Improvement in the Effectiveness of Cutting Skill Practice for Paper-Cutting Creations Based on the Steering Law

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SUMMARY To improve the cutting skills of learners, we developed a method for improving the skill involved in creating paper cuttings based on a steering task in the field of human-computer interaction. TaWe made patterns using the white and black boundaries that make up a picture. The index of difficulty (ID) is a numerical value based on the width and distance of the steering law. First, we evaluated novice and expert pattern-cutters, and measured their moving time (MT), error rate, and compliance with the steering law, confirming that the MT and error rate are affected by pattern width and distance. Moreover, we quantified the skills of novices and experts using ID and MT based models. We then observed changes in the cutting skills of novices who practiced with various widths and evaluated the impact of the difficulty level on skill improvement. Patterns considered to be moderately difficult for novices led to a significant improvement in skills.

key words: cutting, point task, human motor performance, steering law

1. Introduction

Currently, everyone can learn to create artistic designs from books and the Internet. However, it is difficult for novices to adopt motifs created by other artists, because of the difference in skill between novices and experts. For novices to improve their skills more effectively, it is necessary for them to practice at a difficulty level that is correct for their current skills. However, definitions for levels of skill and difficulty are ambiguous, and it is hence challenging to evaluate them quantitatively.

We focus on paper-cutting, which is a craft art. Paper-cutting is an art performed by controlling a knife and cutting paper. We assume that the behavior of cutting a line with a knife is similar to the task of writing a stroke with a pen and hence follows a performance model from the field of human-computer interaction (HCI). The first aim is to evaluate the difficulty level of a pattern and quantify the performance of a cutting action with a knife based on the steering law. And the second aim, we evaluate the difficulty level that novices can gain more effective skill improvement. The ultimate aim of this research is to contribute to the evaluation of skills using the steering task from the HCI field.

For this research, we created a system that has a knife attached to the tip of the stylus of a drawing display. Our system measures the moving time (MT) that elapses when a user cuts a pattern. We analyze the relationship between difficulty level and skill level by quantifying the index of difficulty (ID) based on a steering law. One of the skills of creating paper cuttings is knife pressure. Thus far, we have developed a system to support the improvement of cutting pressure control\textsuperscript{[1]}. Moreover, we have evaluated the effectiveness of practice when a learner repeatedly practices straight patterns of various difficulty levels\textsuperscript{[2]}. In this paper, we focus on improving the model-fitting skill of paper-cutting.

In Chapter 2, we describe the research on Steering law and its application. In Chapter 3, we develop a system for measuring the user’s cutting time. This device is a knife with a blade attached to the tip of a stylus. In Chapter 4, we measure difficulty (ID) from the width (W) and distance (D) of the pattern on a straight line. In Chapter 5, we evaluate patterns of five different widths and two distances using their IDs and our cutting skill measurement system, which consists of a drawing display and stylus. As a result, we confirmed the difference in cutting skills numerically by comparing the ID and MT models of novices and experts. In Chapter 6, we observed the effect of various difficulty levels on the cutting skill of novices. The results confirm the difference in skill improvement according to the ID and MT based model for each difficulty level. We present the discussion and the conclusion in chapters 7 and 8.

2. Related Work

Modeling human movement is a core theme in the field of HCI. A well-known model is Fitts law\textsuperscript{[3]}, which predicts the time required for a one-dimensional pointing task, and a refined model for two-dimensional tasks proposed by Accot and Zhai\textsuperscript{[4]}. Another common model predicts the time required to navigate a long, narrow path, known as the steering law\textsuperscript{[5]}. All these models depict a linear relationship between the ID and MT\textsuperscript{[6]}.

In the steering law, the difficulty level of a straight tunnel is calculated as follow (Fig. 1).

\[
ID = D/W
\]  

(1)

Here, \(D\) is the length of the tunnel and \(W\) is the tunnel width\textsuperscript{[5]}. The steering law is calculated as

\[
MT = a + b \times ID
\]  

(2)

for both straight and curved tunnels\textsuperscript{[7], [8]}. The \(a\) and \(b\)
are empirically determined constants. Pastel has compared the MT at corners with wide and narrow widths [9], where a and b are empirically determined constants. In this paper, we employ the ID and MT of the steering law to determine difficulty level and the overall time required to cut a paper pattern.

