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Biomechanical and perceptual determinants of drawing angles

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Abstract

This study focuses on perceptual and biomechanical determinants of the kinematics of angular drawing movements. Two experiments are reported in which twelve righthanded adults were asked to draw geometrical patterns consisting of three segments comprising either two acute or two obtuse angles. In Experiment 1, a lower frequency of pauses was observed in acute patterns and their segment length tended to be overestimated. The former effect is attributed to the exploitation of elasticity (Guiard, 1993). In order to evaluate whether the latter effect was due to perceptual factors, a second experiment was conducted. Twelve subjects drew a subset of the angular patterns under normal visual conditions and under conditions in which they could neither see their moving limb nor the resulting drawing trace. Again, subjects produced more pauses at obtuse than at acute angles and tended to overestimate the segment length in acute patterns. It is concluded that pauses are likely to occur between segments of discrete movement sequences when potential energy needs to be dissipated. When conditions arise that allow subjects to exploit elasticity, however, segment length tends to increase. The results of Experiment 2 confirm that these phenomena are independent from visual perception.

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I. Introduction

The production of graphic movements is often described in terms of concurrent information processing in separate modules that are hierarchically organized at different levels of the neuromuscular system (Van Galen, 1991; Requin, 1992). Depending on the task demands under investigation, either the role of top-down or of bottom-up processing is emphasized when observed variations of movement kinematics are analyzed. In this context, an important question is whether invariant features of movement production reflect centrally represented optimization principles (such as the minimization of jerk; Flash and Hogan, 1985) or, by contrast, may be seen as resulting from the biomechanical properties of the human effector system. An example of such an invariant kinematic feature is the bell shape of velocity profiles of discrete movements (e.g. Lacquaniti and Soechting, 1982; Bullock and Grossberg, 1988). This typical feature has been attributed to the fact that the end of a movement can be defined as an equilibrium point between the length-tension features of opposing muscle groups (Feldman, 1986; Polit and Bizzi, 1978, 1979) having the elastic properties of a mass-spring system. According to mass-spring models of movement production, planning a movement requires determining a virtual trajectory that consists of a series of equilibrium points between the initial and final positions (Bizzi et al., 1984).

Guiard (1991, 1993) clearly demonstrated the role of the elasticity of muscles and tendons in cyclical motor tasks. He showed that in fast back-and-forth movements, the potential energy accumulated during the execution of one movement is used for the execution of the following movement performed in the opposite direction. Adam et al. (1993, 1995), also studying back-and-forth movements, showed that when end-point accuracy demands were high, the kinematics of two successive movements performed in opposite directions were identical and similar to the kinematics of individual discrete aiming movements. When accuracy demands were low, however, the first movement was executed faster than the second one, and the peak velocity of the first movement occurred earlier in time. These findings were attributed to a reversal advantage by arguing that the execution of the second movement was facilitated by the modifications of the speed profile of the first movement. Analyses of the dynamical organisation of reciprocal aiming movements proved to be coherent with this point of view (Enoka, 1988; Kasai and Seki, 1992).

The aim of the present study is to explore a specific interaction between a lower and a higher level of movement production in a drawing task involving the production of series of three discrete submovements, each submovement performed in a different, non-opposite direction. We assume that in this task subjects will also tend to produce their movements in such a way that they can exploit the elastic properties of muscles and tendons. We expect that the extent to which they can do so will depend on the size of the angle between successive straight-line movements. Additionally, we also investigate the role of perceptual determinants of the kinematics of the drawing movements since the angle between two straight-line segments of a geometrical pattern influences the perceived length of the pattern’s segments.

Recently, Meulenbroek and Thomassen (1993) reported a study which demonstrated the possible role of the elastic properties of muscles and tendons when subjects copy
simple geometrical patterns composed of three straight-line segments and two angles. It was shown that for most patterns, the final segments were drawn in a preferred direction (i.e., toward the bottom right in the horizontal drawing surface). More important for the present study, however, is the finding that the frequency of pauses was higher at obtuse than at acute angles, and higher at the second than at the first produced angle. The authors assumed that during a pause, i.e., the time interval between movements in which there is no observable displacement of the effector system, the potential energy built up during the movement preceding the pause is dissipated when task constraints prevent subjects from using this energy for a following movement.

Meulenbroek and Thomassen also reported that the segment preceding an acute angle was drawn with a larger size than the segment preceding an obtuse angle. This finding was also considered to result from a relationship between the elasticity of muscles and tendons and the planning of copying movements. By increasing the size of the movement leading up to an acute angle, it was assumed that subjects anticipated that the potential energy built up during that movement could be exploited during the execution of the movement following the acute angle.

The research paradigm used by Meulenbroek and Thomassen (1993) is attractive because it not only allows for an investigation of the contribution of biomechanics to the spatial and kinematic features of drawing movements, but also permits an analysis of the contribution of perceptual processing. Consider the following two patterns, Ac1 and Ob1 of Fig. 1. These patterns induce an illusion with respect to the perceived length of the central segment similar to that of the Müller–Lyer illusion. The actual lengths of the central segments of the patterns are identical.

