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Submovement Analysis in Learning Cursive Handwriting or Block Print[1]

Hans-Leo TEULINGS & Diana H. ROMERO
NeuroScript, Tempe, Arizona, USA
hlteulings@NeuroScriptSoftware.com

Abstract. Pen movements were recorded in healthy adults during learning of a sequence of vertical down strokes, a zigzag pattern, or a cursive-script pattern. The strokes had to be performed by moving the pen from target to target while visual feedback was offered via a computer monitor. The movement patterns were segmented into up and down strokes. Each stroke was segmented into primary and secondary submovements, i.e., a preprogrammed, ballistic part and a feedback controlled part, respectively. Results show that learning takes place during the course of 16 trials as the stroke duration decreased. Submovement analysis confirmed the usual increase in the relative duration and size of the primary submovement. However, this increase was observed only in the zigzag and the cursive writing patterns, which are continuous patterns, but not in the vertical down strokes, which is a discontinuous movement. This suggests that submovement analysis can be used to show learning effects in multi-stroke, continuous movement patterns.

1. Introduction

The ability to produce a specific handwriting pattern can be compared to learning to produce a sequence of goal-directed movements. The production of an accurate goal-directed movement with a pen to a visible target as fast and precise as possible requires that the visuo-motor system preprograms the initial part of the movement, with subsequent fine adjustments of amplitude and direction based on visual feedback. The initial ballistic movement towards the vicinity of the target is the primary submovement and the feedback-controlled adjustment(s) are secondary submovements. The Optimized Submovement Model (OSM, Meyer et al., 1988) proposes that the motor system minimizes total movement duration through planning an optimal combination of primary and secondary submovements. During the process of learning a goal-directed movement, the relative duration and size of the primary submovement increase, signifying the motor system's increased ability to preprogram stroke size and direction correctly (Thomas, Yan, and Stelmach, 2000; Seidler-Dobrin and Stelmach, 1998). Another measure to quantify the increase of fluency due to learning is normalized jerk (Teulings et al., 1997). The writing patterns we compared resemble motor tasks that pupils in primary schools may perform during handwriting instruction. Pupils first learn block print, characterized by vertical downward strokes followed by pen lifts. Cursive script consists mostly of loops and movement reversals without pen lifts. We investigate whether measures of movement duration, relative duration and size of the primary submovement, and normalized jerk are able to detect progress in motor learning in multi-stroke patterns.

2. Experiment

Participants. Twelve adult university students and teachers (8 women, 4 males, and ages 21 to 44 years, all right–hand dominant) participated after informed consent.

Equipment. Writing movements were recorded using a non-inking pen on a Wacom Intuos2, XD-0608-U digitizer with an active area of 20.32 cm x 15.24 cm. The surface of the digitizer was very smooth so that the pen-to-digitizer friction was much lower than in normal pen-and-paper settings. The sampling rate was 102 Hz. The resolution was 0.001 cm and the RMS error <0.1 cm. Stimuli were presented using a Princeton E0900, 48-cm CRT display (visible 45 cm) set at 1600x1200 dots and 72 Hz vertical refresh rate. The display was vertical in front of the participant at 50 cm distance. Data were collected on a 2.5 GHz Intel4 PC with Windows XP. The recording and analysis of pen movements were done using MovAlyzeR (Teulings, 2003).

Stimuli. The stimulus was presented in real-size on a computer monitor located in front of the participant. It consisted of 14 circles without any additional information. The circle diameters were 0.3 cm, which turned green when the pen approached the circle within 0.1 cm if it was in the right sequence and red it was not in the right sequence. The circles were designed to allow writing "ehye" in cursive script by going from Circle 1, to 2, then to 3, etc. until Circle 14. The vertical and horizontal distances were a on a grid of 0.7 cm by 0.7 cm (See Figure 1). The visual feedback had the same size as the required patterns on the digitizer. The current position of the pen on

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the digitizer was shown on the computer monitor in real-time by a dot in the same window where the stimulus was shown. Thus the participants could learn to produce the writing patterns while only looking at the computer monitor.

