accuracy	65.56 (6.05)	79.95 (4.93)	70.68 (4.04)	77.96 (4.05)
(%)				
RT (ms)	980.18	902.39	1028.26	980.53
	(42.46)	(49.19)	(47.34)	(45.16)

Table 2.
Mean ($\pm$ SE) accuracy and reaction time (RT) in response to self- and non-self-handwritten characters under familiar and unfamiliar character conditions.

	Familiar		Unfamiliar	
	Self	Non-self	Self	Non-Self
Accuracy (%)	61.75 (3.54)	67.82 (3.46)	70.84 (3.98)	71.19 (4.80)
RT (ms)	1106.40 (70.68)	1034.99 (66.99)	1141.62 (50.85)	1091.41 (50.56)

Figure legends

Figure 1. Example of the stimuli from experiments 1 (A) and 2 (B):

example characters from the familiar condition are in Hiragana and

example characters from the unfamiliar condition are in Thai script.

Schematic display of the stimulus presentation procedure used in both

experiments 1 and 2(C).

Figure 2. Grand-averaged waveforms for self- (black) and non-self-

(gray) written characters under the freestyle (solid line) and stylized

(dotted line) conditions recorded in the left (TP7, P7, P3, and O1) and

right (TP8, P8, P4, and O2) posterior regions (A). Mean ($\pm SE$)

amplitudes of the N170 components under each condition in the left and

right posterior regions (B). Mean ($\pm SE$) amplitudes of the P250

components of each condition in the left and right posterior regions (C).

Significant results ($p < .05$) are indicated by a star.

Figure 3. Grand-averaged waveforms for self- (black) and non-self-

(gray) written characters under the freestyle (solid line) and stylized

(dotted line) conditions recorded in the anterior midline region (Fz, FCz, and Cz) (A). Mean ($\pm SE$) amplitudes of the LPC of each condition in the anterior midline region (B). Significant results ($p < .05$) are indicated by a star.

Figure 4. Grand-averaged waveforms for self- (black) and non-self- (gray) written characters under the familiar (solid line) and unfamiliar (dotted line) conditions recorded in the left (TP7, P7, P3, and O1) and right (TP8, P8, P4, and O2) posterior regions (A). Mean ($\pm SE$) amplitudes of the N170 components of each condition in the left and right posterior regions (B). Mean ($\pm SE$) amplitudes of the P250 components of each condition in the left and right posterior regions (C). Significant results ($p < .05$) are indicated by a star.

Figure 5. Grand-averaged waveforms for self- (black) and non-self- (gray) written characters under familiar (solid line) and unfamiliar (dotted line) conditions recorded in the anterior midline region (Fz, FCz, and Cz) (A). Mean ($\pm SE$) amplitudes of the LPC of each condition in the

1 anterior midline region (B). Significant results ($p < .05$) are indicated by
2 a star.

3

4 *Figure 6.* Schematic presentation of the apparatus used to write characters
5 (A). Participants wrote each character in accordance with verbal
6 instructions from the experimenter under the freestyle condition
7 (experiment 1) (B). Under the stylized condition (experiment 1) and both
8 the familiar and unfamiliar conditions (experiment 2), characters were
9 written according to a specific model (C).

10

11 *Figure 7.* The electrode sites and regions of interest of posterior sites in
12 the left (TP7, P7, P3, and O1) and right (TP8, P8, P4, and O2)
13 hemispheres and of anterior midline sites (Fz, FCz, and Cz).

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7