Because of the potential perceptual illusion induced by the patterns, the central segment of pattern Ob1 is likely to be perceived larger than the central segment of pattern Ac1. This might lead subjects to produce the former segment with a larger size than the latter. However, if the produced length of the central segment would be mainly

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1 We informally checked this length illusion with 10 subjects and found that the illusion was present but slightly weaker than the classical Müller–Lyer illusion.
determined by biomechanical factors, it should be larger for pattern Ac1 (with acute angles) than for pattern Ob1 (with obtuse angles). At the same time, the production of pauses should be more frequent at obtuse than at acute angles according to the findings of Meulenbroek and Thomassen (1993). Consequently, an analysis of produced sizes of the central segments of the patterns shown in Fig. 1, together with an analysis of the incidence of pauses occurring at the angles of these patterns, will allow us to assess the relative strength of perceptual and biomechanical determinants of drawing movements. This is pursued in Experiment 1 in which subjects were asked to draw the patterns in a tracing and in a copying task. Using a tracing or a copying task is obviously important in this context. In tracing, subjects need to produce a drawing trace directly onto a preprinted model. In copying, they need to produce drawing movements at a different location than where the stimulus pattern is presented. Size effects confirming the perceptual hypothesis should be less prominent in a tracing condition than in a copying condition. Furthermore, if both pause-frequency and size effects are mainly determined by biomechanical properties, they should be identical in tracing and copying conditions, insofar as subjects adopt similar speed–accuracy trade-offs in both tasks.

Further hypotheses may also be suggested from a closer inspection of the pattern structures. Patterns Ac2 and Ob2 (Fig. 1), when drawn without a pen lift, are produced through the repeated application of the same movement direction, since the extreme segments (hereafter called segment 1 and segment 3) have identical orientations. In patterns Ac1 and Ob1, however, each segment has a different orientation. The repeated use of identical movement directions may imply a planning benefit that may induce pauses to occur less frequently at the angles of patterns Ac2 and Ob2 than at the angles of patterns Ac1 and Ob1. If we ignore a potential angle effect, there is a priori no reason to expect more pauses in Ob2 than in Ac2 because both patterns imply a repetition of identical movement directions. When, however, in addition to the reduced demands at the level of movement planning, the acute angles induce a further reduction of demands at the level of execution for biomechanical reasons, fewer pauses should be observed in pattern Ac2 than in pattern Ob2 in accordance with the findings of Meulenbroek and Thomassen (1993).

Finally, it must be noted that the execution of pattern Ac2 probably elicits the mobilisation of only two groups of effectors, whereas in pattern Ac1, the direction of the third segment may impose the selection of a new group of effectors (Meulenbroek et al., 1993). We therefore assumed that, among all patterns used in this study, Ac2 is the most optimal pattern to allow for elasticity of muscles and tendons to be exploited. To assure that the effects being studied would not be the result of the use of a particular group of effectors, the patterns were presented under eight different orientations.

2. Experiment 1

2.1. Method

2.1.1. Subjects

Twelve right-handed adults (seven female and five male, mean age: 26 yrs, range: 21–30 yrs), all volunteers and undergraduate students at the university participated in
the study. They were naive as to the aims of the study, and received credits in the context of course requirements.

2.1.2. Models

Four patterns made of three straight-line segments and two angles were used. The patterns differed from each other with respect to the orientations of the extreme segments relative to the orientation of the central segment (see Fig. 1).

Pattern Acl consisted of two acute angles with each segment having a different orientation and pattern Ac2 consisted of two acute angles with the extreme segments having identical orientations. Pattern Ob1 contained two obtuse angles with each segment having a different orientation and pattern Ob2 contained two obtuse angles with the extreme segments having identical orientations. Patterns Acl and Ac2 need to be contrasted with patterns Ob1 and Ob2 to test the biomechanical hypothesis. The perceptual hypothesis calls for the comparison between patterns Acl and Ob1. The length of the extreme segments of each pattern was 0.65 cm, the length of the central segment was 1.20 cm. Acute angles were 45° and obtuse angles 135°. Patterns were rotated in steps of 45° in such a way that eight different orientations of the central segment for each pattern were obtained. Because of the symmetry around the midpoint of the central segment of patterns Ac2 and Ob2, half of the orientations resulted in mirror versions. The models were preprinted in black ink in square stimulus frames of 3 × 3 cm.

2.1.3. Procedure and material

Subjects were asked to copy the patterns in a first session, then to trace them in a second session. A pilot study conducted with six subjects showed that counterbalancing the task order across subjects was not necessary, as no effect of order was observed with respect to the frequency of pauses and the produced segment lengths (p > 0.10 for both variables). The pilot study also revealed that before starting with the copying task, it was necessary that subjects were first trained to draw simple angular figures of different sizes and with different orientations so that their movements became fluent. During the practice session, subjects were asked to pay attention to the accuracy of the angles. In particular, they were trained to avoid rounding corners at the angles.