Conditions. Three stroke multi-stroke writing patterns were performed that required the participant to touch all circles in a sequence from left to right, and from top to bottom. The movement patterns can thus be considered as a to-be-learned sequence of goal-directed movements:

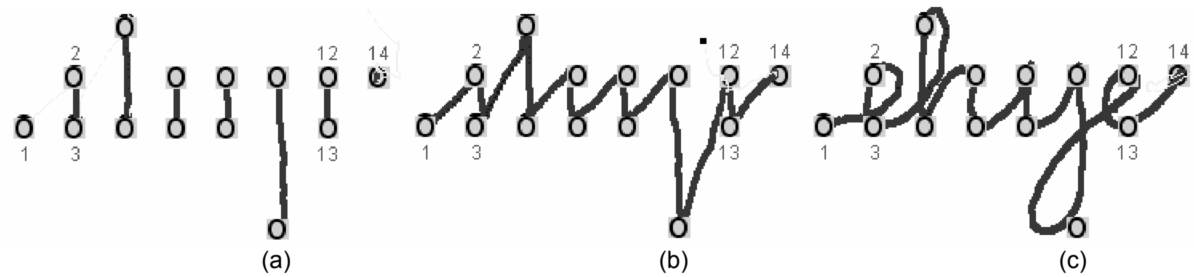


Figure 1. The locations of the 14 circles and the three conditions to produce strokes through Circles 1 through 14: Vertical strokes separated by pen lifts (a), zigzag (b), and cursive script (c).

(1) Separate-stroke pattern (See Figure 1a): Place a dot in Circle 1, then lift the pen and produce vertical lines from top to bottom in consecutive circle pairs, lifting the pen after each line, and then place a dot in Circle 14.

(2) Zigzag pattern (See Figure 1b): Connect Circles 1, 2, 3, ... with straight strokes.

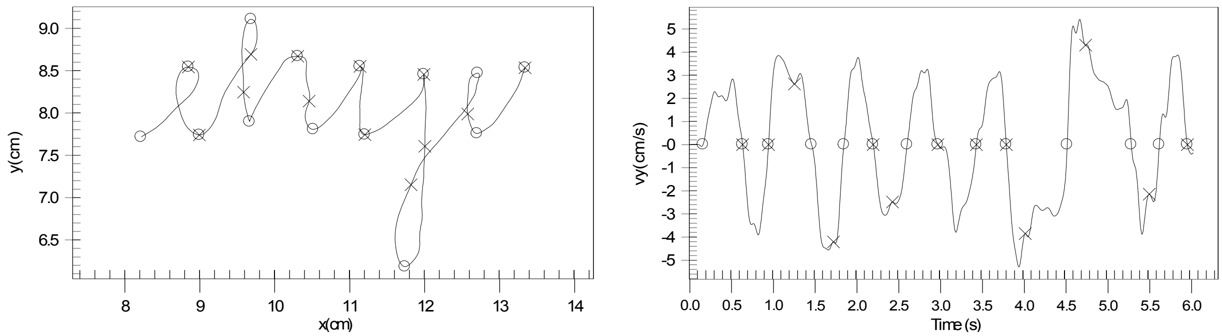
(3) Cursive-script pattern (See Figure 1c): Write cursively "ehye". Start at Circle 1, e-loop top at Circle 2, bottom at Circle 3, etc.

Procedure. The participants were sitting at a desk with the digitizer on top and the computer monitor in front of them. Recording started when the pen touched the tablet and ended when the pen was lifted for more than one second. Each condition was repeated 16 times. The sequence of conditions was randomized. The participant initially performed the trials as an exercise, during which the experimenter trained the proper execution of each of the conditions, with the instruction that the writing patterns had to be performed as rapidly and accurately as possible. Data was processed immediately after a trial was recorded, and the experimenter could monitor whether the trials were consistent. When the subject produced a sufficient number of consistent trials, the practice series was terminated and the recording of the experimental data commenced. The experiment took 15 minutes.

Analysis. Writing patterns were low-pass filtered at 10 Hz (transition band 5 Hz to 16 Hz), differentiated, and velocity and acceleration curves were estimated. Differentiation and filtering were performed by Fourier transforming the x and y time functions into a frequency spectrum, after making the functions circular by adding a sine wave, and subsequently multiplying the spectral components with the frequency or the filter characteristic, respectively, and finally applying the inverse Fourier transform (Teulings & Maarse, 1984). Stroke segmentation was at points where the vertical velocity passed through zero. Movements above the paper as in Condition 1 are considered strokes as well, so that every pattern counted 13 strokes. Submovement analysis appears little sensitive for the choice of the low-pass filter frequency around 10 Hz (Teulings, in prep.). Subsequent zero crossings within 0.04 seconds were discarded. A stroke was further segmented into primary and secondary submovements by the first negative-to-positive zero crossing of the vertical acceleration (in positive or upward strokes) after the absolute peak velocity. Duration and vertical size were estimated for the entire stroke and for each submovement. The relative duration of the primary submovement was defined as $T1/T$ and $S1/S$, respectively, where $T1$ and $S1$ are the duration and size of the primary submovement and S and T the size and duration of the entire stroke, respectively.

