TITLE:

Paper-cutting operations using scissors in Drury's law tasks

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ABSTRACT (120 WORDS):

Human performance modeling is a core topic in ergonomics. In addition to deriving models, it is important to verify the kinds of tasks that can be modeled. Drury's law is promising for path tracking tasks such as navigating a path with pens or driving a car. We conducted an experiment based on the observation that paper-cutting tasks using scissors resemble such tasks. The results showed that cutting arc-like paths (1/4 of a circle) showed an excellent fit with Drury's law ($R^2 > 0.98$), whereas cutting linear paths showed a worse fit ($R^2 > 0.87$). Since linear paths yielded better fits when path amplitudes were divided ($R^2 > 0.99$ for all amplitudes), we discuss the characteristics of paper-cutting operations using scissors.

KEYWORDS:

Drury's law, human motor performance, paper-cutting tasks.

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1. INTRODUCTION

Humans have used scissors as an everyday tool since their invention circa 1500 B.C. in Egypt [4]. In their original design, scissors were U-shaped, and consisted of two connected blades, called shears [31]. In their current form as a pair of crossed blades, scissors are used to cut paper, hair, threads, clothes, plants, packages, meat, vegetables, and so on. Their use scenarios include education, work in offices and industry, and, of course, our everyday housework.

We can imagine various indices to measure the effectiveness of the use of scissors. For example, the time or speed to cut a food packages, the deviation from a line drawn on a piece of paper (cutoff line), and the degree of complexity of shapes (e.g., spirals or stars). However, although the effectiveness of scissors, in terms of both the skills required to use them and the difficulty of the task at hand, can critically affect efficiency in offices, factories, and our daily activities, few studies have been conducted in the field of ergonomics on quantitative indices to evaluate operations using a scissor.

In this paper, we discuss the applicability of Drury's law [8] (or steering law [1]) to evaluate the effectiveness of scissor-cutting operations (actions involved in cutting materials using scissors). Hoffmann [13] conducted a Drury's law experiment to study the performance differences between the use of the preferred and non-preferred hands; the results showed that Fitts' law [10] is a more suitable model for scissor-cutting tasks than Drury's law. However, many researchers have showed that Fitts' law models tasks that require endpoint accuracy [22] and Drury's law models tasks that require trajectory accuracy [14]. Therefore, Hoffmann [13] provided a counter-example against these models, and we have wondered the reason. The fact that Fitts' law can model the time required to cut along a path has neither been denied nor supported by other researchers. Thus, we replicate the task with a greater variety of conditions to investigate a better performance model.

2. RELATED WORK

2.1. Measurement of Hand Skill using Scissors

It is well known that the use of scissors requires a certain level of skill and motor development. Therefore, psychologists have conducted experiments involving paper-cutting tasks to measure cognitive and motor development in children. For example, according to Folio and Fewell [11], children aged 36-41 months can only cut straight lines, those aged 42-47 months can cut circular lines, and 48-57-month-olds can cut square (i.e., polygonal) lines. Other researchers [6, 15, 26, 32] agree that humans develop fine motor skills over time, and hence are able to cut more complicated shapes with age. To evaluate this growth, Gesell [12] proposed an experiment that involved a material cutting along a line without any numerical guideline regarding its length or width. To the best of our knowledge, there is no uniformed method to evaluate the indices relevant to skill in the use of scissors in terms of path conditions and their results (time or error). If a certain performance model holds for scissor-cutting tasks, we can use the knowledge of quantitative indices investigated in the ergonomics field (e.g., index of difficulty) to measure the task difficulty or hand skills.

2.2. Drury's Law

When a user makes a stroke along a path of amplitude *A* and width *W* using a stylus, the time required to navigate the path *MT* is:

$$MT = a + b \times \frac{A}{W} \tag{1}$$

where *a* and *b* are empirically determined constants [8]. This model, called Drury's law or the steering law [14, 25], only holds when visual feedback is required [25, 30]. If the ratio A/W, called the index of difficulty (*ID*) in bits [1], is less than eight, users perform ballistic movements [25, 30]. Such tasks do not require visually-controlled operations [25, 30]. Equation 1 has been confirmed in tasks involving one- and two-handed styli [8], folk-lift truck driving [9], sewing machines [18], indirect-input styli [1, 2, 3], direct-input styli [21, 27, 35], computer mice [2, 23, 24, 25, 29, 30], trackballs [2], trackpoints [2], touchpads [2], touchscreens [25], driving in a virtual reality world [38], 3D manipulations [5], and motion-capturing systems [17].

The relationship between the time required and the path parameters of *A* and *W* has been confirmed not only for linear tracks, but also for circular tracks [2, 3, 8, 19, 21, 27, 35]. For circular shapes, the track amplitude *A* of a loop can be calculated as $A = 2\pi R$, where *R* is the mean radius of the inner and outer constraints [14].

Another formula for Drury's law presents speed *V* as:

$$V = c + d \times W \tag{2}$$

where *c* and *d* are empirically determined constants, and $V = MT/A$ [14].