In the copying condition, subjects had to draw the patterns in square response frames of identical size to that of the stimulus frame. The response frame was located immediately below the model. In the tracing condition, subjects had to draw directly onto the model. Sixteen models per sheet of paper (format A4) were randomly presented in two rows of eight models each. The total number of stimuli per subject was 128 (2 conditions × 2 trials × 4 patterns × 8 orientations) and the total number of movement sequences recorded in Experiment 1 was 1536. Starting points were free. Subjects were instructed to trace or copy the model quickly while reproducing the orientation of the stimulus pattern and the size of the pattern segments accurately.

Pen-tip displacements were recorded by means of a Calcomp Drawingboard with a special-purpose pen (Teulings and Maarse, 1984), both connected to an IBM 486 PC. Movements were sampled at a rate of 100 Hz with a spatial accuracy of 0.2 mm. During the practice session, subjects were allowed to position the digitizer into a comfortable
position. The lower edge of the response sheet (format A4) was always aligned with the lower edge of the digitizer.

Subjects were asked to position the pen at the center of the response frame before the start of each trial. A trial started with a high-frequency acoustic signal which indicated to the subject s/he had to trace or draw the model presented in the stimulus frame as fast and precise as possible in the corresponding response frame. When finished, an interactive recording procedure allowed the experimenter to stop the data acquisition. Subsequently, the subject was asked to position her/his pen at the center of the following response frame. No feedback of performance measures was given to the subjects.

Fig. 2. Typical example of a recording of the drawing movements of pattern Ob2 at the top. The bottom graph displays the tangential velocity profile and the time points (circles) corresponding to the start and the end of submovements. Note the pause between the second and third submovements.
2.1.4. Data analysis

Data were analyzed off-line by means of an interactive program (Teulings and Maarse, 1984). Pen-tip displacements data were low-pass filtered with a Finite Impulse Response filter having a transition band between 12 and 24 Hz. The filtered data were displayed alongside tangential velocity profiles. Fig. 2 displays a typical example of a recording of the displacement of the pen tip alongside the corresponding tangential velocity profile. Individual drawing movements corresponding to the segments of the model were isolated by selecting time points at the velocity minima that were closest to the beginning and the end of the model-defined segments. A pause was defined by the time interval between two drawing segments of which the duration exceeded 10 ms and during which the average tangential velocity approximated 0 cm/s. In other words, a pause was defined as a time interval longer than 10 ms, comprised between two velocity minima, one corresponding to the end of a stroke, the other to the beginning of the subsequent stroke.

For each submovement, the dependent variables were movement direction (deg), segment length (cm), mean tangential velocity (cm/s), and movement dysfluency (the number of velocity inversions). In addition, the frequency and duration (s) of pauses were analyzed.

The first four variables, i.e., those relating to the drawing movements, were evaluated for each submovement separately by means of ANOVAs for repeated measures according to a 2 Condition (copying/tracing) × 2 Angle (acute/obtuse) × 2 Pattern (extreme segments with same orientation/with different orientation) factorial design. Pause frequency and pause duration were analyzed by means of separate ANOVAs according to a 2 Condition (copying/tracing) × 2 Angle (acute/obtuse) × 2 Pattern (extreme segments with same orientation/with different orientation) × 2 Position (1st angle/2nd angle) factorial design. The data were pooled across the eight pattern orientations for which arguments are given in the next section. Further analyses concerned ANOVAs of the dependent variables for the copying and tracing conditions separately, and evaluations of the variability of spatial and temporal measures that will be specified in the relevant sections.

2.2. Results

2.2.1. Movement direction

Subjects produced the patterns without intermediate pen lifts in 94% of the trials in the copying condition, and in 96% of the trials in the tracing condition. In these trials, the central segment of the pattern (always the second segment produced), was either drawn in downward, rightward or right-downward direction. These results correspond to the findings of Meulenbroek and Thomassen (1993).

The analysis of pause frequency, pause duration, and the kinematics of the drawing movements as reported in the following sections were based on the set of patterns in which no pen lifts occurred, which corresponded to 1459 figures of the total of 1536 observations collected. Preliminary analyses showed no systematic effects of pattern orientation on the pauses of the angles or on the kinematics of the drawing movements. The data were therefore pooled across the eight different pattern orientations.
2.2.2. Pause frequency

Fig. 3 shows the frequency of pauses at the first and at second angle in the copying and tracing conditions for each pattern. Condition (copying versus tracing) did not affect the frequency of pauses ($F(1,11) = 1.13, p > 0.10$).

Separate ANOVAs for each Condition showed that pauses occurred more frequently at obtuse than at acute angles ($F(1,11) = 15.06, p < 0.01$ for copying; $F(1,11) = 27.52, p < 0.01$ for tracing). Pauses were also more frequent at the second than at the first angle ($F(1,11) = 8.64, p < 0.01$ for copying and $F(1,11) = 15.77, p < 0.01$ for tracing), though a significant interaction between Angle and Position was found in the copying condition. In the copying condition, the difference between the frequency of pauses at the first and at the second angle was more pronounced for acute patterns than for obtuse ones ($F(1,11) = 25.40, p < 0.01$). It is clear that a ceiling effect may account for the fact that no significant increase of the frequency of pauses at the second angle was found in the case of obtuse angles, as this frequency was already 90% of the cases for the first angle. A comparison between Ac2 and Ob2 patterns, which are patterns which elicited a repetition of movement directions, showed a significantly larger frequency of pauses in the obtuse Ob2 than in the acute Ac2 pattern ($F(1,11) = 10.41, p < 0.01$). Finally, concentrating on acute patterns only, results showed that, in the copying condition, pauses were less frequent for pattern Ac2 than for pattern Ac1 ($F(1,11) = 8.67, p < 0.01$).

