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# How Folks See Strokes

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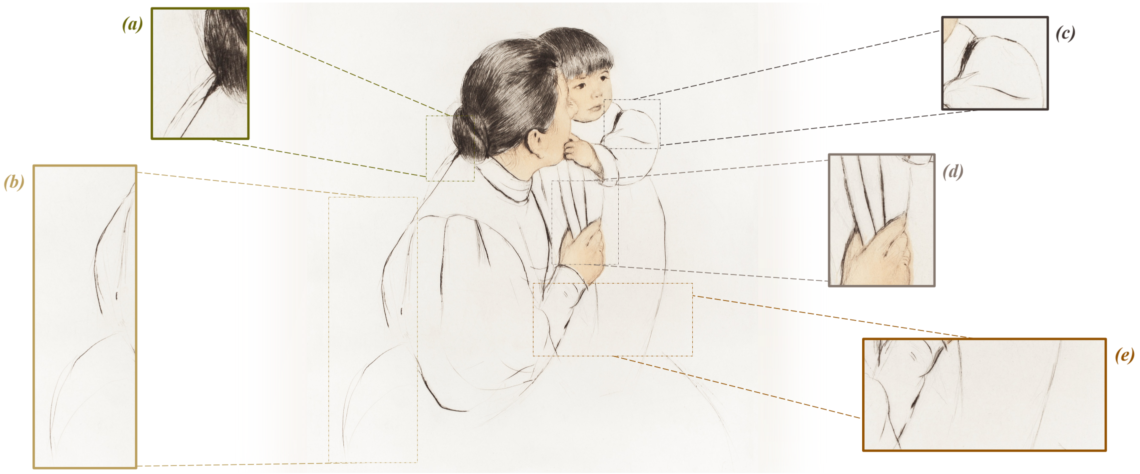

Figure 1: A sketch showcasing the applications of weighted lines in art. The insets highlight various uses for **(a)** Light and shadow (heavier lines at the points of contact between clothing), **(b)** Hierarchy of importance (contrast in stroke weight between the subjects and their clothing), **(c)** Object depth (a line of diminishing weight from foreground to background), **(d)** Emotion (expressive strokes around the grip), and **(e)** Scene depth (difference in line-weight between the mother's and child's garments). Peasant Mother and Child, Mary Cassatt, 1894.

## Abstract

*Sketches have been a well-studied field of research in recent years due to their power in communicating concepts in an abstract manner. Paradoxically, the building blocks of these sketches, namely strokes, have been less analysed, leaving room for a deeper understanding of how individual stroke attributes are perceived and collectively shape the sketch's overall visual character. Tapered strokes, in particular, have been under-represented in sketch generation and analysis, despite conveying meaning beyond their geometry. To highlight the power of these strokes, we conduct a user study and provide evidence that tapers yield timeline inference for artists and untrained viewers alike, which showcases the importance of line weights. Furthermore, we introduce a parameter that defines the principal orientation of complex strokes using Principal Component Analysis (PCA) over the stroke's area. Our findings suggest that this implementation is consistent with human perception as opposed to other methods that rely on temporal characteristics. Although the effects of tapering remain inconclusive as a depth cue, the results presented here make a case for broader inclusion of tapered strokes in sketch analysis and generation.*

### CCS Concepts

• ***Human-centered computing*** → ***Empirical studies in visualization;*** *User studies;* • ***Computing methodologies*** → *Shape modeling;*

## 1. Introduction

The term "sketch" can cover a wide range of illustrations, from rudimentary scribbles to the refined works of artists and architects. This inclusivity makes the analysis and understanding of these forms more complicated, as they differ in purpose, level of abstraction, and, most importantly, the drawing instruments employed.

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The final appearance of a stroke is determined by a combination of technique and drawing tool, and the application of the same technique across multiple pens or brushes can yield markedly different results. One of these important techniques is pressure, which underpins the artistic concepts of line quality, weight and tapering, as well as the more technical notion of line width. Line quality in art communicates far more than its shape, depending on the end goal. Namely, it carries weight, emotion and intent. For example, in animation, line quality is used to represent flow in a character's movements; in perspective drawings, to define depth; and in concept sketching, to highlight areas of importance. As such, these considerations for generating weighted lines have been of interest in Non-Photorealistic Rendering (NPR), for generating 2D appearances from 3D models using tapered strokes [GVH07; LFHK21], or in Human-Computer Interaction (HCI) for implementing more varied brushes to help artists control line intensity [CGL*24].

With all the attempts to generate tapered strokes and means to create them in different formats, one missing piece is how individual strokes are perceived, and what information can be extracted from them in isolation that impacts the bigger picture. The importance of these individual analyses becomes clear when considering the target audience for any illustrations. Where artists aim to communicate meaning through their techniques, some of this information remains imperceptible to untrained viewers; for instance, in an informal pilot study, non-artists most readily identified depth and shadow as perceptible stroke qualities, while concepts such as ‘flow’ proved more ambiguous to untrained viewers. Understanding whether tapering impacts perceived attributes is a necessary step for building systems that support the generation or analysis of illustrations composed of weighted lines.

The obstacles to studying such an approach are twofold: first, what are the criteria to categorise someone as a non-artist? The answer to the first question can narrow down the options for the latter by limiting how intuitive the term should be for laypeople. While some people may not be considered artists in the literal sense, their understanding of art may have been shaped through different art-related activities, from visiting art galleries and museums to reading graphic novels. The closest assessment to this approach is presented in Chatterjee et al.'s work [CWS*10], which proposes a questionnaire that separates artists from non-artists based on the aforementioned interactions.

The second obstacle concerns terminology: what term can better describe the perceptual qualities expressed through tapered sketches? The answer to the second question stems from examining what tapered strokes can communicate and the qualities that are second nature to human perception. In most cases, line weight is used to indicate one or more of the following: scene depth, object depth or mass, hierarchy of importance, light and shadow, and, finally, emotion [Cli23]. Novice viewers may not perceive emotion; light and shadow have more meaning for realistic objects than for abstract ones; and importance and scene depth can be defined only through the interaction of multiple elements in the scene, where the hierarchy of the elements is visible. To better understand the impacts of tapering, we shift our focus to individual objects or strokes, making object depth the primary variable of interest. Depth perception arises from both binocular and monocular cues [HR08], the latter of which is commonly exploited in art through perspective or occlusion, making it a broadly accessible quality to assess.