2.3. Considering Scissor Operations as Drury's Law Tasks

One simple task that involves the use of scissors is cutting along a line drawn on worksheets or food packages. In this situation, users cut as close to the given line as possible. When the scissor blades deviate from the line, the users direct them back to the line. Another condition is a "user-determined" guideline or tolerance. When we cut a piece of paper, there is often no pre-drawn line to guide the scissor blades. We thus determine a certain level of deviation tolerance before beginning. This imaginary tolerance can be determined even if a piece of paper or a package has a cutoff line. Imagine that we want to open a food package using scissors. Although a cutoff line is printed on the package, we do not have to cut exactly along it. The scissor blades had better avoid deviating greatly from the line, but there is no serious problem in misalignment while maneuvering the blades. Such a difference between explicit and implicit constraints in Drury's law tasks was studied by Kulikov et al. [16] using a mouse and a direct-input pen tablet. Their results showed that implicit constraints allowed the participants to operate more quickly but introduced more errors. In our study, we use explicitly printed constraints as traditional Drury's law tasks. This condition was also adopted by Hoffmann for his cutting tasks [13].

The operations involved in cutting paper using scissors within an explicitly drawn line resemble Drury's law tasks from several perspectives, e.g., the operators maneuver the scissor blades along a line as quickly and accurately as possible, and the required time may decrease given a short or wide path. However, Hoffmann [13] reported that, in scissor-cutting tasks with circular paths of A = 314 mm, and W = 2.5, 5.0, 10, and 20 mm, there was considerable curvature in the data of MT as a function of $ID = A/W$. He found that the following relationship held with R^2 = 0.93 to 0.99, depending on the use of the dominant or the non-dominant hand:

$$MT = a + b \times \log_2 \frac{A}{W} \tag{3}$$

which is the one of variations of Fitts' law [10] (see Equations 11 and 12 in [7] for the derivation of this formula), where a and b are empirically determined constants. Hoffmann claimed that the scissor operations did not follow Drury's law because the participants performed the tasks with the blades stationary and the piece of paper in motion, which was quite different from standard Drury's law tasks.

The question is whether Drury's law holds for different conditions from the ones explored in Hoffmann's study [13], i.e., linear paths and paths of even narrower width. Fitts' law was confirmed to hold for scissor-cutting tasks in a limited set of conditions described above. Furthermore, since Hoffmann [13] did not report the effects of clutching the scissors in the hand (repetitive opening and closing operations) or the case where, due to the looseness of the piece of paper being cut, the user has to re-adjust his/her grip on the paper in order to cut it properly, we cannot discuss them here. Although we have no doubt that Fitts' law holds for the data in Hoffmann's experiments, we expect that users' strategies differ depending on the conditions pertaining to path shape and width. If so, it is possible that Drury's law holds for scissor-cutting tasks, rather than Fitts' law, in different conditions. As no study on scissor-cutting tasks has been conducted that has involved both linear and circular paths, we would like to discuss the differences based on data from our experiment.

3. EXPERIMENT

3.1. Procedure

A PC monitor on a table displayed the condition number of the given trial (1 to 10, described below). A recorded voice also reminded the participants of the number at any given time. A participant chose a piece of paper and cut it along a black line drawn on it. The instructions were as follows:

(1) Cut along the line as quickly and accurately as possible.

(2) Do not stabilize your hands by resting them or your arms on the table.

(3) During a trial, do not re-adjust the piece of paper being held.

Even when a participant deviated from the black line, he/she was required to complete the trial to the end and report to the authors about the error. The participant then retried the same task on another piece of paper. When a trial was interrupted by incidents such as a piece of paper clinging to a participant's hand, causing the participant to shake his/her hand to disentangle the paper, we asked the participant to retry the task under the same conditions. The total time taken by each participant was approximately 35 minutes.

3.2. Participants

The participants were 12 graduate and undergraduate local university students (three females, nine males; mean age ± *SD* = 22.4 ± 1.93 years). The dominant hand was right for all participants, and they held the scissors using this hand.

3.3. Apparatus

A pair of scissors was used in this study. It had a standard form, with stainless steel blades 65 mm long, where the length of the entire pair of scissors was 174 mm; the blades were each 1.8 mm thick, and weighed 53 g (manufactured by Plus Corporation). The blades required clutching to cut paper with even the shortest A value.

We ordered a professional company to print the pieces of paper. In preparation for many retrials, we asked them to print 400 pieces for each $A \times W \times$ shape pattern. The paper was offset printed and weighed 104.7 g/m^2, which was thicker and stiffer than the standard copier paper (60-70 g/m^2). This thicker paper would allow participants to hold it more stably and concentrate on controlling the scissor [15]. According to the interview of the printing company, path width W was precisely printed, but the accuracy with which the edges of the paper were cut had an error of less than 1 mm. Therefore, as a technical limitation of this experiment, the amplitude A could have included a 2-mm error in the worst case.

Such characteristics of paper as softness and curl are affected by the environment. ISO 187: 1990 suggests that pieces of paper should be at 23 ± 1ºC and 50 ± 2% R. H. (relative humidity) as the standard conditions. However, this was a rule to *test the paper*, whereas our purpose was to test human performance. Therefore, although we used an air conditioner to maintain temperature at 23ºC, this was changed according to the participants' preference. Overall, our digital thermo-hygrometer placed on a table recorded temperatures of 21-25ºC and 55-76% R. H.

