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A dot that went for a walk: People prefer lines drawn with human-like kinematics

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A dominant theory of embodied aesthetic experience (Freedberg & Gallese, 2007, *Trends in Cognitive Sciences*, 11, 197) posits that the appreciation of visual art is linked to the artist's movements when creating the artwork, yet a direct link between the kinematics of drawing *actions* and the aesthetics of drawing *outcomes* has not been experimentally demonstrated. Across four experiments, we measured aesthetic responses of students from arts and non-arts backgrounds to drawing movements generated from computational models of human writing. Experiment 1 demonstrated that human-like drawing movements with bell-shaped velocity profiles (Sigma Lognormal [SL] and Minimum Jerk [MJ]) are perceived as more natural and pleasant than movements with a uniform profile, and in both Experiments 1 and 2 movements that were perceived as more natural were also preferred. Experiment 3 showed that this effect persists if lower-level dynamic stimulus features are fully matched across experimental and control conditions. Furthermore, aesthetic preference for human-like movements were associated with greater perceptual fluency in Experiment 3, evidenced by unbiased estimations of the duration of natural movements. In Experiment 4, line drawings with visual features consistent with the dynamics of natural, human-like movements were preferred, but only by art students. Our findings directly link the aesthetics of human action to the visual aesthetics of drawings, but highlight the importance of incorporating artistic expertise into embodied accounts of aesthetic experience.

Embodied accounts of aesthetic experience posit that sensorimotor processing contributes to the appreciation of visual art (Freedberg & Gallese, 2007). To provide an oft-cited example, the aesthetic appeal of abstract expressionist works by Jackson Pollock is related to the spraying and dripping actions by which his paintings were created (Freedberg & Gallese, 2007). According to this view, 'Action painting' (Rosenberg, 1952) is beautiful not just because of its visual content or spatial composition, but because it vividly conveys the effort and dynamics of the actions that the artists performed in making the artwork.

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Indeed, studies have shown that visible brushstrokes contribute to visual art appreciation. Priming people with specific movements, such as dabbing or stroking, increases liking for images that were created using the same movements (Leder, Bär, & Topolinski, 2012; Taylor, Witt, & Grimaldi, 2012; Ticini, Rachman, Pelletier, & Dubal, 2014). While these studies show that a painting's aesthetic appeal depends on engaging with the visible traces of its creation, they do not show that the drawing movement itself carries aesthetic value. Yet, if aesthetic appreciation of static visual art is linked to the aesthetics of action perception, then some drawing movements should be more aesthetically pleasing than others. In a related study, Humphries, Rick, Weintraub, and Chatterjee (2021) have recently shown that the perception of motion in abstract art is reduced in Parkinson patients compared to controls, suggesting that impaired motor abilities can have a direct consequence for the aesthetic evaluation of static visual art that implies motion. In this study, across four experiments, we show that the aesthetic responses to line drawings are indeed related to the perceived naturalness of the drawing movements.

Kinematics are an important predictor of the aesthetic appreciation of dance movements. Spectators without dance experience prefer dance movements that comply with the biomechanical constraints of the human body (Cross et al., 2016) and dance moves with salient, yet predictable changes in speed and acceleration (Orlandi, Cross, & Orgs, 2020). People also prefer familiar movements that they have learnt to perform themselves (Kirsch, Dawson, & Cross, 2015; Kirsch, Drommelschmidt, & Cross, 2013). Importantly, all human actions exhibit a symmetric, bell-shaped velocity profile (Lacquaniti, Terzuolo, & Viviani, 1983) and an inverse relationship between the curvature of a movement trajectory and movement speed; movements with curved trajectories are performed slower than movements with a straight trajectory. This relationship between movement curvature and speed of the movement is mathematically formulated in the minimum jerk model (Flash & Hogan, 1985; Viviani & Flash, 1995), and more recently the sigma-lognormal model (Plamondon, 1995). Movements with such natural, human-like velocity profiles are not just easier to perform (de'Sperati & Viviani, 1997) but are also easier to perceive (Bidet-Ildei, Orliaguet, Sokolov, & Pavlova, 2006; Meary, Chary, Palluel-Germain, & Orliaguet, 2005). Movement with this velocity profile also signal animacy (Troje & Westhoff, 2006) and intentionality (Pelphrey, Morris, & Mccarthy, 2004).