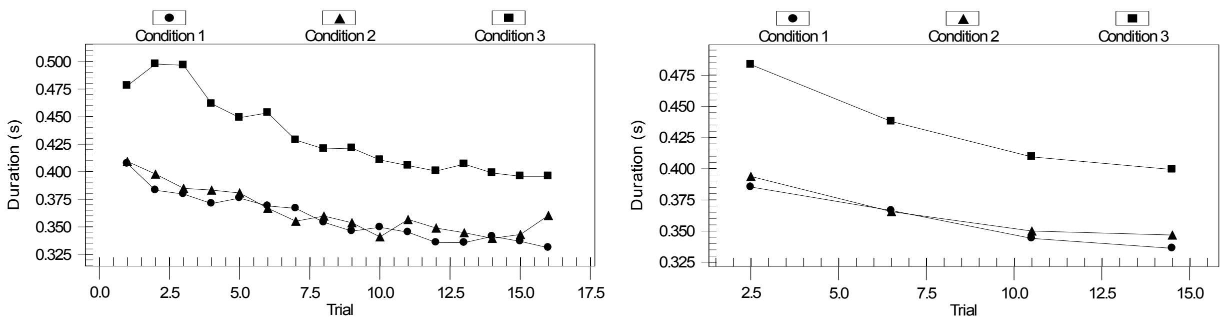
Trials were automatically discarded if they were not consistent, e.g., if the number of strokes was less or more than 13 or if the "ehye" pattern did not form the proper sequence of clockwise, counterclockwise looping, acute, or obtuse movement reversals or did not form the proper sequence of short and long strokes. In total 11% of the 576 trials were discarded.

To reduce the effects of discarded trials in the learning curves as a function of trial, discarded trials were replaced by the last, valid trial, or, in case it was the first trial, by the first valid trial. Finally, Trials 1-4, 5-8, 9-12, 13-16 were pooled, yielding a sequence of 4 data points during the course of 16 trials.



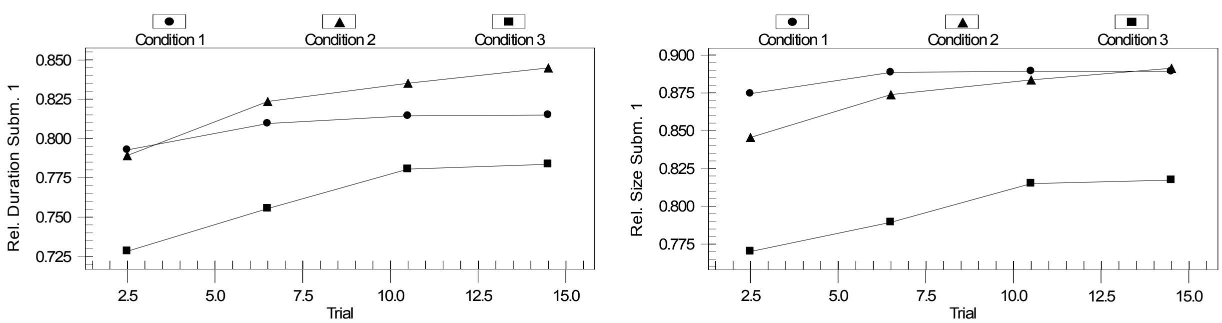
(a) (b)

Figure 2. Example of a writing pattern, e.g., the Cursive writing pattern "ehye" (a), and its vertical velocity as a function of time (b). Circles mark the end-of-stroke segmentation points and the diagonal crosses the submovement segmentation points.



(a) (b)

Figure 3. Average stroke duration declined over the course of 16 trials for all conditions (a). The same graph has been smoothed by pooling blocks of 4 trials (b) and shows more clearly the course of the learning effect.



(a) (b)

Figure 4. Learning effect upon the relative duration (a) and size (b) of the primary submovement for Conditions 1 (Vertical strokes), 2 (Zigzag), and 3 (Cursive script). A significant learning effect was only found in the Zigzag and the Cursive script patterns.