Many researchers have measured performance with various devices and for multiple shapes. For example, researchers have investigated operations for multiple types of input devices (e.g., mice, styluses, touch panels, and trackballs) [7], [10], [11]. Moreover, several researchers have studied pen stroke gestures in letter writing [12] and the drawing of simple figures [13]. Zabramski analyzed drawing tasks as pointing and steering tasks [14], [15]. Arora considered design guidelines for sketch tools in an immersive 3D environment [16]. Tu investigated the difference in stroke gestures between the finger and the pen [17]. Cutting behavior using scissors was modeled in [18]. Yamanaka modeled the cutting behavior by scissors [19]. Many researchers have examined intricate patterns based on the steering law.

3. Measurement of Difficulty Level

3.1 Width for Novices

We interviewed five instructors and artists to design the standards for two patterns (easy and difficult) for novices. These instructors are experts, three have five years of experience and the other two have six years of experience. Considering their advice, we defined a width that a novice can easily cut as 13 mm (SD: 0.89) and defined a narrow width to be 5.0 mm (SD: 0.31). In many workshops, the instructors modify the difficulty level according to the skills of the students within this range.

3.2 Pattern Design

We designed 10 different patterns using combinations of the following values of width (W) and distance (D), as shown in Fig. 2 (A):

\[
\begin{align*}
W & : 1.0, 5.0, 9.0, 13.0, 17.0 \text{mm} \\
D & : 50.0, 100.0 \text{mm}
\end{align*}
\]

In paper-cutting, the artist cuts on the boundary between a white and black area in a monochrome picture to create a paper cutting. In paper-cutting, the width and distance of the pattern constitute the difficulty level: narrower widths and long lengths increase the difficulty for novices. The art of paper-cutting has many fine lines, and artists often cut patterns with widths of 5.0 mm or less. In this paper, our pattern lengths are 50.0 and 100.0 mm. We designed ten patterns that combined two distances (D) and five widths (W) in Fig. 2 (B).

These widths and lengths are sufficient designs to measure the cutting time. We calculated the ID of these patterns from the following formula.

\[ ID = \frac{D}{W} \]

4. System for Measuring Cutting Skill Level

4.1 Stylus with Blade

Our knife is designed to measure the cutting pressure. A blade is attached to the tip of the stylus. The user cuts paper on a drawing display using the knife. The purpose of our system is to measure the cutting time and to determine whether the coordinates of the blade are inside the pattern area.

To use it, a user cuts paper on a drawing display using a blade (NT BDC-200P) glued to the tip of the touch pen (Wacom PenPro2; Fig. 3 (A)) using ultraviolet resin (Fig. 3 (B)). The stylus recognizes cutting distances at a resolution of 0.1 mm and pressure from 0 to 500 g from 7000 degrees at a response speed of 250 ms.

4.2 Display Unit

The drawing display (Wacom Cintiq Pro16, 3860 × 2140 pixels, 275 dpi) shows pictures (Fig. 4). The system only responds when the stylus is close to the screen. Although the tip of the stylus and the surface of the screen are not in direct contact, the display can recognize the stylus’s coordinates and angle data via electromagnetic induction. The user cuts the paper with the device, and our system measures moving time and coordinates.

The system screen is protected by tempered glass, and the paper is placed fixed on the glass. The paper is a commercially available copier paper (thickness 0.09mm), and the user cuts the image on the paper.
5. Experiment 1: Difference in the Skills of Novices and Experts

5.1 Participants and Task

The participants were twenty novices and twenty experts. The novices (average age: 24.2 years old, SD = 1.32) had never created paper-cuttings. The experts (average age: 32.0 years old, SD = 5.00) were artists and instructors for creating paper cuttings. All of the experts are active as artists, and 7 are instructors at a workshop for novices. Moreover, all have more than five years of experience, and 9 have more than ten years of experience. All participants had a visual acuity that does not interfere with creating paper cuttings, and everyone was right-handed. They were instructed to perform the required operation as quickly and accurately as possible.