Kinematics do not just constrain action perception and execution, but also neural representations of action; Such representations contain information about *which* movement is being performed (goals) and also about *how* these movements are performed (Grafton & Hamilton, 2007). Watching movements with natural movement kinematics leads to more accurate predictions of the movement outcome and movement duration (Moscatelli, Polito, & Lacquaniti, 2011; Wang & Jiang, 2012). For example, Stadler, Springer, Parkinson, and Prinz (2012) showed that the time course of a temporarily occluded action is more accurately predicted when the action is performed with feasible movement kinematics, compared to actions whose kinematics have been altered to move according to a non-human, constant velocity profile. Combining apparent biological motion with a temporal bisection paradigm, Orgs, Kirsch, and Haggard (2013) showed that the sensitivity of detecting duration differences between two sequences of visual body postures depends on the saliency of natural movement speed, rather than the saliency of objective duration differences. These studies show that time perception can be used as an indirect measure of the *accuracy* of action representations. The duration of actions with natural kinematics are more accurately estimated than those of actions without natural human movement kinematics.

Natural movements can also be identified from their static outcomes. In support, it has been shown that observers can discriminate between static drawings made by robotic agents and humans differing only in subtle kinematic cues (De Preester & Tsakiris, 2014). In this context, natural, human-like movements are processed more fluently and should therefore be preferred (Reber, Schwarz, & Winkielman, 2004; Topolinski, 2010). However, no research work to date has demonstrated if and how natural kinematics of movement impact on the aesthetic experience of visual art.

In the present studies, we artificially generated complex line drawing trajectories, designed to resemble graffiti tags. An essential characteristic of graffiti, and the tag in particular, is the mastering of very rapid and fluid drawing movements (Berio & Leymarie, 2015; Berio, Calinon, & Leymarie, 2017; Wacławek, 2011). Importantly, fluency of the underlying kinematics function as indicators of the aesthetic quality of a tag (Berio et al., 2017). Graffiti art is ideally suited for studying the link between movement naturalness and drawing aesthetics, as it permits the modelling of artistic movements using existing computational models for human writing and drawing (Flash & Hogan, 1985; Plamondon, 1995). Whilst modelled on graffiti tags, the stimuli used in our experiments are highly abstracted, and are therefore able to represent fluent drawing movements more generally.

Across four experiments, we explored the role of movement naturalness for drawing aesthetics. In Experiments 1 and 2, we explored whether observers without any drawing expertise take into account the kinematics of drawing movements when making preference and naturalness judgements. We compared drawing actions generated from two computational models of writing behaviour against a uniform velocity model and show that observers prefer computer-generated drawing movements that exhibit natural movement kinematics. In Experiment 3, we used time perception as an indirect measure of movement naturalness, and show that preferring natural drawing movements is linked to more accurate duration estimation of the same drawing movements. In Experiment 4, we show that the preference for natural movement dynamics extends to the static visual outcomes of natural, human-like movements, but only for observers with artistic expertise.

EXPERIMENT 1. WITHIN-SUBJECTS ANALYSIS OF PERCEIVED NATURALNESS AND PLEASANTNESS OF SIGMA LOGNORMAL (SL), MINIMUM JERK (MJ), AND UNIFORM MODELS OF MOVEMENT

In the first experiment, we compared three computational models of drawing movements in relation to perceived naturalness and aesthetic value. First, we implemented two biologically plausible models of motor control to computationally generate natural, human-like drawing movements: The MJ model (Flash & Hogan, 1985), which defines movement selection as a process of cost minimization, in which the squared magnitude of jerk (i.e., the first derivative of acceleration) is minimized. In contrast, the SL model (Plamondon, 1995), computes complex hand motions from goal directed movement primitives, each characterized by an asymmetric 'bell shaped' speed profile. Both models successfully capture the kinematics of drawing and writing (Edelman & Flash, 1987; Plamondon, O'Reilly, Rémi, & Duval, 2013; Viviani & Schneider, 1991). Second, to generate unnatural drawing movements, we employed a uniform model characterized by no changes in velocity across the movement trajectory.

We predicted that drawing movements complying with either MJ or SL velocity profiles would be perceived as more natural and aesthetically pleasing than drawing movements with a uniform velocity profile. We also predicted that how natural the movements seemed to observers would predict how aesthetically pleasing they were. Following Experiment 1, we ran a second experiment with a between-subject design in which observers rated *either* aesthetic appeal *or* perceived movement naturalness, to check whether participants explicitly linked naturalness and aesthetics in the within-subject design of Experiment 1.