While depth can be conveyed within a single object, the perceptual contribution of an individual stroke to the overall composition remains largely unexplored, especially in the context of tapered strokes. Therefore, a complementary direction is to take a quantitative approach, analysing strokes using a variable sensitive to width variation—in particular, orientation. The notability of this measure is underlined by its applications in downstream tasks such as vectorisation and clean-up [LB25], as well as in texture generation pipelines [LGH13]. This work extends orientation measurement to tapered strokes by incorporating line weight via a PCA-based parameter and explores its alignment with human perception to assess its practical suitability for interactive tools.

With the importance of line weight motivated and depth perception established as a suitable means of evaluation, we conduct our study with the following contributions:

- A stroke-level parameter derived from stroke area, providing a measure of overall stroke orientation, designed for pipelines that treat individual strokes as discrete elements within a sketch.
- A perceptual user study validating the alignment of the proposed parameter with human perception, outperforming a timeline-based approximation used by Chen et al. [CKF23].
- Insights into the intuitiveness of artistic terminology to both artists and non-artists, through the designed study and qualitative feedback, unveiling the perceptual accessibility of tapered stroke properties to viewers regardless of their background in art.
- Evaluation of the perceptible characteristics resulting from tapering effects—specifically, object depth and drawing timeline—across artists and non-artists.

## 2. Related Work

Considering the background research on tapered strokes in both HCI and NPR, we first discuss how interactive interfaces are designed to help artists, methods used to generate these lines, and lastly perception studies of sketches.

### 2.1. Interactive Creativity Support Tools

Drawing assistant systems are divided according to their target audience and drawing styles. For training purposes, interfaces such as Painting with Bob [BWCS14], designed for novice sketch artists, and Magical Brush [HSZ23], targeting Chinese art style, aim to provide feedback and enhance the learning experience. For professional users, the most common approach is to look at individual strokes as elements. This way, the patterns drawn by the artist can be imitated, and then used to autocomplete the rest of the drawing [XCW14], or to generate stroke patterns on an image derived from the sampled drawn area [CKF23]. In the latter, stroke orientation is determined by averaging vectors along the stroke's medial axis, with all vectors originating from the starting point of the drawing and ending at a point mid-stroke. The focus on the stroke's skeleton inherently disregards variations in width, and can lead to miscalculations in more complex lines. More broadly, these interfaces consider all strokes to be short and simple, rendering them unable to handle more complex lines.

The studies with greater facilitation of complex strokes are commonly found in texture synthesis from an exemplar. These approaches generally simplify the elements of a texture, either strokes or other primitives, through the following techniques: medial axis transforms [LBW*14], simplified boundary representations [LGH13], or bounding boxes [BBT*06; dPWS10; OMC22]. These primitives are then used to determine the arrangements, orientations, and repetitions of components in a pattern, with the downside of data loss due to these simplifications. As such, our method aims to achieve perceptually accurate orientation results without data loss through calculations within the stroke geometry.

### 2.2. Generating Sketches with Tapered Strokes

Establishing isophote distance as a means of controlling stroke thickness, Goodwin et al. [GVH07] inspired subsequent work on line-art rendering of 3D models. One such work is that of Ejiri et al. [EMT14], who apply line weight variation to communicate light and shadow by computing tapered areas dependent on the positioning of a 2D light source. Recent works have extended the field further by employing machine-learning techniques to generate stylised line drawings from 3D models by transferring style from a single artist example [LFHK21]. To increase the control over the generated results, some works use the option of programmable rendering [GTDS10; LH25], while others propose alternatives to conventional strokes in 2D, replacing them with ribbons to render the contours for more artistic effect [WdGF*23]. Parallel to 3D rendering, works on generating 2D sketches with width-varying brushes have explored stroke thickening based on curvature [SKCN07], interactive stylisation [LYFD12], and GPU-accelerated rendering of vector brush strokes [CGL*24].

### 2.3. Perception of Sketches

Understanding human perception when it comes to hand-drawn sketches goes back to noting how artists decide which parts to draw based on the subject [CGL*08]. In analysing hand-drawn sketches, recent papers depend on the human perception in defining stroke clusters [LRS18; VLV*21] or intended connectivity [YLL*22], considering the geometrical aspects of single strokes in accordance with human perception. The focus of some research, on the other hand, has been to examine perceptual differences between trained and untrained observers in the context of drawing [OKS12]. In our work, we aim to bridge these two viewpoints by examining how tapered stroke properties are perceived by both groups.

## 3. A Perceptually-Motivated Stroke Orientation Parameter

To study the geometrical properties of drawn strokes, we consider the sketches in their vectorised form, most commonly stored in SVG files. This format stores the boundary of a drawn stroke as a path composed of lines, arcs, and Bézier curves, providing precise geometrical boundary extraction and accounting for tapering effects on the edges. Following this representation, we proceed as below to calculate orientation, as shown in Fig. 2:

1. Fitting a bounding box to a given stroke.
2. Sampling the area inside the bounding box uniformly, and filtering out the points that fall outside of the stroke's outline.
3. Using Principal Component Analysis (PCA) [Jol86] to determine the main directionality of the points.

PCA is a dimensionality reduction technique that identifies the directions of greatest variance in a dataset. These principal components are eigenvectors of the covariance matrix of sampled points, where the first vector represents the direction that maximises the variance of the projected points, and the other vector (in the 2D case) is orthogonal to the first and captures the direction of the second greatest variance. The first eigenvector—known as the dominant principal component—is what we consider to be the orientation of a stroke, which, accompanied by the eigenvalues, can represent the proportion of variance along each axis.