3.4. Design

We set the amplitude *A* to 80 and 130 mm, which required one or more clutches. The width *W* was 1, 2, 3, 4, and 5 mm, which were narrower than Hoffmann's study [13] to test more visually-controlled movements. The path shape conditions were linear and arc-like (1/4 of a circle), as shown in Figure 1.

The number of parameter combinations for a path shape was 2 (*A*) × 5 (*W*) = 10 conditions = one session. The *ID* ranged from 16.0 to 130 bits. Participants cut 10 pieces in a random order for four sessions. The first was a practice session, and the remaining three sessions were the actual tasks. The total number of actual tasks was 2 (*A*) × 5 (*W*) × 3 (sessions) × 2 (shape) × 12 (participants) = 720 trials. The order of the shapes of paths that needed to be cut was reversed between half the participants. That is, six of the participants cut the paper into a linear shape as the other six cut the arc-like shape, and the other way round.

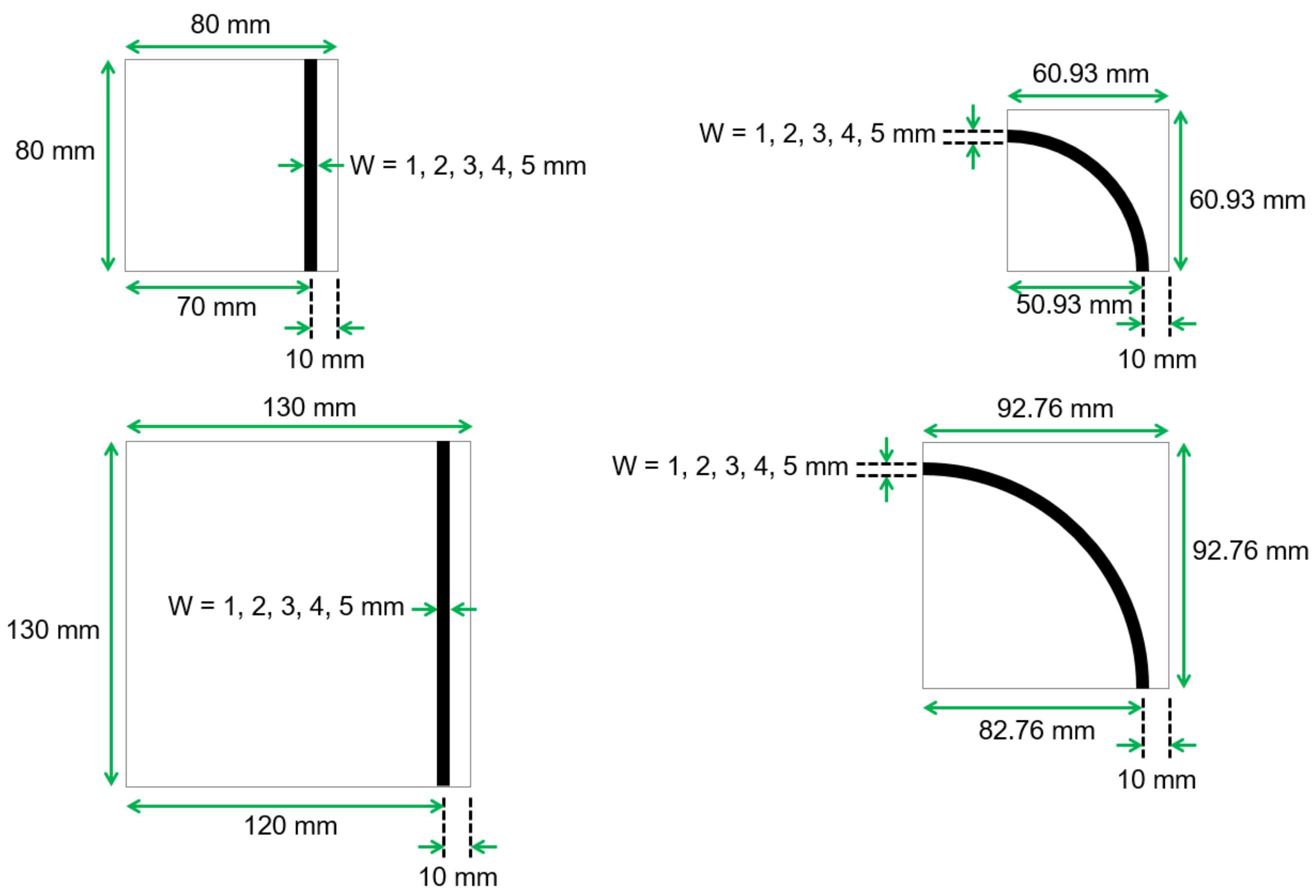

Figure 1. Parameter settings in the experiment.

3.5. Video Analysis

The collected data were movement time *MT*, the number of retrials including deviations and interrupts, and the number of clutching operations.

The trials were video-recorded, and we ordered a professional data analysis corporation to analyze them. The participants' consent was obtained for both these steps. Two people separately watched the video and entered data for (a) the time cutting began, (b) the time it ended, and (c) the number of clutchings. The start time was the previous frame of when the scissor blades entered a piece of paper. The end time was the frame of when a piece of paper was separated. A clutching operation was considered to have occurred when a participant opened the blades of the scissors. Following video analyses, the average data were used for statistical analysis. If the start and end times reported by the two observers were significantly different (> 1 s as threshold), the analysts analyzed the given video again. The number of retrials was counted by us during the experiment. Retrials occurred when (a) the black line was deviated from, or (b) a scissor operation was interrupted.