Method

Design

Experiment 1 used a within subject design, with computation model for drawing actions as the within-subject factor with three levels: SL, MJ, and uniform velocity model. We conducted linear mixed-effects models (LMEMs) using the package lme4 in R (Bates, Mächler, Bolker, & Walker, 2015) to assess the effect of movement model on aesthetic value and naturalness. As fixed effects, we added movement model, with the uniform model as the reference level. As random effects, we added intercepts of subject and video, as well as by-subject effects of movement model, following guidance on maximal random effects structure justified by design (Barr, 2013). All participants rated drawing actions for movement pleasantness (Block 1) and naturalness (Block 2). For all participants, we collected pleasantness before naturalness ratings to exclude the possibility that participants would explicitly use naturalness as an indication of aesthetic quality. In the final block of the experiment, half of all participants rated drawing outcomes for pleasantness, the other rated drawing outcomes for perceived meaningfulness (Block 3), to control for the influence of shape specific preferences and potential resemblance of specific shapes to meaningful objects or letters, such as a star or the letter 'B'. An overview of the task structure in Experiment 1 can be found in Figure 1 (top panel).

Power analyses

Sample size calculations for all experiments were based on power of .8 and alpha .05, using the 'pwr' and 'pwr2' packages for R (Champely, 2018; Pengcheng et al., 2017). On the basis of existing empirical research that required participants to perceptually discriminate between drawings of natural and non-natural origin (De Preester & Tsakiris, 2014), we estimated an effect size of $\eta_p^2 = .17$ (Cohen's $f = .45$) for within-subjects ANOVAs of perceived naturalness and aesthetic rating across different movement models ($n = 3$), which indicated a minimum sample size of 17 participants. This calculation also formed the basis of our participant recruitment for all within (Experiments 1 and 3) between-subjects designs (Experiments 2 and 4).[5]

Participants

Participants were recruited voluntarily from within the student population at Goldsmiths, University of London ($n = 40$; 19F; $M_{age} = 24.21$, $SD_{age} = 9.02$), All experimental procedures were approved by the ethics committee at Goldsmiths, University of London.

[5] *Note that power calculations were performed on the assumption of performing ANOVA analyses across all experiments. At the suggestion of one of the reviewers we reran analysis using linear mixed effects modelling.*

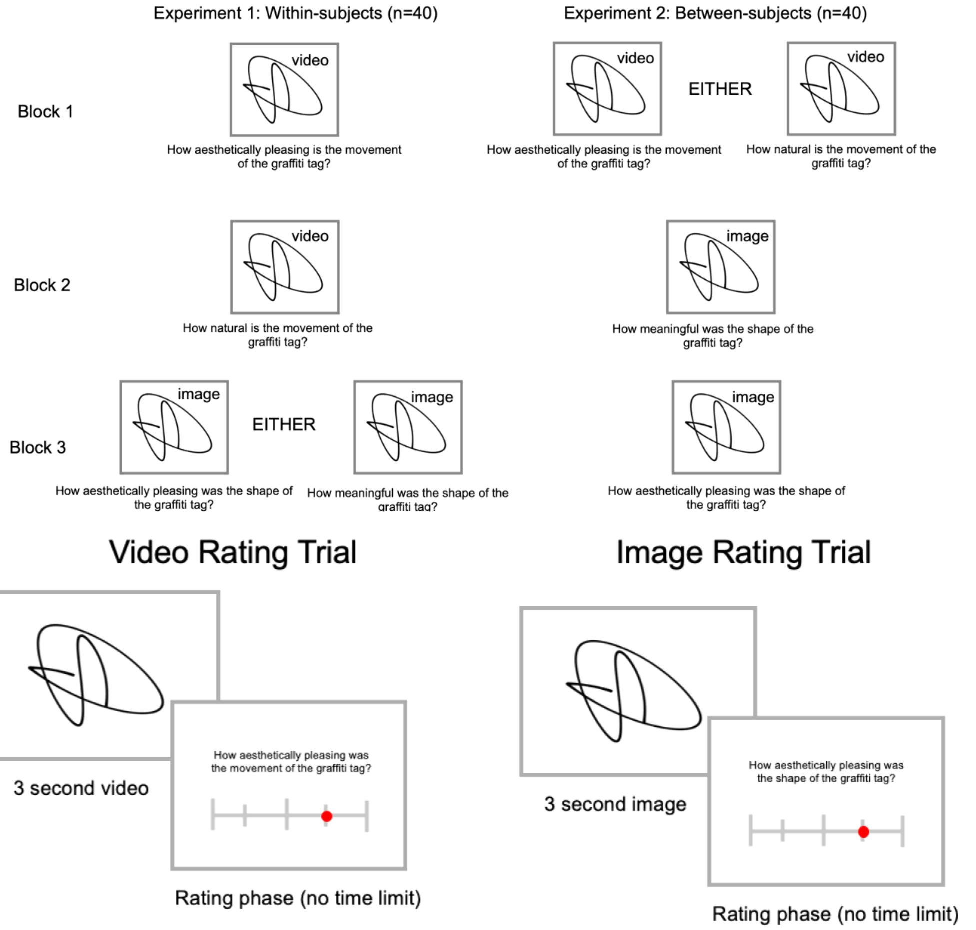

Figure 1. Overview of task order in Experiment 1 (top left) and Experiment 2 (top right) and individual trial structure (bottom).