Compared to methods using Oriented Bounding Boxes (OBBs) [BBT*06; OMC22], our parameter results in fewer clustering problems in pattern extension applications, since our method's definition is confined within the geometric boundaries of a stroke; as opposed to OBBs, which are enclosing approximations that may overlap with neighbouring elements. Furthermore, weighting the orientation towards the thicker regions of a stroke accounts for the visual dominance of weighted areas over thinner regions. As demonstrated in perception-driven sketch processing tasks such as stroke connectivity [YLL*22], parameters that align with human perception are essential for artist-targeted tools. Whether this area-weighted orientation closely matches human-perceived orientation is examined in the following user study.

## 4. Materials & Methods

### 4.1. Participants

We recruited a total of $N = 33$ participants (48.5% male, 39.4% female, 12.1% non-binary or preferred not to disclose), consisting of 25 non-artists and 8 artists, with a mean age of $M = 28.8$ years ($SD = 8.4$, range: 22–57). Advertisements were shared through UK higher education channels, with inclusion criteria of normal or corrected-to-normal vision and university-level English reading proficiency. Participation was voluntary, and respondents were free to withdraw at any point during the study.

The classification of artists and non-artists was conducted using the questionnaire of Chatterjee et al. [CWS*10], which assesses participants' prior engagement in art-related activities. Following the threshold recommended by the original authors, participants with $score \geq 14$ were assigned to the artist category. Ethical approval was granted by The University of Manchester's Computer Science departmental ethics panel (Ref: 2026-25405-45947).

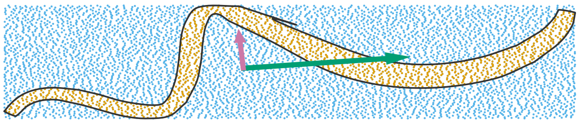


Figure 2: The process of calculating the orientation based on the dominant principal component. The sampled points are filtered based on whether they fall inside (orange) or outside (blue) the stroke boundary. The PCA eigenvectors are overlaid on the figure, with the longer green arrow representing the final orientation.

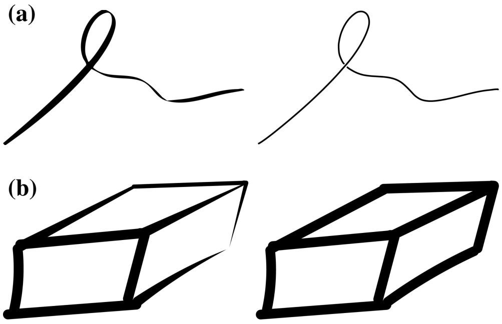


Figure 3: Representative stimuli for depth perception (H1) in **(a)** Isolated stroke and **(b)** Within-object strokes. In both cases, the left image shows the tapered version and the right shows the uniform-width counterpart.

All participants provided informed consent electronically via the Qualtrics survey platform prior to beginning the study.

### 4.2. Perceptual Study Design

We propose the following hypotheses for investigating the effects of tapered strokes on depth perception:

**Hypothesis 1 (H1):** Perception of depth in tapered strokes is independent of art experience, i.e., there is no significant difference in depth perception accuracy between artists and non-artists.

**Hypothesis 2 (H2):** Participants' perceived stroke orientation aligns with the orientation predicted by the PCA-based parameter.

**Hypothesis 3 (H3):** Participants more readily associate a definite start and end point with tapered than with uniform-width strokes.

We examine all these hypotheses across both groups of art enthusiasts and untrained viewers.

#### 4.2.1. Depth Perception (H1)

Given that the term 'depth' is more accessible to non-professionals following our informal pilot study, participants were asked to compare side-by-side images of tapered and non-tapered sketches and respond to the question, "Which image gives you a stronger sense of depth?" As individual strokes may not convey a strong sense of depth in isolation, participants were shown images of both individual strokes and complete objects (as shown in Fig. 3). The test images also include varying levels of tapering, as well as comparisons between non-tapered objects of differing widths, to assess participants' comprehension of the task. The sub-hypotheses for this section are as follows:

**H1.a.** Isolated tapered strokes carry perceivable depth information without reliance on object context.

**H1.b.** Tapered strokes convey depth more effectively when part of a complete object than when presented in isolation.

**H1.c.** Artists perceive depth in isolated strokes more readily than non-artists, while both groups perform similarly in object contexts.

This block consists of 17 trials: 10 comparisons between tapered and non-tapered drawings, 5 trials exploring the effect of varying tapering intensities, and 2 catch trials using uniform-width strokes. Trials are designed separately for isolated strokes and strokes within objects.

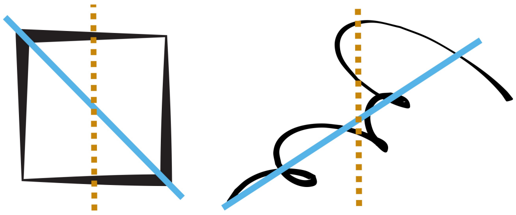


Figure 4: Representative stimuli for orientation perception (H2), with the computed PCA orientation (blue line) and Chen et al. [CKF23] method (yellow dashed line). Divergence between methods on different cases allows us to test which computational approach better predicts human perception.

#### 4.2.2. Orientation Perception (H2)

Given four main axes—horizontal, vertical, and two diagonals—as options, participants were asked: "Which axis best describes the overall orientation of this stroke?" The stimuli in this section consist of tapered and non-tapered strokes of varying complexity and directionality (Fig. 4). While some orientations are unambiguous, others are more challenging, motivating the following sub-hypotheses:

**H2.a.** Perceived orientation responses agree with our PCA-based orientation parameter at above-chance rates.

**H2.b.** The perceived orientation aligns more closely with our spatial PCA-based method compared to temporal averaging methods [CKF23].

The orientation block consists of 17 trials: 3 questions per orientation axis, 1 catch trial, 2 ambiguous samples with no definitive correct answer, and 2 challenging stimuli for exploratory analysis.