4. RESULTS

In total, 762 trials were performed. There were 34 retrials (4.46%) due to interruptions and the re-adjustment of the paper by moving it in the left hand. Omitting the relevant 34 data items, we observed eight retrials due to deviation from the path (i.e., steering error). Thus, the steering error rate was 8 / (762 – 34) = 1.10%. We discuss steering errors, and hence exclude errors due to interruptions and the re-adjustment of the paper in the hand; this is consistent with previous work on Drury's law tasks [3, 33]. In the following, we analyze the data from the *MT* and clutching operations without error trials.

We analyzed the data via repeated-measures ANOVA and the Bonferroni post-hoc test. The independent variables were path shape *S*, amplitude *A*, and width *W*. The dependent variables were movement time *MT*, error rate, and the number of clutching operations.

4.1. Movement Time (*MT*)

We observed the main effects of *S* ($F_{1, 11} = 64.866$, $p < 0.001$), *A* ($F_{1, 11} = 184.20$, $p < 0.001$), and *W* ($F_{4, 44} = 50.907$, $p < 0.001$). The post-hoc test showed that cutting linear paths is significantly faster than arc-like paths ($p < 0.001$). The average *MT*s for linear and arc-like paths were 3.68 and 6.76 s, respectively. The participants took a significantly longer time for $A = 130$ than 80 mm ($p < 0.001$). The wider path required a significantly shorter *MT* ($p <$ 0.001–0.05). We also observed significant interactions of $S \times W$ ($F_{4, 44} = 24.178$, $p < 0.001$) and $A \times W$ ($F_{4, 44} = 39.297$, $p < 0.001$), and no significant interaction of $S \times A$ ($F_{1, 11} = 2.355$, $p = 0.176$). Figure 2a-c show these interactions.

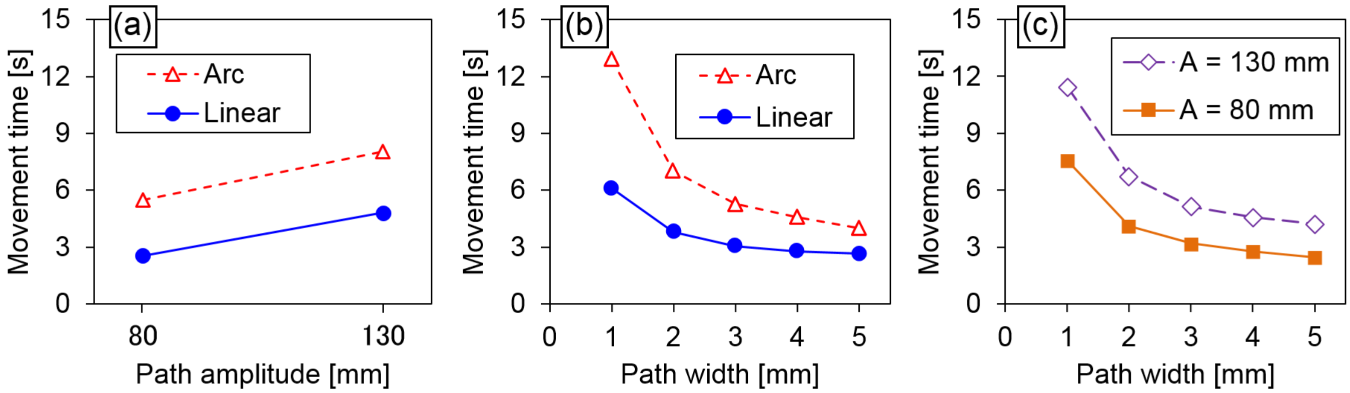

Figure 2. Movement time for each parameter. (a) *S* × *A*, (b) *S* × *W*, and (c) *A* × *W*.

4.2. Error Rate

Figure 3 shows the error rates for each path width divided by the amplitude and shape. The participants made more mistakes under narrow width conditions. However, because only eight errors were committed, we observed no major effect of S ($F_{1, 11} = 0.379$, $p = 0.551$), A ($F_{1, 11} = 4.714$, $p = 0.053$), and W ($F_{4, 44} = 1.711$, $p = 0.165$).

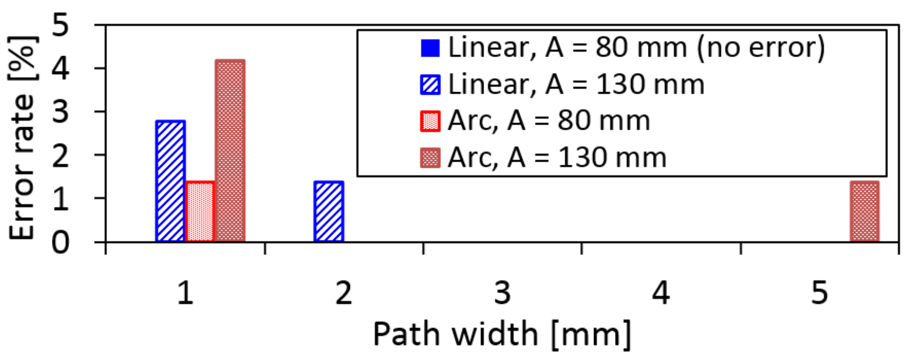

Figure 3. Error rate for each parameter.