Our system displayed ten patterns that combined two distances (D) and five widths (W) in random order. The participants repeat cutting each of these patterns ten times. They cut the paper on the display at the start area, moved along the cutting line, and finished at the end area (Fig. 5 (A)). The timer started when the knife passed the start line and stopped when the blade crossed the end line. When the user cuts the paper wider than the specified width, the system beeped, signaling a failure. In that case, the system recorded the number of errors. For example, a pattern of W = 1.0 mm and D = 100 mm is shown in Fig. 5 (B), and a pattern of W = 9.0 mm and D = 50.0 mm is shown in Fig. 5 (C).

5.2 Design and Procedure

We measured the cutting time and knife coordinates during pattern-cutting. The total number of combinations of the parameters was 5 D × 2 A = 10. One block consists of a random order of these ten combinations. Participants first performed one practice block, and then completed ten blocks for data collection. The recorded data for the actual tasks were ten conditions × 10 blocks × 40 participants = 4,000 trials. If the participant cut the paper beyond the width, he or she cut the same pattern again.

We observed the following two results:

1. the effect of pattern width and distance;
2. the difference between novices and experts.

In result 1, we confirmed the effect of width and distance on the difficulty level and observed the fit with the steering law. In result 2, we confirmed the differences between novices and experts.

5.3 Result 1: Effect of Width and Distance

In Sect. 5.3, we evaluate MT and error rate as 40 participants, including 20 novices and 20 experts. We observed the change in MT and error rate by each width and distance of the pattern. Moreover, we analyzed the difference between five-ways by width and two-ways by distance by the Steel-Dwass test.

5.3.1 MT with D and W

Figure 6 shows the change in MT with respect to D and W, where the horizontal axis is the length of the pattern, the vertical axis is the cutting time, and the error bar shows the standard error. We observed the main effect for W (F_{4,95} = 77.7, p < .05) and D (F_{1,38} = 25.0, p < .05). The test
5.3.2 Error Rate

Figure 7 shows the error rate results, where the horizontal axis is the length of the pattern, the vertical axis is the error rate, and the error bar shows the standard error. The error is the number of times the participant cut the paper beyond the width of the pattern, and the error rate is the ratio of the total number of cuttings to the number of errors. The values in the figure indicate the average number of errors. We observed a main effect for W ($F_{4,95} = 13.68, p < .05$) and D ($F_{1,38} = 33.70, p < .05$). The test shows that the error rate increases as D ($p < .05$) increases and W ($p < .05$ for 1.0, 5.0, and 9.0 mm) decreases. In contrast, there were no significant differences in the error rate at wide widths (W = 13.0 and 17.0 mm). Accordingly, even for identical paths, we found that the MT increased as the width narrowed.

5.3.3 Model Fitting

Figure 8 shows the results for model fitting, where the horizontal axis is the ID of the pattern and the vertical axis is the MT. This figure shows that steering law held, with a high fit of $R^2 > 0.948$ for MT data consisting of 10 W × D data points.

5.4 Result 2: Difference between Novices and Experts

In this section, we compared the results of cutting time and error rate with respect to the 20 novices and 20 experts. We measured the variance of each MT and error rate. Moreover, we analyzed only error-free trials via ANOVA using the Mann Whitney U test.

5.4.1 MT with Novice and Expert

Figure 9 shows the difference in MT with respect to novices and experts, where the horizontal axis is the length of the pattern, the vertical axis is the cutting time, and the error bar shows the standard error. The average MT of the novice decreased as the width increased. However, the MTs of the experts did not change as much as those of the novices.
confirmed the effect of participants (F = 2.00, p < .05) for patterns (1.0, 50.0), (5.0, 50.0), (9.0, 50.0), (1.0, 100.0), (5.0, 100.0), and (9.0, 100.0). We confirmed that the difference between novices and experts increased as the ID increased.

5.4.2 Error Rate

Figure 10 shows the results for the error rate, where the horizontal axis is the length of the pattern, the vertical axis is the error rate, and the error bar shows the standard error. The values in the figure indicate the average number of errors. In the error rate, we confirmed the effect (F = 5.00, p < .05) with patterns (W = 1.0, 5.0, and 9.0 mm) similarly to the result for MT. In contrast, for large widths (W = 13.0, 17.0 mm), the errors of novices and experts decreased. Especially for patterns with W = 17.0 mm, the novices and experts all cut accurately.