Stimuli

The stimuli were 3 s video clips of abstract, stylized, planar curvatures simulating the motion paths embodied in the creation of graffiti tag-like forms. The computer-generated trajectories were deliberately designed so as not to resemble letter forms in order to avoid linguistic processing. 180 videos were generated in total, 60 for each model movement models (Figure 2; for detailed information on the models, see Berio et al. (2017; 2018)). The stimuli for all experiments can be accessed at osf.io/h9njb.

For each video clip, we also created one image of the final drawing outcome by taking the last frame of each video clip. 120 static images were created (SL [$n = 60$]; MJ [$n = 60$]). The uniform model was not used to generate static images as these would have been exact replications of the SL images. Due to the constraints of the modelling process, the final frame images of the sigma-lognormal ($n = 30$) and MJ ($n = 30$) differed slightly, but these differences were not discriminable at the level of aesthetic value, $t(59) = 0.88$, $p = .38$, $d = .12$, 95% CI of difference [−0.05, 0.13], or image meaningfulness, $t(59) = 1.10$, $p = .28$, $d = .14$, 95% CI of difference [−0.05, 0.19].

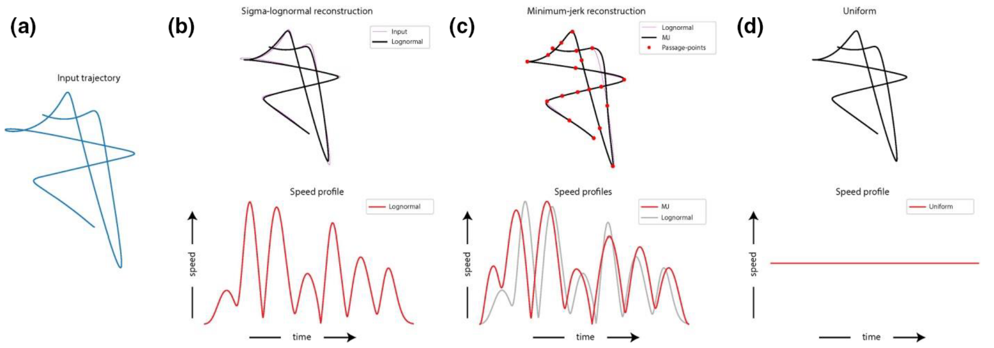

Figure 2. Stimuli generation approach. (a) Initial trajectory randomly generated with the method described in Berio et al. (2017). (b) Sigma-lognormal reconstruction of the input trace using the method described in Berio, Fol Leymarie, and Plamondon (2018). (c) Reconstruction of the Sigma-lognormal trajectory using the MJ. This is done according to the method described by Todorov and Jordan (1998) by selecting a series of passage points (in red) along the trace of the Sigma-Lognormal trajectory. (d) Uniform trajectory, generated by sampling the Sigma-lognormal trajectory at equi-distant time steps, which results in a motion with constant speed. Below each stimulus, the corresponding speed profile (in red).

Procedure

The experimental tasks were run using PsychoPy (Peirce, 2007) on a 13" MacBook Air. Participants were instructed to watch a series of videos and images of drawing movements and to then make judgements about their naturalness and aesthetic value. Participants were not informed that the drawing movements were computer-generated. Image/video order was randomized within blocks, and ratings were taken after each trial (Figure 1: bottom panel). The experimental session lasted between 30–45 min. In the first block, participants were asked to view each 3 s drawing movement video (n = 180). After each video, participants rated how pleasant they found the movement of the drawing movement in the video on a Likert scale (1 = Not all pleasing; 7 = Very pleasing). In the second block, participants watched the same videos as in the first block, but this time rated naturalness of the drawing movement in the video on a Likert scale (1 = Not at all natural; 7 = Very natural). In the third block, participants were presented with the last static frame of each drawing video for 3 s (n = 120). After image presentation, half of participants rated the static images for meaningfulness on a Likert scale (1 = Not at all meaningful; 7 = Very meaningful) to assess the drawing's resemblance to a recognizable letter or object. The other half of participants rated the images for pleasantness on a Likert scale (1 = Not all pleasing; 7 = Very pleasing).