4.3. Number of Clutching Operations

We observed the main effects of S ($F_{1, 11} = 4.970$, $p < 0.05$), A ($F_{1, 11} = 91.411$, $p < 0.001$), and W ($F_{4, 44} = 6.980$, $p < 0.001$). The post-hoc test showed that cutting linear paths requires significantly less clutching operations than arc-like paths ($p < 0.05$). The average numbers of clutching actions for linear and arc-like paths were 3.32 and 4.45, respectively. The participants performed significantly more clutching operations for A = 130 mm than for 80 mm ($p < 0.001$). A tendency whereby wider widths required fewer clutching operations could be seen: 4.89, 4.08, 3.75, 3.56, and 3.15 times for W = 1 to 5 mm. However, the pair-wise comparisons show only a difference between W = 2 mm and 5 mm ($p < 0.05$). We also observed a significant interaction of $A \times W$ ($F_{4, 44} = 3.605$, $p < 0.05$), but no significant interactions of $S \times A$ ($F_{1, 11} = 0.360$, $p = 0.854$) and $S \times W$ ($F_{4, 44} = 1.398$, $p = 0.250$). Figure 4a-c show these interactions.

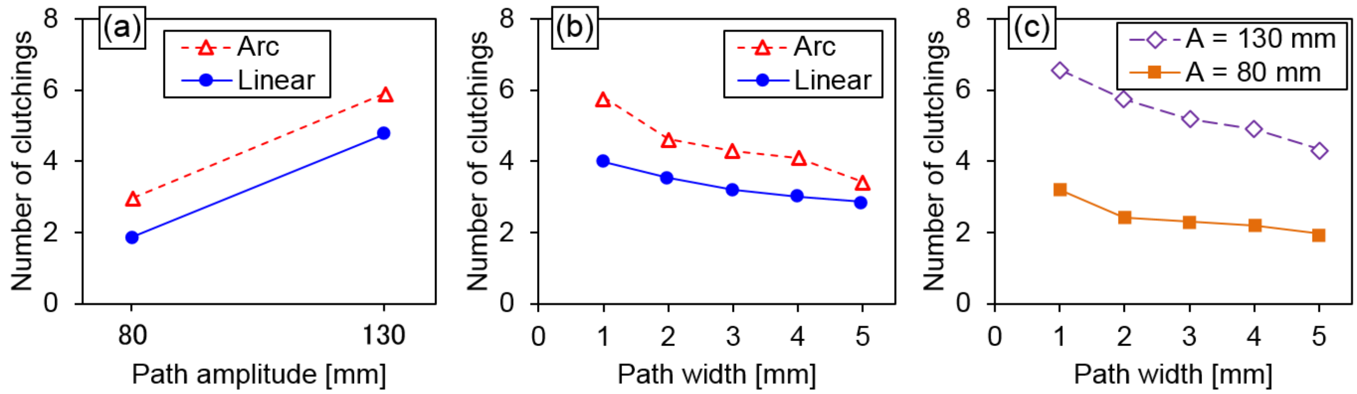

Figure 4. Number of clutching operations for each parameter. (a) $S \times A$, (b) $S \times W$, and (c) $A \times W$.

4.4. Drury's Law Fitness

Figure 5a shows the relationships between Drury's *ID* and *MT* for both path shapes. The arc-like shape shows a good fit ($R^2 > 0.98$), while the linear shape shows a worse fit than the arc-like shape ($R^2 > 0.87$). We can see two separated lines in the linear shape, where the division seems to be made due to path amplitude. Thus, we plotted data along the linear shape for each value of amplitude in Figure 5b, which showed a good fits for both values of A ($R^2 > 0.99$). The arc-like shape also showed better fitness when the A values were separated ($R^2 > 0.99$, Figure 5c), since the number of plotted points decreased.

Another model formula for Drury's law, the V form (Equation 2), is shown in Figure 6a. Both shapes showed good fits ($R^2 > 0.93$ for the linear shape, $R^2 > 0.96$ for the arc-like shape). When dividing path amplitudes, we see the different characteristics of the two shapes: the linear shape in Figure 6b shows a good fit for $A = 80$ mm ($R^2 > 0.97$), but not for $A = 130$ mm ($R^2 > 0.85$), whereas the arc-like shape in Figure 6c shows good fits for both A values ($R^2 > 0.95$).