2.2.3. Pause duration

Mean pause durations are displayed in Fig. 4. Mean pause durations ranged between 40 and 100 ms and were identical in the copying and tracing conditions ($F(1,11) = 0.87, p > 0.10$). On average, pause durations were longer at obtuse than at acute angles ($F(1,11) = 16.85, p < 0.01$). Pauses lasted significantly longer when they occurred at the second than when they occurred at the first angle ($F(1,11) = 11.69, p < 0.01$). An additional analysis concerned the variability of pause duration as expressed by the

![Graph showing frequency of pauses](image-url)
coefficient of variation of pause duration. Whereas pause-duration variability was larger in acute than in obtuse patterns ($F(1,11) = 8.01$, $p < 0.01$) no such difference was observed between the first and at the second angle ($p > 0.10$).

2.2.4. Segment length

Mean absolute lengths of the individual drawing movements of each pattern are displayed in Fig. 5. The embedded graphs in the figure represent the root mean square errors (RMSE) of the produced lengths, and the dashed lines correspond to the lengths of the model's segments.

Overall, subjects produced segments longer than those of the models, even in the tracing condition, except for the central segment of pattern Ob1 in the copying condition.
condition. In the copying condition, the produced lengths of central segments of acute patterns were larger than those of obtuse patterns ($F(1,11) = 18.75$, $p < 0.01$), but no such differences occurred in the tracing condition ($F(1,11) = 4.15$, $p > 0.05$). When selecting only the couple of patterns which most likely induced the Müller–Lyer illusion (Ac1 and Ob1), larger sizes of central segments of acute patterns occurred only in the copying condition ($F(1,11) = 18.58$, $p < 0.01$) but not in the tracing condition ($F(1,11) = 2.07$, $p > 0.05$). Similar results were found when the horizontal orientation of the patterns was selected ($F(1,11) = 17.75$, $p < 0.01$ and $F(1,11) = 1.14$, $p > 0.10$ for the copying and tracing conditions, respectively).

Finally, the RMSE values showed that, in the copying condition, the central segment’s length tended to be less accurate and less consistent in acute than in obtuse patterns ($F(1,11) = 10.47$, $p < 0.01$). In the tracing condition, the RMSEs were smaller than in the copying condition ($F(1,11) = 9.71$, $p < 0.01$), indicating a better and more stable correspondence with the length of the model’s segment, without any significant differences found between acute and obtuse patterns ($p > 0.15$).

Fig. 5 provides some additional interesting information with respect to the length of segments 1 and 3. Regarding the first segment, no differences were found between acute and obtuse patterns in the copying condition ($F(1,11) = 2.30$, $p > 0.05$), while, in the tracing condition, segment 1 was larger in obtuse than in acute patterns ($F(1,11) = 17.95$, $p < 0.01$). Thus, a length increase of segment 1 in acute patterns, as reported by Meulenbroek and Thomassen (1993), was not replicated in the present experiment. The type of angle did not affect the length of segment 3 ($F(1,11) = 0.61$, $p > 0.10$). However, it is worth adding an unexpected result with regard to this third segment in the copying condition: while it was produced with an overshoot for pattern Ac2, it was executed with a significantly shorter length for the closed-like acute pattern Ac1 ($F(1,11) = 14.71$, $p < 0.01$). The latter effect was not found in the tracing condition ($p > 0.06$). An analysis of the variability of the produced lengths showed that, for segment 3, the RMSEs were smaller in the tracing condition than in the copying condition ($F(1,11) = 16.85$, $p < 0.01$). We will return to this finding in the discussion.

Regarding the condition effect, results have shown so far that pause production (in terms of frequency and duration) was not different in copying and tracing. These findings support the biomechanical hypothesis. The results were less clear, however, with respect to size production. Consequently, it is important to check whether copying and tracing elicited differential effects in terms of movement dysfluency and/or velocity. In resonance with the biomechanical hypothesis, movement dysfluencies and velocities should be comparable in both conditions.

2.2.5. Movement dysfluency and tangential velocity

Movement dysfluency was neither affected by Angle ($p > 0.40$, $p > 0.93$ and $p > 0.95$ for segments 1, 2 and 3, respectively), nor by Condition ($p > 0.12$, $p > 0.25$ and $p > 0.96$, for segments 1, 2, and 3, respectively). Globally, mean dysfluency indexes were never larger than 1.30, which indicates that patterns were drawn in a ballistic manner, regardless of patterns or conditions.