#### 4.2.3. Drawing Timeline (H3)

The final block analyses the drawing timeline, assessing participants' sense of start and end points based on line weight. Given a tapered or non-tapered stroke, participants were asked "Which point does the stroke start from?", selecting either point A or point B marked at each end of the displayed stroke (Fig. 5). Familiarity with hatching techniques implies an awareness of how pen pressure and drawing speed influence line weight. This variation, however, differs from the intentional changes in thickness employed by

Figure 5: Representative stimuli for the drawing timeline (H3). The images show a uniform-width and a tapered example, from left to right, respectively.

artists using calligraphy brushes or ink. To examine potential differences in timeline perception across experience levels, we propose the following sub-hypotheses:

**H3.a.** The tendency to perceive a definite start and end point for tapered strokes does not differ between artists and non-artists.

**H3.b.** Participants' familiarity with specific drawing tools influences their tendency to identify the thick end of a tapered stroke as the start point.

The timeline block consists of 11 trials: 3 samples drawn from thin-to-thick taper, 3 samples drawn from thick-to-thin, 3 non-tapered samples, and 2 samples with tapering at both ends.

#### 4.2.4. Response Formats

All hypotheses used multiple-choice questions, with the following available choices per block:

**H1 (Depth):** "Image A", "Image B", "Both seem the same", and "Neither gives me a feeling of depth".

**H2 (Orientation):** "Vertical", "Horizontal", "Diagonal (top-right, bottom-left)", "Diagonal (top-left, bottom-right)", and "Cannot determine the orientation for this image".

**H3 (Timeline):** "Point A", "Point B", "Both seem equally valid", and "Cannot be determined / None".

Options such as "None" or "Cannot be determined" were included to increase flexibility when none of the available options accurately reflected the participant's response. Note that for all question types, responses aligning with the hypothesised outcome were coded as 'correct' for ease of interpretation. Accuracy per condition was therefore calculated as the percentage of correct responses.

### 4.3. Design & Procedure

The study employed a mixed design: a between-subjects factor of Group (Artists vs Non-Artists) and within-subjects factors of stimulus characteristics (taper presence, stroke context, and orientation).

All participants started the study with the same consent forms and the art experience questionnaire from [CWS*10], with an additional section on art tools and frequency of usage per tool. Afterwards, they were presented with the same three hypothesis blocks, with the order randomised within each block to prevent any learning or order effects.

The questionnaire was designed in Qualtrics, with an average completion time of 9–12 minutes. For the depth block, two images were shown side by side, with the sides randomised within questions. The orientation and timeline blocks each had one stimulus per question, and any additional information required was shown either in the response choices (illustrated axes for the orientation block) or on the stimulus itself (Points A and B highlighted for start/end in the timeline block). Participants who failed the orientation catch trial were excluded from the analysis. The depth catch trials were retained for quality monitoring purposes but did not result in any exclusions, due to the inherently subjective nature of depth perception in drawn stimuli.

At the end of every section, participants were asked two questions assessing their confidence in understanding the questions and in their responses. These were followed by open-ended qualitative feedback via optional comment boxes, which provided contextual insight into participants' reasoning.

## 5. Results & Analysis

All statistical analyses were conducted in JASP 0.95.4 [JAS25], with data pre-processing pipelines implemented in Python using the Pandas (v2.3.3) and NumPy (v2.4.0) packages.

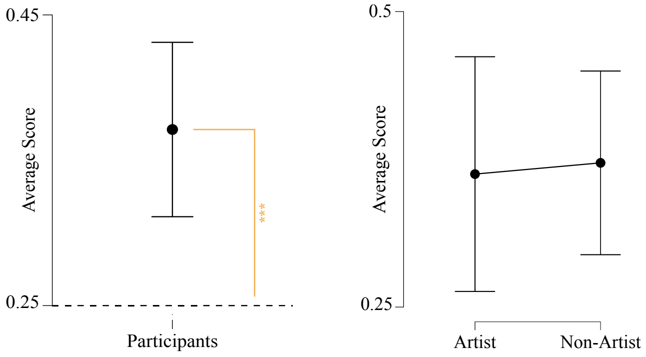
### 5.1. Depth Perception (H1)

*One Sample Wilcoxon Signed-Rank Test:* Participants as a whole reliably perceived depth above the chance level of 0.25—corresponding to the four response options—regardless of group ($V = 483.5$, $p < .001$, $r = .724$), supporting H1 (Fig. 6a).

*Bayesian Independent Samples t-Test:* Artists and Non-Artists showed comparable depth perception accuracy, with a nearly identical mean scores ($BF_{01} = 2.672$; Artists: $n = 8$, $M = .36$, $SD = .12$; Non-Artists: $n = 25$, $M = .37$, $SD = .19$), providing additional support for H1 (Fig. 6b).

Both tests were conducted on the average score across 10 trials, and the tests were selected after Shapiro-Wilk tests confirmed normality of the average score residuals ($W = .938$, $p = .058$). The Bayesian approach was chosen to provide evidence in favour of the null hypothesis of group independence, whereas a frequentist test can only fail to reject the null hypothesis without supporting it.

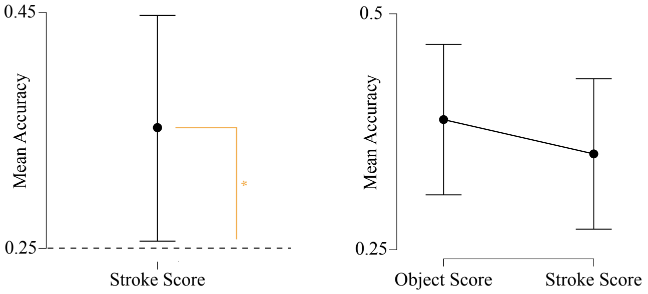
**H1.a.** *One Sample Wilcoxon Signed-Rank Test:* Participants perceived depth information from isolated tapered strokes above chance level, albeit with a small-to-moderate effect size (chance level of 0.25, $V = 377.0$, $p = .042$, $r = .344$), supporting H1.a



(a) Overall depth perception accuracy across all participants, significantly exceeding chance level ($V = 483.5$, $p < .001$, $r = .724$).

(b) Average depth accuracy by group. Artists and Non-Artists show nearly identical means ($BF_{01} = 2.672$).