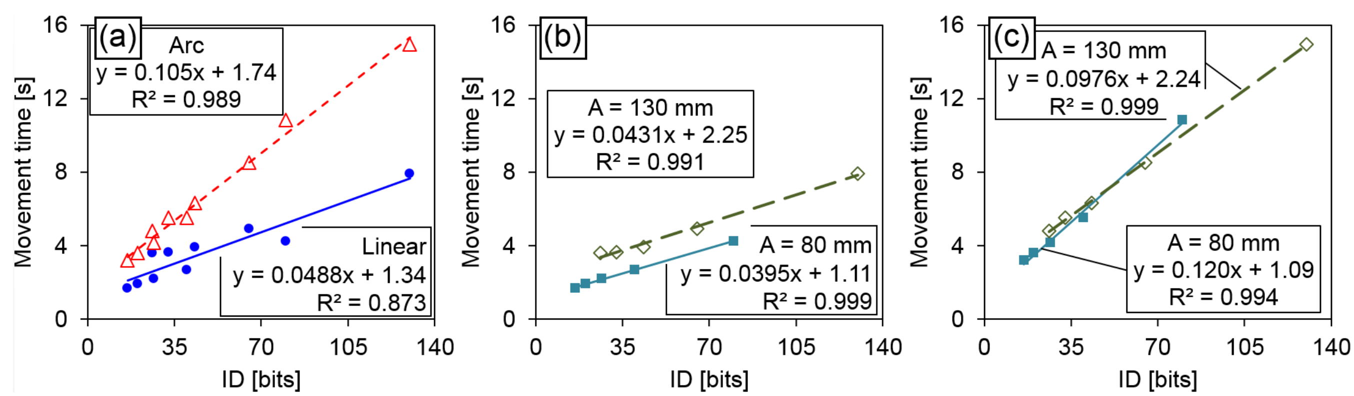

Figure 5. Movement time versus Drury's index of difficulty. (a) Relationships for the linear and arc-like shapes, and relationships obtained by dividing two A values for (b) linear and (c) arc-like shapes.

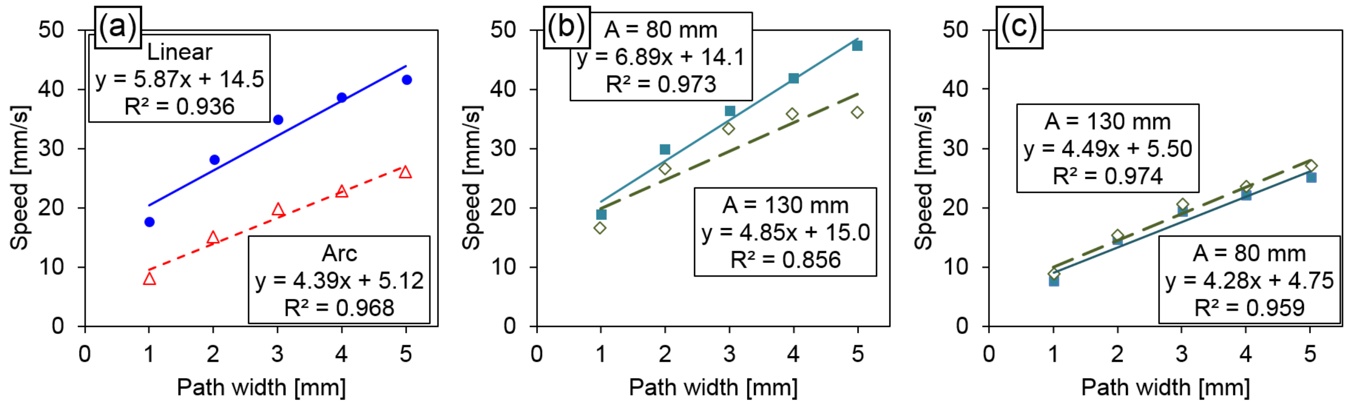

Figure 6. Speed versus path width. (a) Relationships for the linear and ark-like shapes, and relationships obtained by dividing two *A* values for (b) linear and (c) arc-like shapes.

4.5. Fitts' Law Fitness

Figure 7a-c show the relationships between Fitts' *ID* (Equation 3) and *MT* as the same manner of Figure 5a-c. Drury's law always showed better fits than Fitts' law for scissor-cutting tasks.

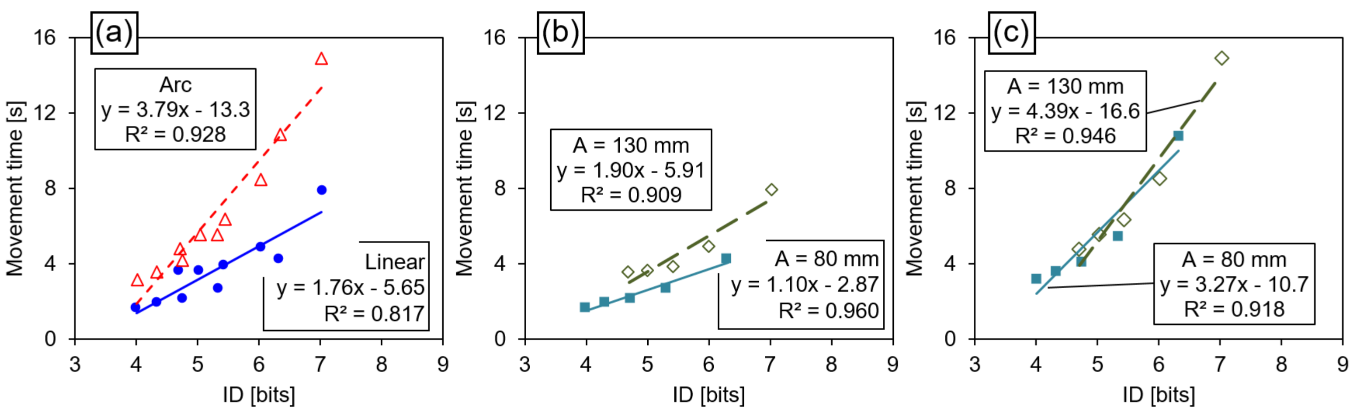

Figure 7. Movement time versus Fitts' index of difficulty. (a) Relationships for the linear and arc-like shapes, and relationships obtained by dividing two *A* values for (b) linear and (c) arc-like shapes.