For segment 1, the mean tangential velocity was 4.09 cm/s in the copying condition and 3.58 cm/s in the tracing condition ($F(1,11) = 4.82$, $p < .05$). For segment 2, the
mean tangential velocity was 5.39 cm/s in the copying and 4.75 cm/s in the tracing condition \((F(1,11) = 5.09, p < 0.05)\). These marginally significant velocity differences were absent in segment 3 (4.14 and 3.73 cm/s for the copying and tracing conditions, respectively; \(F(1,11) = 2.14, p > 0.15\)).

2.3. Discussion

The results of Experiment 1 are in agreement with the findings reported by Meulenbroek and Thomassen (1993) regarding the effects of the type of angle and the angle position on the incidence of pauses in drawing simple geometrical patterns. Obtuse angles elicited more frequently pauses and pauses of longer durations than acute angles. We interpret these findings as follows. When drawing obtuse angles, a pause is needed for the dissipation of potential energy built up during movement execution, probably because of a mobilisation of a different combination of effectors for the execution of the segment following the angle in a non-opposite direction (Meulenbroek and Thomassen, 1993). The potential energy can not be used for the execution of a movement following the angle in the opposite direction (Guiard, 1993; Adam et al., 1995). When pause durations would have been very short, the process of energy dissipation would be unlikely. However, pause durations varied between 40 and 100 ms, which is considered long enough for energy dissipation to occur. By contrast, drawing an acute angle is facilitated by the exploitation of the elastic properties of muscles and tendons by using the stored potential energy during the movement leading up to the angle for the execution of the movement following the angle. The results show also that this kind of relationship between the type of angle on the one hand and the frequency and duration of the pauses on the other hand, was present in a tracing condition which supports the biomechanical hypothesis.

Additional support of the biomechanical hypothesis was provided by the fact that facilitation of planning by conditions in which movement directions could be repeated (in patterns Ac2 and Ob2) did not seem to be strong enough to rule out biomechanical influences. As a matter of fact, the repetition of identical movement directions composing an obtuse pattern like Ob2, did not elicit less frequent or shorter pauses as compared to a pattern without any repetition of movement directions like Ob1. By contrast, pattern Ac2 elicited less frequent and shorter pauses than pattern Ac1 which confirms the biomechanical prediction that pattern Ac2 provided the most optimal context to exploit elastic energy.

Finally, because larger central segments were produced in acute than in obtuse patterns in the copying condition, the biomechanical hypothesis must be favoured rather than the perceptual hypothesis.

Although the main results tended to give support for the biomechanical hypothesis, it is hard to assert that some kind of on-line visual control did not affect performance, especially when subjects drew the central segments of patterns, of which durations were about 240 ms. More precisely, subjects might have visually monitored their movement when drawing the central segment of obtuse patterns, and this continuous control might have led to shortening that segment, in comparison to its perceived length. Although a larger increase of the central segment's length together with shorter pause durations were found in acute patterns, arguments for biomechanical as opposed to perceived
visual-illusion influences might be better highlighted by contrasting a condition in which visual feedback would be available to a condition where visual feedback would be absent. The perceptual hypothesis would predict that in the no-vision condition, central segments of obtuse patterns should be longer than those of acute patterns, while the biomechanical hypothesis would predict the reverse effect, longer central segments for acute patterns. Of course, the biomechanical hypothesis also implies that the frequency of pauses should again be higher in obtuse patterns, and pause duration longer, even if the patterns are drawn without visual feedback.

In a second experiment, we asked subjects to draw the angular patterns under normal visual conditions, and then to perform the task without vision of their moving limb and of the trace. The patterns of interest here are patterns Acl and Ob1 in an horizontal orientation, i.e., those patterns that resemble Müller–Lyer patterns most closely. Again, the perceptual and biomechanical hypotheses lead to clear-cut predictions when a vision condition is compared to a no-vision condition. In accordance with the perceptual hypothesis, we expected that central segments of obtuse patterns would be produced longer than in acute patterns in the no-vision condition, while no differences would be expected in the vision condition. In contrast, the biomechanical hypothesis would predict shorter central segments for obtuse patterns than for acute patterns in the no-vision condition, as well as a similar effect, even if weaker, in the vision condition. Furthermore, the latter hypothesis would also predict a strong pattern effect with regard to pause production regardless of the presence or absence of visual feedback.

3. Experiment 2

3.1. Method

3.1.1. Subjects
Twelve right-handed adults (four male and eight female, mean age of 25 yrs, age range: 22–34 yrs) participated in the second experiment. They were volunteers and were undergraduate students at the university. They were naive as to the aims of the study. None of them participated in the first experiment.

3.1.2. Material
Patterns Acl and Ob1 described in Experiment 1 (see Fig. 1) were used. They were presented in such a way that the central segments were horizontally oriented. Segment 1 and segment 3 had a size of 0.65 cm and segment 2 had a size of 1.20 cm. Acute angles were 45° and obtuse angles 135°. Fifteen stimulus patterns distributed in five rows of three patterns were printed on a white sheet of paper (format A4). All patterns on a sheet were of the same type, either Acl or Ob1. In order to make the vision and no-vision conditions comparable, patterns were not embedded in square frames, as was the case in Experiment 1. This to avoid the potential influence of spatial cues on the produced sizes.