Figure 6: Depth perception results. **(a)** Depth perception significantly exceeds chance level across all participants, supporting H1. **(b)** Depth perception accuracy is independent of art experience, corroborating H1.



(a) Depth accuracy for isolated tapered strokes against chance level. Participants perceived depth significantly above chance ($V = 377.0$, $p = .042$, $r = .344$).

(b) Mean accuracy for isolated strokes and object-embedded strokes. No significant difference was observed ($t(32) = .657$, $p = .258$, Cohen's $d = .114$).

Figure 7: Depth perception results by stroke type and Context. **(a)** Isolated tapered strokes convey perceivable depth information, supporting H1.a. **(b)** Object context did not improve depth perception over isolated strokes, not supporting H1.b.

(Fig. 7a). This analysis was based on *Stroke Score*, calculated as the average of correct responses to isolated-stroke questions, which deviated from normality (Shapiro-Wilk $W = .915$, $p = .014$), supporting the use of a non-parametric test.

**H1.b.** *Paired Samples t-Test:* Participants perceived the depth from object-embedded strokes with a slightly higher mean compared to isolated strokes, though non-significant ($t(32) = .657$, $p = .258$, Cohen's $d = .114$; object-embedded: $M = .39$, $SD = .19$; isolated: $M = .35$, $SD = .27$), not supporting H1.b (Fig. 7b). Normality of the scores was confirmed by the Shapiro-Wilk test ($W = .953$, $p = .164$), supporting the use of a parametric test.

**H1.c.** *Mixed Repeated Measures ANOVA:* Neither the main effects of Context ($F(1,31) = 0.245$, $p = .624$, $\eta_p^2 = .008$) and Group ($F(1,31) = 0.001$, $p = .895$, $\eta_p^2 < .001$), nor their interaction ($F(1,31) = 0.013$, $p = .910$, $\eta_p^2 < .001$) reached significance (Tables 1 and 2; Fig. 8), not supporting H1.c. Homogeneity of variances was confirmed by Levene's test for both Stroke Score ($F(1,31) = 2.337$, $p = .136$) and Object Score ($F(1,31) = 0.230$, $p = .635$).

Table 1: Within-Subjects Effects: Context × Group ANOVA

| Cases | $df$ | Mean Square | $F$ | $p$ | $\eta_p^2$ |
|---|---|---|---|---|---|
| Context | 1 | 0.013 | 0.245 | .624 | 0.008 |
| Context × Group | 1 | $< 0.001$ | 0.013 | .910 | $< 0.001$ |
| Residuals | 31 | 0.052 | | | |

Table 2: Between-Subjects Effects: Artist vs. Non-Artist ANOVA

| Cases | $df$ | Mean Square | $F$ | $p$ | $\eta_p^2$ |
|---|---|---|---|---|---|
| Group | 1 | 0.001 | 0.018 | .895 | $< 0.001$ |
| Residuals | 31 | 0.061 | | | |

## 5.2. Orientation Perception (H2)

The orientation values produced by our PCA-based parameter and Chen et al. [CKF23]'s method are in degrees, and were first clamped to the nearest available response option (0°, 45°, 90°, 135°) to enable comparison with participants' discrete responses. A mean match rate was then calculated for each participant as the proportion of trials in which their response matched each parameter's clamped prediction.

**H2.a.** *One Sample Wilcoxon Signed-Rank Test:* The mean match rate of the PCA-based orientation parameter significantly exceeded the chance level of 0.25 ($V = 561.0$, $p < .001$, $r = 1.0$), indicating near-perfect alignment with perceived orientation and strongly supporting H2.a (Fig. 9a). Deviation from normality (Shapiro-Wilk $W = .901$, $p = .006$) supported the use of a non-parametric test.

**H2.b.** *One-Way Repeated Measures ANOVA:* The PCA-based parameter produced significantly lower angular error than Chen et al. [CKF23] ($\Delta M = 15.73$, $t(32) = -14.29$, Cohen's $d = -2.57$, $p < .001$), while remaining significantly higher than the questionnaire-defined ground truth ($\Delta M = 6.60$, $t(32) = -14.55$, Cohen's $d = -1.08$, $p < .001$) in post hoc comparisons with Bonferroni correction, suggesting our parameter closely approximates but does not fully recover the intended stroke orientation, supporting H2.b (Fig. 9b). The large effect size partly reflects the constraints of the discrete response format used for the ground truth category, rather than a fundamental limitation of the PCA parameter. The main effect across methods was significant ($F(1.079, 34.525) = 227.2$, $p < .001$, $\eta_p^2 = .877$), with degrees of freedom corrected using the Greenhouse-Geisser estimate ($\varepsilon = .539$) following a violation of sphericity (Mauchly's $W = .146$, $p < .001$).

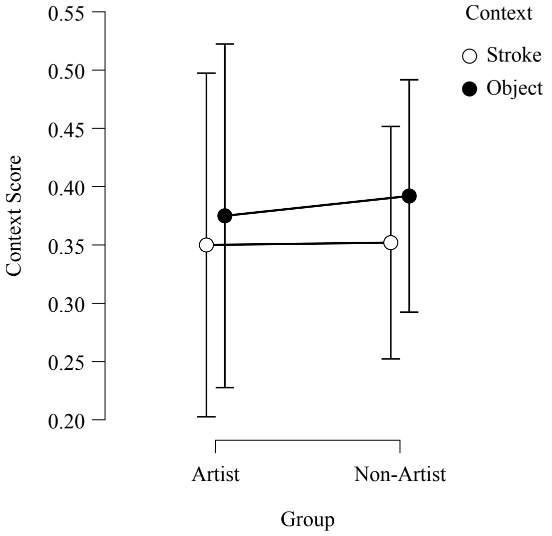
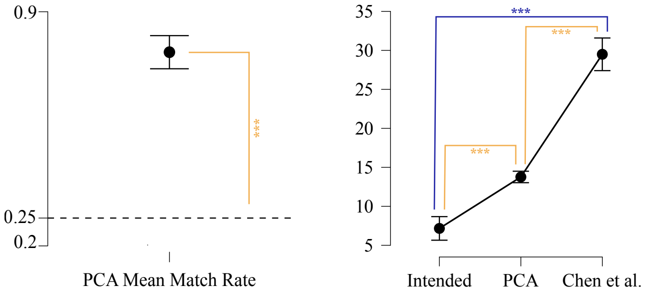


Figure 8: Mean depth perception accuracy across stroke and object contexts for Artist and Non-Artist groups. Neither the main effects of Context ($p = .624$) and Group ($p = .895$), nor their interaction ($p = .910$) reached significance, not supporting H1.c.