5.4.3 Model Fitting

Figure 11 shows the results for model fitting, where the horizontal axis is the ID of the pattern, and the vertical axis is MT. The model of novice shows that steering law held with a high fit of $R^2 > 0.905$ for MT data consisting of 10 W × D data points. Similarly, the expert’s model has a higher fit of $R^2 > 0.985$. Table 1 shows the coefficient of the ID × MT models for the novices and experts, where a is the slope, which is the increase MT with respect to the increase in ID, and b is the intercept coefficient, which is the minimum cutting time required by the participants. The novices’ a and b were 6.7 and 1.23 times higher, respectively, than those of the experts.

5.5 Experiment 1 Conclusion

In result 1, we observed the relationship between difficulty level, measured using width and distance, and skill level, measured as cutting time, from 4,000 trials (40 participants × 10 patterns × 10 times). We confirmed a great fit with the steering law by observing the effect on the cutting time for various difficulty levels. The results show that, as the difficulty level increased (ID > 6.88), the cutting time and errors increased. However, for distances of 13.0 and 17.0 mm, which did not lead to significant differences in MT and error rate, we interviewed the participants after the task was over. All the participants felt that the difficulty levels of the patterns of these two widths were equally simple. Therefore, the pattern of both widths did not have a significant effect on MT.

In result 2, we observed the difference between novices and experts using width and distance, and skill level, measured as cutting time. We confirmed a significant difference in MT between novices and experts in a narrow width (W < 9.0mm). However, as in the result 1, MT with a wide width (W >= 13.0mm) showed no significant difference. The reason is that both novices and experts felt that the wide patterns were as easy as difficulty level. The skilled person cut the performance with all IDs with the same MT. On the other hand, novices also increased their MT as ID increased. From these results, we confirmed the difference in cutting performance between beginners and experts.

6. Experiment 2: Changes in Skill Improvement

6.1 Participants

The participants consisted of fifty novices (average age: 24.0 years, SD: 1.55) that were different from those who participated in experiment 1 and had never created a paper
HIGASHI and KANAI: IMPROVEMENT IN THE EFFECTIVENESS OF CUTTING SKILL PRACTICE FOR PAPER-CUTTING CREATIONS BASED

6.2 Design and Procedure

To analyze the appropriate level of difficulty of practice for a novice, we measured the change in the skill of the novice when they cut at various difficulty levels.

The participants performed the following procedure:

- Step 1: The participant cut ten patterns ten times.
- Step 2: Each group practiced with patterns of various IDs, as shown in Fig. 12.
- Step 3: Step 1 was repeated.

We divided the participants into five groups of 10 people based on the participants’ average MTs in Step 1 so that the skills of the participants in each group were at approximately the same level.

Because all the participants cut the same pattern in Step 1, we divide the participants into five groups of 10 based on the average MT in Step 1. In Step 2, the participants cut one of the practice patterns shown in Fig. 12. They were instructed to perform the required operation as quickly and accurately as possible. The practice cutting patterns were composed of $W = 1.0, 5.0, 9.0, 13.0,$ and $17.0$ mm for Groups 1 - 5, respectively. During Step 3, they repeat Step 1. We verify the difference between the effectiveness of the system by comparing the MT of each group in Step 1 and 3.

6.3 Results

6.3.1 Change in MT between Steps 1 and 3

The change in MT when each group cut each pattern in Steps 1 and 3 is shown in Fig. 13, where the horizontal axis is the length of the pattern, the vertical axis is the cutting time, and the error bar shows the standard error. We confirmed a significant decrease in MT decrease in the widths of Groups 2 and 3 ($D = 5.0$ mm and $10.0$ mm, respectively). In contrast, the changes in MT of Groups 1 and 5 showed no significant difference in all patterns.

We also compared the rate of change of MT when each group cut each pattern in Steps 1 and 3 (Fig. 14). The value in each cell is the rate of change of MT from Steps 1 and 3. The results show that Group 2 decreased its MT rate most for all patterns. In particular, the MT rates at $(5.0, 50.0)$ and $(13.0, 100.0)$ changed most for each distance. On the other hand, the rate of change of Group 1 was 0.9 or more in all patterns and was the poorest of all groups.