3.1.3. Procedure
Both types of patterns were drawn by all subjects, who were asked to perform two tasks. One task consisted of drawing each pattern directly over the model (vision
condition). This tracing task was similar to the tracing condition in Experiment 1. The second task consisted of drawing each pattern without vision of the trace and of the moving limb (no-vision condition). In the no-vision condition, an opaque box was placed over the drawing limb. However, in order to allow a straightforward view of the model, a preprinted sheet of paper identical to that used in the vision condition was lying on top of the opaque box. Subjects had to reproduce as accurately and as fast as possible the visually presented model, but no particular requirements were made in the no-vision condition with respect to the spatial location of the performed drawings on the response sheet of paper beneath the opaque box covering their arm.

Four series of 60 identical patterns (two series of acute patterns and two series of obtuse patterns) were successively drawn by subjects, resulting in 240 patterns per subject. A total of 2880 patterns were drawn in Experiment 2. The order of the vision and no-vision conditions was counterbalanced across subjects. Within a series of 60 patterns, 30 patterns were executed in the vision condition and 30 patterns in the no-vision condition. The first two series of 60 patterns were always started with the vision condition, followed by the no-vision condition, whereas the two final series were always started with the no-vision task, followed by the vision condition.

Starting points were free and subjects were instructed to draw as fast and as accurate as possible. Subjects were first trained to produce accurate and fluent movements by letting them perform a series of the angular patterns in a preliminary practice session. For each pattern, the start of a trial was indicated by an acoustic signal. No feedback of performance measures was given to the subject during the experiment.

3.1.4. Data analysis

Data were recorded and analyzed by means of the same method used in Experiment 1. The dependent variables were identical to those analyzed in Experiment 1. The frequency and duration (s) of pauses were analyzed by means of separate ANOVAs for repeated measures according to a 2 Condition (vision/no-vision) \times 2 Pattern (acute/obtuse) \times 2 Position (1st angle/2nd angle) factorial design. Movement direction (deg), segment length (cm), mean tangential velocity (cm/s), and movement dysfluency (the number of velocity inversions) were evaluated by means of separate ANOVAs for repeated measures according to a 2 Condition (vision/no-vision) \times 2 Pattern (acute/obtuse) factorial design. Note that in Experiment 2 the factor Pattern is identical to the factor Angle of Experiment 1 because the patterns Ac1 and Ob1 only differ with respect to their angles.

3.2. Results

3.2.1. Movement direction

Patterns were drawn without pen lifts both in the vision and in the no-vision condition and subjects organized their movements in such a way that the horizontal central segment was always drawn from left to right. This movement direction is a preferred movement direction (Goodnow and Levine, 1973; Meulenbroek and Thomassen, 1991). Thus, the syntactic data observed in Experiment 2 were globally similar to those found in Experiment 1.
3.2.2. Pause frequency

As shown in Fig. 6, the frequency of pauses was higher in obtuse than in acute patterns \((F(1,11) = 32.65, \ p < 0.01)\), but no effect of Condition was found \((p > 0.60)\). Whether or not the subjects had at their disposal visual information, pauses were produced as frequently in one condition as in the other. This result is in line with the biomechanical hypothesis. As in Experiment 1, pauses were also more frequent at the second angle than at the first one \((F(1,11) = 6.73, \ p < 0.01)\).

3.2.3. Pause duration

Pause durations were shorter in acute than in obtuse patterns \((F(1,11) = 58.94, \ p < 0.01)\). Again, no differences were observed between vision and no-vision Condition \((p > 0.65)\), nor between pauses observed at the first or second angle \((p > 0.45)\). Mean durations of pauses at the first angle were 42 ms and 81 ms for acute and obtuse patterns, respectively. At the second angle, mean pause durations were 39 ms and 97 ms for acute and obtuse patterns, respectively. Regarding the variability of pause durations, an ANOVA carried out on the coefficient of variation revealed no differences between acute and obtuse patterns \((p > 0.70)\), between vision and no-vision conditions \((p > 0.10)\), and between the first and the second angle \((p > 0.28)\).

3.2.4. Segment length

Fig. 7 depicts the length of the produced segments as a function of Condition and Pattern. Dashed lines represent the lengths of the model's segments. The figure shows that the size of the central segment (segment 2) was smaller in the no-vision than in the vision Condition \((F(1,11) = 8.58, \ p < 0.01)\). Separate ANOVAs for each Condition showed that whereas there was no effect of Pattern in the vision Condition \((p > 0.05)\), in the no-vision Condition, the size of the central segment was larger in acute than in obtuse patterns \((F(1,11) = 5.35, \ p < 0.05)\). This result does not confirm the perceptual hypothesis. As shown in the embedded graphs, RMSEs were larger in the no-vision condition.

![Graph](image-url)
Condition than in the vision Condition \( (F(1,11) = 36.32, \ p < 0.01) \). No effects of Pattern or of the first-order interaction between Condition and Pattern were found \((p > 0.12 \text{ and } p > 0.20, \text{ respectively})\).