(a) Mean PCA match rate across participants, significantly exceeding chance level of 0.25 ($V = 561.0$, $p < .001$, $r = 1.0$).

(b) Mean angular error per parameter across participants. All pairwise differences are significant ($p < .001$).

Figure 9: Orientation perception results. **(a)** PCA match rate significantly exceeds chance, supporting H2.a. **(b)** PCA achieves significantly lower angular error than Chen et al. [CKF23], approaching the questionnaire-defined orientation, supporting H2.b.

## 5.3. Drawing Timeline (H3)

The variables *Taper Definiteness* and *No-Taper Definiteness* were calculated based on participants' choices for the start and end points, using the following scoring scheme: "Point A" or "Point B": 1 (definite choice), "Both seem equally valid": 0.5, and "Cannot be determined / None": 0 (indefinite choice), as illustrated in Fig. 10. These scores were then averaged across tapered and non-tapered strokes, yielding the preceding variables.

*Wilcoxon Signed-Rank Test (Paired, One-Tailed):* Participants responded with significantly greater definiteness when judging tapered strokes compared to non-tapered strokes ($V = 214.0$, $p = .002$, $r = .692$; tapered: $M = .922$, $SD = .078$; non-tapered: $M = .783$, $SD = .258$, respectively), supporting H3 (Fig. 11a). Deviation from normality in the difference scores ($W = .815$, $p < .001$) supported the use of a non-parametric test.

**H3.a.** *Mann-Whitney U Test:* No significant difference in Taper Definiteness was found between artists and non-artists ($U = 122.0$, $p = .344$, $r = -.220$; artists: $M = .938$, $SD = .100$; non-artists: $M = .918$, $SD = .072$), indicating that the tendency to make definite start and end point judgements for tapered strokes is consistent across both groups, not supporting H3.a (Fig. 11b). Deviation from normality (Shapiro-Wilk $W = .881$, $p = .002$) supported the use of a non-parametric test.

**H3.b.** *Linear Regression & Spearman Correlation:* No significant relationship was found between drawing tool familiarity and thick-end preference rate (Table 3; $F(6,26) = 0.849$, $p = .544$, $R^2 = .164$, adjusted $R^2 = -.029$). A supplementary Spearman correlation identified a weakly negative association for the other tools category ($\rho = -.481$, $p = .005$), though this was not reflected in the regression model ($p = .085$) and is difficult to interpret given the nature of this category. These results do not support H3.b.

## 6. Discussion

In this work, we proposed a PCA-based orientation parameter to calculate the principal orientation axis of a stroke, covering tapered

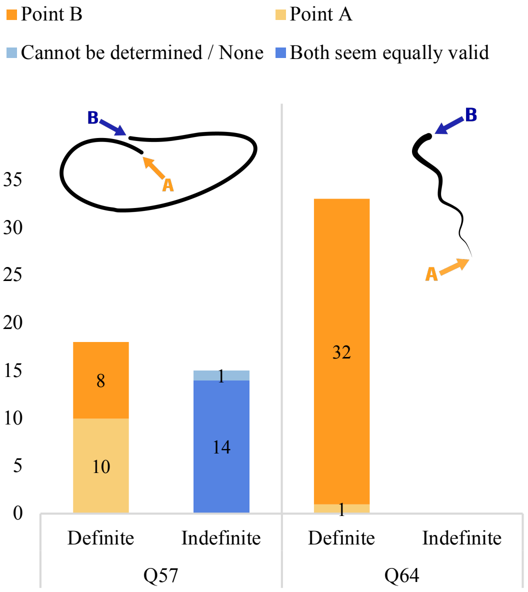
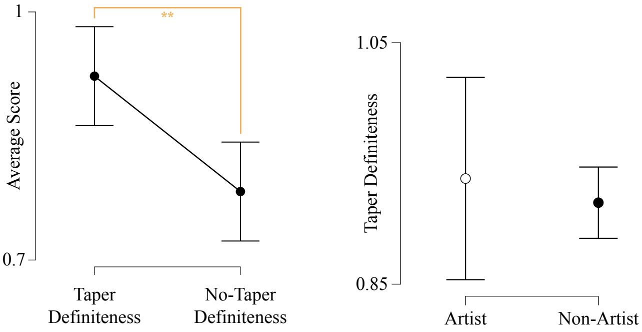


Figure 10: Response distributions for Q57 (uniform-width stroke) and Q64 (tapered stroke), grouped into Definite (Point A or B) and Indefinite (Both seem equally valid or Cannot be determined / None) categories. The contrast between Q57 and Q64 illustrates the strong directional cue introduced by tapering, with all 33 participants giving a definite response for the tapered stroke.



(a) Mean definiteness scores for tapered and uniform-width strokes across all participants ($V = 214.0$, $p = .002$, $r = .692$).

(b) Mean definiteness scores for tapered strokes by group ($U = 122.0$, $p = .344$, $r = -.220$).

Figure 11: Timeline perception results. **(a)** Participants responded with significantly greater definiteness to tapered strokes than to uniform-width strokes, supporting H3. **(b)** No significant difference in definiteness was found between Artists and Non-Artists, not supporting H3.a.