6.3.2 Change in the Model between Steps 1 and 3

In experiment 2, we compare the amount of skill improvement using the changes in the models of Steps 1 and 3 in each group. Figure 16 and Table 2 show the results of the average model for each group. The results show that the coefficients of all the groups in Step 3 were smaller than those in Step 1. In particular, the values of $a$ and $b$ of Group 2 and Group 3 showed a significant decrease. Moreover, we compared MT reduction rates from Step 1 to Step 3 of each group. The results show that the rate of decrease in MT
for the pattern (5, 50) had the most significant change in all groups. In particular, the change in MT increased up to ID = 11.1, but decreased for higher values of ID.

6.4 Experiment 2 Conclusion

In this experiment, we evaluated the effects of cutting time and cutting models when practicing with pictures of various difficulty levels. We measured the change in the cutting time when they cut straight patterns in Step 1 and Step 3. The results show that the practice at each difficulty level improved the skill of the novices. The cutting with a design of W = 5.0 and 9.0 mm had the most excellent effect on the MT and model coefficients. On the other hand, the participants felt that the width (W = 1.0 mm) between these patterns was a difficulty level commensurate with the participants.

This study focuses on the appropriate difficulty level for production and production activities. The balance between skill level and difficulty level has various influences in creative activities, one of which is the concentration at the time of production. Focused efforts help improve skill acquisition. However, it is difficult for novices to maintain their concentration due to the difficult tasks. Therefore, in the paper-cutting workshop, the instructor uses a picture designed with difficulty for beginners to support the state where participants can concentrate. The participants to work on their skills with an appropriate degree of difficulty.

Concentrated work is an indispensable element in skill acquisition and accuracy in various efforts including the production stage of creative activities. It is difficult for beginners to maintain a concentration state due to failure in the process of working on the production stage and difficulty of the tasks to be tackled. Therefore, in the paper-cutting workshop, the instructor uses a picture designed with difficulty for beginners to support the state where participants can concentrate. The balance between skill level and the difficulty level is particularly crucial for inducing a psychological state called concentration state (“zone” in sports psychology and “flow” in positive psychology). Some researchers in the field of psychology have observed similar results with respect to the flow state, which is defined as the “comprehensive feeling felt when a person is immersed in action” and indicates a high concentration of action[20]–[22]. Massimini has noted that it is essential for the challenge level to be higher than the ability level before flow can be achieved.

7. Discussion

To improve the cutting skills of novices, we designed 10 patterns with five widths and two distances. In experiment 1, we compared the effect of width and distance on the difficulty level as well as and the difference between novices and experts. The results show that the cutting time was affected by the width and distance, and fit well to the steering law. Moreover, we quantified the skill differences of novices and experts using a model. In experiment 2, we compared the effect of training novices at various degrees of difficulty using the rate of decreasing of the cutting time. As a result, when the width was difficult for beginners (W = 5.0 mm), the reduction rate of cutting time was the highest. In addition, the reduction rate decreased for more difficult widths (W = 1.0mm) and lower widths (13.0, 17.0mm). In the interview after the experiment, we obtained the opinion that the width (W = 5.0, 9.0mm) between these patterns was a difficulty level commensurate with the participants.
occur [23]. Within flow theory, a challenge that is too low leads to a state of boredom and one that is too high leads to a state of anxiety (Fig. 17).

In these experiments, because we focused on novices, the measurements were made on those who had no experience of cutting paper. Therefore, for an intermediate person with some experience of paper-cutting, the effectiveness of the practice could vary.

8. Conclusion

The aim of this study was to improve the skills of paper-cutting for novices. We created patterns of black and white lines that make up a cut paper picture and quantified their difficulty level. In this study, we quantified the improvement in cutting skill caused by practice in two experiments. In experiment 1, we determined the relationship between distance and width difficulty levels and skill levels with respect to cutting time. We confirmed that it has high conformity with the steering law. We compared the difference between novices and the experts using a model, which shows that cutting time increased with respect to difficulty level more for novices than for experts. The expert model fit the steering law better than the novice model. In experiment 2, we observed the effect of practice at various difficulty levels on the improvement of novices’ cutting skills. The results show that all difficulty levels improve skill, but practice at high difficulty levels improves skill more effectively. These results indicate that, as in flow theory in psychology, practice at high difficulty levels for novices is effective. However, the results of this paper are limited to the case where novices practice for the first time. Therefore, we aim to expand the types of participants in our experiments by having novices repeat the challenge and observing learners at an intermediate skill level practice at various difficulty levels.

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