Fig. 7 also displays the results obtained for the first and third segments. The length of the first segment in the vision Condition was smaller in acute than in obtuse patterns \( (F(1,11) = 15.86, \ p < 0.01) \). Inverse results were found in the no-vision Condition, with larger first segments in acute than in obtuse patterns \( (F(1,11) = 4.97, \ p < 0.05) \). Thus, the length effect described by Meulenbroek and Thomassen (1993) was reproduced only in the no-vision Condition. For segment 3, a significant interaction between Condition and Pattern showed that length differences between acute and obtuse patterns were observed in the no-vision Condition \( (F(1,11) = 12.44, \ p < 0.01) \), with a larger third segment in acute than in obtuse patterns. Finally, for both segments, the RMSEs were always smaller in the vision than in no-vision Condition \( (F(1,11) = 16.85, \ p < 0.01) \), and no differences were observed between acute and obtuse patterns \( (p > 0.05) \).

**3.2.5. Movement dysfluency and tangential velocity**

No differences on the dysfluency measurements were found, whatever the patterns \((p > 0.93, \ p > 0.07 \text{ and } p > 0.21 \text{ for segments } 1, 2 \text{ and } 3, \text{ respectively})\), and whatever the condition \((p > 0.85, \ p > 0.99 \text{ and } p > 0.18 \text{ for segments } 1, 2, \text{ and } 3, \text{ respectively})\). Mean dysfluency measurements never exceeded 1.42, indicating that movements were of a ballistic nature in all patterns and in both conditions. This result is in line with what was found in Experiment 1.

For segment 1, the mean tangential velocity was 4.18 cm/s in the vision condition and 4.58 cm/s in the no-vision condition \( (F(1,11) = 5.02, \ p < 0.05) \). For segment 2, the mean tangential velocity was 5.87 cm/s in the vision condition and 5.80 cm/s in the no-vision condition \( (F(1,11) = 0.08, \ p > 0.77) \). For segment 3, mean velocities were 4.45 and 4.46 cm/s for the vision and no-vision conditions, respectively \( (F(1,11) = 0.01, \ p > 0.90) \).
3.3. Discussion

Experiment 2 confirmed the main results found in Experiment 1. In the no-vision Condition, a higher frequency of pauses and longer pause durations were observed at obtuse than at acute angles, and at the second angle than at the first one. Moreover, the central segment of the patterns was, like in the copying condition of Experiment 1, executed with a larger size in acute than in obtuse patterns. Thus, depriving the subjects from visual information did not modify the way in which acute and obtuse patterns were drawn. These results support the hypothesis of a strong influence of biomechanical determinants in angle production rather than of perceptual influences.

As stated in the discussion of Experiment 1, it might be argued that since the mean durations of the drawing movements were relatively long, visual and proprioceptive information may have been used by the subjects during movement execution to adjust the size of the central segment of the patterns on-line. If this would have allowed subjects to compensate for the perceptual illusion induced by the pattern structures rather than to replicate or mimic the perceptual illusion in their performance, it could be considered as no surprise that the produced length of the central segments of acute patterns was larger than the produced length of the central segments of obtuse patterns. The robustness of the present findings, however, in both tracing and copying conditions, and in conditions with and without direct visual control of the drawing traces during execution, lead to us to conclude that such illusion-compensation effects are unlikely to have determined the kinematics of the drawing movements of the subjects in the present study. Moreover, this line of argument would predict a size undershoot of the central segment of obtuse patterns when vision is available, which is not what was found in the present experiments.

In acute patterns pauses were more frequent in Experiment 1 than in Experiment 2 whereas they occurred equally often in obtuse patterns in both experiments. In a post-hoc comparison of the results from Experiment 1 and Experiment 2, we focused on the relationship between the frequency of pauses and the movement speed in the tracing of acute patterns in both experiments. As Guiard (1993) pointed out, exploitation of elasticity will be more pronounced at high movement speeds, because according to the laws of dynamics and to the properties of elastic bodies, an increase of kinetic energy will be transformed into potential energy at the end of each segment. The mean tangential velocity in the tracing condition of Experiment 1 appeared to be lower than the mean tangential velocity in the tracing condition of Experiment 2, for both the 1st segment (3.39 cm/s versus 4.27 cm/s in Experiment 1 and 2, respectively; $F(1,22) = 20.34$, $p < 0.01$) and the 2nd segment (4.90 cm/s versus 6.05 cm/s in Experiment 1 and 2, respectively; $F(1,22) = 29.30$, $p < 0.001$). An analysis of correlations between movement speed and pause frequency showed that acute patterns executed at a high speed elicited, in general, fewer pauses than acute patterns executed at a lower speed ($R_{xy} = -0.516$, $p < 0.01$; $R_{xy} = -0.591$, $p < 0.01$, for segments 1 and 2, respectively). Apparently, increasing movement speed enhanced the opportunity for subjects to exploit the biomechanical properties of muscles and tendons because at higher movement speeds more potential energy is built up and stored during the execution of a movement, which may then be used for the execution of a following movement.
Thus, Experiments 1 and 2 confirmed the role of biomechanical determinants as far as the production of pauses is concerned. However, as far as the spatial domain is concerned, i.e., the production of segment lengths, results obtained in both experiments appear interestingly more ambiguous with respect to the dichotomy between biomechanical and perceptual determinants. Let us concentrate on the differences obtained between tracing and copying in Experiment 1. A comparison between both conditions showed that pauses, and dysfluency results were globally similar in tracing and copying, despite a slight difference in tangential velocity which was higher in copying than in tracing. We may consequently consider that biomechanical processes remained effective in both tasks, whereas the role of visual feedback in the control of task execution was limited. However, we also recognize that perceptual factors may account for some of the results obtained with respect to the produced sizes of the first and third segments of patterns. Recall that a smaller size of the first segment of acute patterns than the first segment of obtuse patterns was observed in the tracing condition. Furthermore, when we consider which movement directions the subjects used, the first segment of acute patterns was almost always drawn in a non-preferred direction (towards the top left; Meulenbroek and Thomassen, 1991), whereas the first segment of obtuse patterns was drawn in a preferred direction (towards the bottom right). Given the position of the pen and of the hand, subjects had a constant vision of the end-point of the model's segment when they traced in a non-preferred direction. In contrast, in a preferred direction, seeing the extremity of the segment's model is more difficult, because it is partially masked by the pen and the hand (see also Van Sommers, 1984). Consequently, as vision permits a more accurate movement in a non-preferred than in a preferred direction, the length of the first segments was larger for obtuse patterns than for acute patterns. In the copying condition, no such differences between acute and obtuse patterns were found.