Table 3: Linear Regression Coefficients for Drawing Tool Familiarity and Group as Predictors of Thick-End Preference Rate ($M_1$)

| Predictor | Unstandardised | SE | Standardized[a] | $t$ | $p$ |
|---|---|---|---|---|---|
| Pen | 0.042 | 0.034 | 0.343 | 1.229 | .230 |
| Brush | −0.031 | 0.045 | −0.191 | −0.697 | .492 |
| Pencil | 0.005 | 0.038 | 0.037 | 0.134 | .895 |
| Digital | −0.046 | 0.038 | −0.289 | −1.214 | .236 |
| Other | −0.073 | 0.041 | −0.397 | −1.788 | .085 |
| Group (Artist) | −0.002 | 0.078 | — | −0.030 | .976 |

[a] Standardized coefficients are not computed for categorical predictors.

and uniform widths alike, within the boundaries of their shape. Following the statistical analyses, we show that such an implementation is closely aligned with participants' perceived orientation, as supported by H2 analyses, yielding greater benefits than the temporal-based model of Chen et al. [CKF23]. This parameter was motivated by the limitations of bounding-box and oriented bounding-box approaches commonly used in discrete pattern extension pipelines, where directionality is typically approximated at the cost of introducing clustering artefacts and unnecessary object overlap. The PCA-based parameter instead computes orientation within the stroke's bounds, while remaining consistent with human perception. While a significant difference between PCA and the intended responses remains in H2.b, the questionnaire's multiple-choice format may partly explain this gap, as intended responses were constrained to discrete angle options, whereas the orientation methods produce continuous values. Besides our main contribution, we also provide evidence on the effects of tapering on depth and inferred timeline through H1 and H3 hypotheses.

The absence of a significant difference in depth perception between artists and non-artists was unexpected, as was the lack of improvement when strokes were presented within object context (H1.b). These results prompted a closer examination of the responses, participants' confidence in their answers, and their comments. Overall confidence scores for the depth task were similar across artists ($M = 2.875$, $SD = .876$) and non-artists ($M = 2.920$, $SD = .943$), suggesting participants did not find the task particularly difficult on average. An interesting observation from H1.c—though insignificant due to artists being the minority—was the poor performance of artists in both contexts, with a notably larger standard deviation than non-artists, suggesting that greater domain knowledge may have introduced uncertainty rather than aiding performance. Their comments offered a possible explanation: due to their training, artists did not interpret tapering as a depth cue unless it was implemented correctly in context. This prior mastery likely contributed to greater mismatches between artists' responses and the intended answers. As for non-artists, a single isolated stroke is likely a weak depth cue, and a richer pictorial context may be required to convey reliable depth perception.

Through the H3 analyses, we provide evidence that tapered strokes play an important role in understanding perceptions of drawing timeline, regardless of people's artistic expertise. Participants reliably associated tapered strokes with definite start or end points, as opposed to untapered strokes. The consistent pattern of responses regarding timeline associations provides an exciting avenue of work. Namely, rasterised sketches, within the applications of vectorisation and the temporal disentanglement of raster paths, can benefit significantly from such an implementation. In the current study, we did not capture sufficient data to fully examine the impact of tool usage on artists' preference for the thicker or thinner end of a tapered stroke as the start point, and the heterogeneity of tools used further obscured any meaningful pattern. The small artist sample also limited statistical power for between-group comparisons, making H3.b difficult to evaluate conclusively.

## 7. Conclusion & Future Work

In this work, we proposed a PCA-based orientation parameter that covers both simple and complex strokes, inherently accounting for stroke weight variation. Through a user study, we provided evidence that our parameter is closely aligned with human perception, increasing its usability for perceptually-based sketch generation and analysis. We further highlighted the importance of focusing on tapered strokes in the field by providing evidence for hypotheses surrounding the perceived timeline of strokes amongst artists and non-artist viewers. As the field grows, tapered strokes deserve the same attention as uniform lineart, and recognising their perceptual richness is a necessary step towards more complete sketch analysis and generation systems.

For future work, a more detailed analysis of subjective perceptual attributes—such as depth in this study—could yield interesting findings, especially with more balanced participant groups to enable targeted comparisons. Recruiting a larger, more homogeneous artist sample with controlled tool experience—e.g., allowing participants to draw their perceived orientation or highlight depth cues—can also provide more insight into the impact of tools on timeline perception, thereby solidifying the relationship between taper and drawing timeline. Furthermore, exploring additional factors such as handedness (right- or left-handed), the text directionality of the primary language, and the inclusion of less intuitive characteristics like 'flow' or 'emotion' in place of depth could yield interesting insights into how strokes are perceived and how different levels of artistry perceive them.

To support open science and reproducibility, the anonymised study data, used stimuli, and pre-processing scripts will be made available on The University of Manchester Figshare repository upon publication.

## References

[BBT*06] Barla, Pascal, Breslav, Simon, Thollot, Joëlle, et al. “Stroke pattern analysis and synthesis”. *Computer Graphics Forum*. Vol. 25. 3. Wiley Online Library. 2006, 663–671 3.

[BWCS14] Benedetti, Luca, Winnemöller, Holger, Corsini, Massimiliano, and Scopigno, Roberto. “Painting with Bob: assisted creativity for novices”. *Proceedings of the 27th annual ACM symposium on User interface software and technology*. 2014, 419–428 2.

[CGL*08] Cole, Forrester, Golovinskiy, Aleksey, Limpaecher, Alex, et al. “Where do people draw lines?”: *ACM SIGGRAPH 2008 papers*. 2008, 1–11 3.

[CGL*24] Ciao, Shen, Guan, Zhongyue, Liu, Qianxi, et al. “Ciallo: GPU-Accelerated Rendering of Vector Brush Strokes”. *Special Interest Group on Computer Graphics and Interactive Techniques Conference Conference Papers* (July 2024), 1–11. doi: `https://doi.org/10.1145/3641519.3657418` 2, 3.

[CKF23] Chen, Yilan, Kwan, Kin Chung, and Fu, Hongbo. “Autocompletion of repetitive stroking with image guidance”. *Computational Visual Media* 9.3 (2023), 581–596 2, 4, 6–8.

[Cli23] Clip Studio Tips. *How to Use Line Weight in Your Art*. Accessed: 2024. 2023 2.