4.6. Index of Performance (*IP*)

As suggested by Accot and Zhai [2], we calculated the index of performance (*IP*) as $1/b$ [bits/s]. The *IP*s for linear and arc-like shapes were 20.5 and 9.54 bits/s, which means that cutting an arc-like path requires more careful manipulation.

5. DISCUSSION

5.1. Steering Time and Error Rate

As in previous studies [2, 3, 21, 36], the scissor-cutting operations showed that linear shapes require shorter movement times than arc-like shapes. It is also consistent with previous work that longer and narrower paths require longer times (Figure 2a and b). These results show that, as expected, the effects of path parameters A and W on movement time follow Drury's law.

Surprisingly, the error rates in our experiment show very low scores compared to previous studies (Figure 3). As an example, input device comparison by Accot and Zhai [2] yielded the following results: (device, error rate) = (mouse, 9.00%), (indirect pen tablet, 18.8%), (trackball, 18.7%), (touchpad, 17.5%), and (trackpoint, 18.9), with *ID* ranging from 3.6 to 28.6 bits. Senanayake and Goonetilleke [25] showed that the mouse causes 8.50 to 21.6% error, depending on the control-display (CD) gain, and finger-touch operations cause 12.1 to 16.3% error depending on the established angle with the touchscreen, with *ID* ranging from 1.00 to 45.0 bits. Because their *ID*s and input devices are different from those used in our study, we could not directly compare our error rates with theirs. However, we chose *ID* values from 16.0 to 130 bits, and thus more difficult conditions than in previous studies.

One explanation for the low error rate is that the hard pieces of paper required stronger force to cut, and thus the distance moved by the scissor blades was short within a certain time. This compelled the participants to take longer to move, but enabled them to make fewer mistakes. However, even with a small gain (low speed), Senanayake and Goonetilleke [25] showed that a mouse produced 8.50% error. Our result of 1.10% (or 5.51% including retrials) was considerably smaller than in previous studies. Another possible reason is that the participants prioritized accuracy rather than speed. In our study, participants were instructed to perform tasks as quickly and accurately as possible, but it is possible that the participants involuntarily prioritized the avoidance of error.

5.2. Drury's Law Fitness

As shown in Figure 5a, the linear shapes did not show as a good a fit ($R^2 > 0.87$) as recorded in past work, or yielded by the arc-like shapes. Observing recorded videos of trials involving the linear shape, we noted that the participants tended to make a longer first cut in a piece of paper, and subsequent cuts were shorter. Furthermore, the speed with the first cut was higher than that of subsequent cuts. We assume that this was because the participants carefully adjusted the position and direction of the blades before the start, and were then able to cut longer for the first cut with fewer fine adjustments. Since the ratio of this first-cut distance for A = 80 mm was greater than that for A = 130 mm, the intercept of A = 80 mm was significantly lower (Figure 5b). On the contrary, the arc-like shapes showed an excellent fit without dividing the A values ($R^2 > 0.98$, Figure 5a). Unlike with linear shapes, the participants had to continue to carefully change the directional angle of the scissor blades throughout the arc-like path. Therefore, the ratio of the distance for the first cut to the entire amplitude was comparatively smaller than for linear shapes.

Some past studies measured the time required to navigate the entire path (e.g., [1, 16]), and others measured the time for a certain part of the entire amplitude, e.g., the time taken to navigate 67% of the entire path for sewing machine operations [18] and 50% for stylus operations [19]. The latter method was adopted to exclude the accelerations and decelerations occurring around the start and the end [18]. Since Drury's law holds for both measurement methods, we used the entire measurement. If we had used the middle measurement method, which omits the effect of a long distance for the first cut, Drury's law could show a better fit without dividing the A values.

5.3. Clutching Operations

Our results showed that although the number of clutching operations significantly varied according to path parameters (Figure 4a-c), Drury's law held (Figure 5). This is consistent with Accot and Zhai's report [2].

Another interesting finding was that the participants often performed clutching even when unnecessary. Considering the blade length (65 mm), we expected that the number of clutchings for A = 80 and 130 mm would be about one and two, respectively. However, the actual averages were 2.42 and 5.34. This meant that comfortable use of the scissors was achieved by repetitive closing and opening the blade for shorter durations rather than using its full length, because when blades are completely gathered, the tip of the scissors tires the paper and thus the participants might want to avoid that.