Other studies on effects of visual deprivation on handwriting have shown that trajectories executed without vision tend to increase in length (e.g. Van Doorn and Keuss, 1993). The results of Experiment 2 confirm these findings as far as the lengths of the first and the third segments are concerned. The central segment of the patterns, however, decreased in length in the no-vision condition. If these findings reflect a regression-to-the-mean effect regarding the lengths of the pattern segments, then the present results indicate that visually monitoring movement execution has a functional role with respect to accurate size production.

The production of the length of the third segment in acute patterns may also be seen as essentially perceptually based. The closed-like structure of Ac1 seems to set a virtual limit for the length of this segment, inducing the observed undershoot of this segment, especially in the copying condition. Subjects may have organized their movement in such a way that they took care to avoid drawing the third segment further than a point located at the virtual intersection of segment 1 and 3. In this view, the length of the third segment may be seen as mainly perceptually determined. Supporting evidence for this interpretation are results obtained in Experiment 2. Perceptual constraints being lower in the no-vision Condition of Experiment 2, explain the finding that the third segment of pattern Ac1 was not drawn shorter than the third segment of pattern Ac2. More specifically, 47% of the Ac1 patterns were drawn completely in a closed manner in the no-vision Condition of Experiment 2, i.e., with segments 1 and 3 intersecting.
Compared to Meulenbroek and Thomassen (1993) some divergent points have to be mentioned. The difference between acute and obtuse angles regarding pause frequency was smaller in the present experiments than in their experiment. Moreover, durations of pauses were found to be longer at obtuse than at acute angles in our experiments, whereas identical pause durations were found by Meulenbroek and Thomassen (1993). Finally, we did not observe an increase of the length of the first segment of acute patterns, in contrast to their study. Regarding this set of divergences, a pattern-size effect may have been a causal factor, as larger patterns were used in the present experiments. It might be that the overall size range of patterns determines the likelihood of movement interruptions as reflected by pauses. In this case, it is likely that the exploitation of elastic properties of muscles and tendons would be optimal only within a certain range of segment sizes, possibly related to the characteristics of the involved effector segments.

4. General discussion

In conclusion, the present experiments allowed us to examine interactive effects of biomechanical and perceptual determinants of the spatial and kinematic features of drawing movements. Further research may focus on a parametric investigation of angle size and segment length in order to manipulate the amount of potential energy being stored during the execution of movements on a more continuous scale than used presently with only acute and obtuse angles of constant size.

According to motor control models that emphasize hierarchically organized information processing (e.g., Van Galen, 1991), a parameter-setting stage is responsible for size adaptations whereas possible exploitation of biomechanical properties of the effector system can only emerge from processes occurring at the stage of movement initiation. Indeed, as temporal variables were similar across conditions, it must be recognized that the movement-initiation stage which, according to Van Galen’s model follows the parameter-setting stage, might be influenced by the dynamical context in which movements have to be performed. We thus would advocate some kind of integration of models that take into account hierarchical information processes and models that stress the adaptive reactions to the intrinsic dynamics of the moving effector system, e.g., in terms of the exploitation of the elastic properties of muscles and tendons. This would link hierarchical information processing models of movement control to models like the mass-spring model (Polit and Bizzi, 1978, 1979) in which planning a stable endpoint – or a virtual trajectory composed of successive equilibrium points (Bizzi et al., 1984) – permits both economy of trajectory representations and exploitation of biomechanical properties as a function of the physical context in which the movements are performed. In the case of drawing movements, where top-down oriented processes are considered to be an important aspect of movement planning, bottom-up processes have presently been shown to interact contextually with movement execution. Our study therefore has shown how variations of pause frequency, pause duration, and trajectory length may be seen both as consequences of the biomechanical properties of the effector system and the result of centrally planned aspects of movement production.
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