[CWS*10] Chatterjee, Anjan, Widick, Page, Sternschein, Rebecca, et al. “The Assessment of Art Attributes”. *Empirical Studies of the Arts* 28.2 (2010), 207–222. doi: `10.2190/EM.28.2.f`. eprint: `https://doi.org/10.2190/EM.28.2.f` 2, 3, 5.

[dPWS10] Dos Passos, Vladimir Alves, Walter, Marcelo, and Sousa, Mario Costa. “Sample-based synthesis of illustrative patterns”. *2010 18th Pacific Conference on Computer Graphics and Applications*. IEEE. 2010, 109–116 3.

[EMT14] Ejiri, Takashi, Morimoto, Yuki, and Takahashi, Tokiichiro. “Shading approach for artistic stroke thickness using 2D light position”. *ACM SIGGRAPH 2014 Posters* (July 2014), 1–1. doi: `https://doi.org/10.1145/2614217.2614259` 3.

[GTDS10] Grabli, Stéphane, Turquin, Emmanuel, Durand, Frédo, and Sillion, François X. “Programmable rendering of line drawing from 3d scenes”. *ACM Transactions on Graphics (TOG)* 29.2 (2010), 1–20 3.

[GVH07] Goodwin, Todd, Vollick, Ian, and Hertzmann, Aaron. “Isophote distance”. *Proceedings of the 5th international symposium on Non-photorealistic animation and rendering* (Aug. 2007), 53–62. doi: `https://doi.org/10.1145/1274871.1274880` 2, 3.

[HR08] Howard, Ian P. and Rogers, Brian J. *Seeing in Depth: Volume 1: Basic Mechanics/ Volume 2: Depth Perception 2-Volume Set*. Oxford University Press, Feb. 2008. isbn: 9780195367607. doi: `10.1093/acprof:oso/9780195367607.001.0001` 2.

[HSZ23] Haoran, Xu, Shuyao, Chen, and Zhang, Ying. “Magical brush: A symbol-based modern chinese painting system for novices”. *Proceedings of the 2023 CHI conference on human factors in computing systems*. 2023, 1–14 2.

[JAS25] JASP Team. *JASP (Version 0.95.4)[Computer software]*. 2025 5.

[Jol86] Jolliffe, Ian T. “Principal components in regression analysis”. *Principal component analysis*. Springer, 1986, 129–155 3.

[LB25] Liu, Chenxi and Bessmeltsev, Mikhail. “State-of-the-art Report in Sketch Processing”. *Computer Graphics Forum* 44.2 (2025), e70079 2.

[LBW*14] Lu, Jingwan, Barnes, Connelly, Wan, Connie, et al. “Decobrush: Drawing structured decorative patterns by example”. *ACM Transactions on Graphics (TOG)* 33.4 (2014), 1–9 3.

[LFHK21] Liu, Difan, Fisher, Matthew, Hertzmann, Aaron, and Kalogerakis, Evangelos. “Neural strokes: Stylized line drawing of 3d shapes”. *Proceedings of the IEEE/CVF International Conference on Computer Vision*. 2021, 14204–14213 2, 3.

[LGH13] Landes, Pierre-Edouard, Galerne, Bruno, and Hurtut, Thomas. “A shape-aware model for discrete texture synthesis”. *Computer Graphics Forum*. Vol. 32. 4. Wiley Online Library. 2013, 67–76 2, 3.

[LH25] Lee, Yun-Chen and Hou, June-Hao. “Generative Tonal Art: An Artistic Rendering Workflow using Programmable TAMs”. *Proceedings of the SIGGRAPH Asia 2025 Posters*. 2025, 1–3 3.

[LRS18] Liu, Chenxi, Rosales, Enrique, and Sheffer, Alla. “StrokeAggregator”. *ACM Transactions on Graphics* 37.4 (July 2018), 1–15. doi: `https://doi.org/10.1145/3197517.3201314` 3.

[LYFD12] Lu, Jingwan, Yu, Fisher, Finkelstein, Adam, and DiVerdi, Stephen. “HelpingHand”. *ACM Transactions on Graphics* 31.4 (July 2012), 1–10. doi: `https://doi.org/10.1145/2185520.2185542` 3.

[OKS12] Ostrofsky, Justin, Kozbelt, Aaron, and Seidel, Angelika. “Perceptual constancies and visual selection as predictors of realistic drawing skill.” *Psychology of Aesthetics, Creativity, and the Arts* 6.2 (May 2012), 124–136. doi: `https://doi.org/10.1037/a0026384` 3.

[OMC22] Olivier, Pauline, Memari, Pooran, and Cani, Marie-Paule. “Structured shape-patterns from a sketch: A multi-scale approach”. *Graphics Interface 2022*. 2022 3.

[SKCN07] Saito, Suguru, Kani, Akane, Chang, Youngha, and Nakajima, Masayuki. “Curvature-based stroke rendering”. *The Visual Computer* 24.1 (Aug. 2007), 1–11. doi: `https://doi.org/10.1007/s00371-007-0165-0` 3.

[VLV*21] Van Mossel, Dave Pagurek, Liu, Chenxi, Vining, Nicholas, et al. “StrokeStrip”. *ACM Transactions on Graphics* 40.4 (July 2021), 1–18. doi: `https://doi.org/10.1145/3450626.3459777` 3.

[WdGF*23] Willett, Nora S, de Goes, Fernando, Fleischer, Kurt, et al. “Stylizing ribbons: Computing surface contours with temporally coherent orientations”. *IEEE Transactions on Visualization and Computer Graphics* 30.8 (2023), 5623–5634 3.

[XCW14] Xing, Jun, Chen, Hsiang-Ting, and Wei, Li-Yi. “Autocomplete painting repetitions”. *ACM Transactions on Graphics (TOG)* 33.6 (2014), 1–11 2.

[YLL*22] Yin, Jerry, Liu, Chenxi, Lin, Rebecca, et al. “Detecting viewer-perceived intended vector sketch connectivity”. *ACM Transactions on Graphics* 41.4 (July 2022), 1–11. doi: `https://doi.org/10.1145/3528223.3530097` 3.

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