3. Results

An example of a recorded writing pattern and its segmentation are shown in Figure 2. Data was initially analyzed by an Analysis of Variance. Average stroke duration as a function of trial number showed a gradual reduction in all conditions, demonstrating evidence of learning (See Figure 3) ($F_{3,33} = 15.5$, $p < 0.001$). Stroke duration differed per condition ($F_{2,22} = 10.6$, $p < 0.05$): The cursive pattern took more time than the pattern of straight strokes. A significant condition by trial interaction was also evident for stroke duration ($F_{6,66} = 2.51$, $p < 0.05$) which suggests the greatest learning rate in the Cursive-script condition and the smallest learning rate in the separate Vertical strokes.

The relative duration of the primary submovement was significantly influenced by condition ($F_{2,22} = 3.93$, $p < 0.05$), and trial ($F_{3,33} = 6.84$, $p < 0.001$). Post-hoc analysis demonstrated that during the learning process, relative duration of the primary submovement increased in the Zigzag and the Cursive script patterns (regression coefficients are positive, $t(11)>2.70$, $p<0.05$) but not in the separate Vertical strokes ($t(11)=1.24$, $p>0.2$) (See Figure 4(a)). Similarly, the relative size of the primary submovement demonstrated significant effects of condition ($F_{2,22} = 13.5$, $p < 0.001$) and trial ($F_{3,33} = 5.21$, $p < 0.01$). Post-hoc tests indicated that the relative size of the primary submovement increased with practice in the Zigzag and Cursive patterns (regression coefficients are positive, $t(11)>2.53$, $p<0.05$), but not in the separate Vertical strokes ($t(11)<1$).

Figure 5 depicts the gradual reduction of normalized jerk during practice. Normalized jerk demonstrated significant effects of condition ($F_{2,22} = 7.1$, $p < 0.01$), and trial ($F_{3,33} = 13.6$, $p < 0.001$). Post-hoc analysis indicated that normalized jerk was significantly reduced in the separate Vertical stroke and the Cursive script patterns ($t(11)<3.23$, $p<0.01$) but not in the Zigzag pattern ($t(11)=1.56$, $p>0.1$). Learning is also confirmed by the decline in frequency of submovements in all conditions from 53% during the first 4 trials to 44% for the last 4 trials ($t(11)=4.0$, $p<0.001$) (no graph shown).

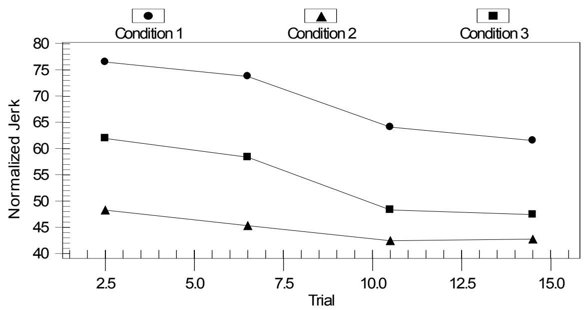


Figure 5. Normalized jerk declined during the course of 16 trials for Conditions 1 (Vertical) and 3 (Cursive script), but not for Condition 2 (Zigzag Strokes).

5. Discussion

The participants learned 3 different writing patterns (conditions) connecting the same set of 14 points: (1) Separate, vertical strokes, similar to the typical movements required in printing; (2) Zigzags consisting of straight strokes that do not require pen lifts; and (3) a Cursive script pattern ("ehye"). The results indicate that learning takes place over the course of 16 trials as shown by a reduction of the average stroke duration, an increase in the relative duration and size of the primary submovement, and a reduction of normalized jerk. However, not all patterns demonstrated these trends to the same extent and for all measures of learning. Whereas stroke duration appeared to reduce in all patterns, submovement analysis did not show a significant learning effect in the sequence of separate strokes. This is remarkable as submovement analysis was developed for single, goal-directed strokes. Other studies (e.g., Thomas, Yan, and Stelmach, 2000; Seidler-Dobrin and Stelmach, 1998) have shown that in "single-stroke" goal-directed movements, the relative duration of the primary submovement increased during learning. We may not have observed learning in sequences of separate strokes is that the vertical stroke sequence is simple compared to the other patterns. This simple pattern was already sufficiently learned while the more complex patterns were just learned well enough to be able to produce them. These results seem at odds compared to the zigzag pattern, since the separate-stroke pattern had still ample space for improvement in terms of increasing duration and size of the primary submovement. Similarly, normalized jerk showed no learning effect in the zigzag pattern. A possible reason is that the zigzag pattern was already very fluent from the beginning of the experiment so that additional learning would require many more trials. In summary, this study shows that submovement analysis is a powerful method to quantify progress in motor learning of fluently connected multi-stroke patterns.

6. References

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