5.4. Comparison with Hoffmann's Scissor-cutting Study [13]

Interestingly, while Hoffmann [13] concluded that scissor-cutting tasks follow Fitts' law, our results showed that Drury's law holds for such tasks (Figure 5), and Fitts' law showed lower fits (Figure 6). Hoffmann claimed that the reason for Fitts' law fitting was that participants fixed the position of the probe (scissor blades) and moved the path (a piece of paper), and the curvature in fitting Drury's law was corrected by the logarithm of Fitts' law. One counter-example is that Drury's law holds for sewing machine operations, which requires that the probe (a needle) be stationary and the path (a line drawn on a cloth) be moved by hands [18].

A difference between Hoffmann's experiment and ours was in the values of path width. Under a wide tolerance, steering behavior along the path resembles ballistic movements for mouse and finger-touch operations [25]. Thibbotuwawa, Hoffmann himself, and Goonetilleke [30] showed that when the ID of a linear path is less than eight bits, the behavior of the mouse becomes ballistic, and $ID = \sqrt{A}$ shows better fitness than the original Drury's law, because the constraint of such a large width can be ignored. Hoffmann's scissor-cutting study was conducted with A = 314 mm (50 mm radius) and W = 2.5, 5.0, 10, and 20 mm; thus the ID values were 15.7, 31.4, 62.8, and 126 bits. This ID range seems sufficiently difficult for Drury's law tasks according to the eight-bit threshold [30], but we should consider the differences in the input devices (scissors [13] and mice [30]) and path shapes (circular [13] and linear [30]). Since actual scissor-cutting tasks sometimes involve wide tolerance widths compared to our experimental conditions, Fitts' law can yield better fits in such cases, as suggested by Hoffmann. Another controlled study is needed to find a significant point in the path width where Drury's law transitions to Fitts' law.

5.5. Speed

For arc-like shapes, as suggested by Hoffmann [14], Drury's law of the MT form (R^2 = 0.989, Figure 5a) showed a slightly better fit than the V form (R^2 = 0.968, Figure 6a). However, the linear shapes showed a worse fit (R^2 = 0.873 for MT and R^2 = 0.936 for V). Figure 6b shows that both plotted points of A = 80 and 130 mm have curves, and A = 130 yields a stronger curvature. When the path is wide, the speed becomes independent of the width, and movement time is affected to a greater extent by amplitude; thus, the width cannot linearly affect speed [25, 30]. Similar curves are observed in Drury's law tasks involving mouse operations (Figure 5 in [30]), fork-lift driving (Figure 3 in [9]), and driving tasks in virtual worlds (Figure 13 in [38]). Under the condition of A = 130 mm, the speeds for W = 3, 4, and 5 mm were 33.1, 35.6, and 36.0 mm/s, respectively. The differences in speed between the W values tended to become smaller, and thus W greater than 5 mm is expected to reduce the capacity to limit speed. For studies on scissor-cutting tasks, we suggest that the tolerance width be less than 5 mm; otherwise, the conditions can be satisfied with more ballistic movements.

We were interested in the fact that A = 130 mm was faster than A = 80 mm for arc-like shapes (Figure 6c), whereas the linear shapes showed the inverse relationship (Figure 6b). However, the interaction of $S \times A$ on MT was not significant, and thus a wider range of experimental parameters is needed to confirm this tendency.

5.6. Limitations

The data and discussion are somewhat limited by the path parameters, the directions to steer, the scissors, the instructions, and other conditions. In addition, we did not test a path with a corner [20], a narrowing path [1], or a widening path [33]. Below, we discuss two other limitations.

5.6.1. Variation in Curvature

The path parameter of a curvature in arc-like shapes, κ, was calculated by κ = 1/radius [mm^{-1}]. The curvature in our experiment was κ = 0.0196 and 0.0121 mm^{-1} for A = 80 and 130 mm, respectively. Drury's law held for arc-like shapes regardless of curvature, whereas stylus steering tasks showed different movement times depending on the curvature of circular paths [19]. Since we have empirical evidence whereby Drury's law holds for different radii in circular paths [2, 3, 27, 28, 34, 35, 37], our results support Drury's law for different curvatures, even for scissor operations. However, Figure 5c shows different slopes depending on the values of *A*. It is possible that Drury's law shows worse fits under a greater range of *ID* values because the gap between the slopes can be greater. Thus, another limitation of our experiment is the use of only two variations of curvature corresponding to the *A* values.

5.6.2. Measurements of MT and the Number of Clutchings

MT and the number of clutching operations were measured by video observation. Subjective variance of criteria for starting/finishing and clutching behavior was not completely eliminated. This concern can be mitigated by increasing video observers, but this is not an in-principle solution to video analysis. Although video analysis can provide more reliable data than measuring by a stopwatch [9, 18] with regard to re-analysis, there is a technical limitation to our study.

6. CONCLUSION

Our experiments in this study showed that scissor-cutting operations follow Drury's law. Tasks involving cutting linear paths showed a fit with $R^2 > 0.87$ without dividing path amplitudes, whereas arc-like shapes fitted with $R^2 > 0.98$. Scissor-cutting tasks resemble previously reported Drury's law tasks in several aspects, such as linear shapes outperforming arc-like shapes, and that the model showed a good fit with arc-like shapes regardless of curvature. Moreover, we confirmed and discussed the characteristics of scissor-cutting steering tasks, e.g., clutching operations were performed more often than necessary, and different strategies could be adopted for the linear and arc-like shapes.

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