Results

All data were checked for influential outliers prior to performing the analysis. No participants were excluded for failing to adequately employ the rating scales we provided. Table 1 displays the descriptive statistics for pleasantness and naturalness ratings for the three movement models, showing that pleasantness and naturalness ratings are higher for the natural, human-like movement models (the SL and MJ) compared with the uniform model.

Table 1. Descriptive statistics for pleasantness and naturalness ratings of drawing movement videos generated using the SL, Minimum-Jerk, and Uniform Models of movement from the within-subjects' sample in Experiments 1 (n = 40) and 2 (n = 20)

	Naturalness Ratings: Mean (*SD*)		Pleasantness Ratings: Mean (*SD*)	
Model	Expt. 1	Expt. 2	Expt. 1	Expt. 2
SL	3.99 (0.79)	3.92 (0.57)	4.12 (0.83)	3.78 (0.66)
MJ	3.98 (0.82)	4.02 (0.52)	4.09 (0.81)	3.96 (0.60)
Uniform	3.84 (0.81)	3.79 (0.44)	3.97 (0.84)	3.78 (0.69)

We fitted a mixed effects model with pleasantness/naturalness rating ~ movement model + (1|subject) + (1|video) to participants' rating data. Due to high correlations between the random slopes and random intercepts across subjects, we dropped the random slopes from the subject factor (Bates et al., 2015). *p*-values were obtained by likelihood ratio tests of the full model with the effect in question against the model without the effect in question: pleasantness/naturalness rating ~ 1 + (1|subject) + (1| video). Significance was calculated using the lmerTest package (Kuznetsova, Brockhoff, & Christensen, 2017), which applies Satterthwaite's method to estimate degrees of freedom and generates p-values for mixed models.

For pleasantness ratings, the full model was a better fit than the null model without the fixed effect, $\chi^2(2) = 6.83, p = .03$. There was a significant effect of movement model on pleasantness ratings: both the SL and the MJ were perceived as more pleasant than the uniform model (Table 2). The estimates for the random effects are shown in Table 3. For naturalness ratings of the video, the full model was also a better fit than the null model without the fixed effect, $\chi^2(2) = 6.25, p = .04$. There was a significant effect of movement model on pleasantness ratings: both the SL and the MJ were perceived as more natural than the uniform model (Table 2). The estimates for the random effects are shown in Table 3.

Correlation between by-video random intercepts pleasantness and naturalness ratings

We performed correlations between the random intercept values of each video for naturalness and pleasantness ratings to assess whether there was a relationship between how natural the movement in each video looked and how pleasant that movement was perceived to be (Figure 3; right panel). The correlation was $r\,(178) = .53, p < .001$, 95% CI of correlation [0.41, 0.63], with the magnitude of correlations equivalent in sigma-lognormal, r (178) = .53, $p < .001$, 95% CI of correlation [0.32, 0.69], minimum-jerk,

Table 2. Fixed effects of movement model on pleasantness and naturalness ratings

	Predictor	Estimate	*SE*	*t*-value
Pleasantness rating	MJ vs. Uniform	.12	.06	1.96*
	SL vs. Uniform	.15	.06	2.51*
Naturalness rating	MJ vs. Uniform	.14	.07	2.13*
	SL vs. Uniform	.15	.07	2.24*

Note. *denotes $p < 0.05$.

Table 3. Random effects of intercept (subject and stimulus) for the linear mixed effects model of pleasantness and naturalness ratings

	Intercept (Subject)	Intercept (Video)
Pleasantness rating	.63	.06
Naturalness rating	.61	.08

r (178) = .46 $p < .001$, 95% CI of correlation [0.24, 0.64], and uniform, r (178) = .58, $p < .001$, 95% CI of correlation [0.39, 0.73], conditions 4.

Role of static image properties in determining the aesthetic response to drawing movement videos

Perceived meaningfulness of shapes is a strong predictor of aesthetic preference (Martindale, Moore, & Borkum, 1990). Therefore, we included an analysis to account for potential similarity of individual line drawings to specific letters (i.e., 'W') or other meaningful shapes, for example a star. We conducted regression analyses to exclude the possibility that the link between naturalness and pleasantness rating could be accounted for by perceived meaningfulness or a preference for specific shapes, instead of movement naturalness. LMEMs would not have been appropriate here since naturalness and meaningfulness of static shapes were assessed only between and not within individuals. Descriptive statistics for image meaningfulness and pleasantness for the SL and MJ static image stimuli can be seen in Table 4.

We ran a regression of pleasantness rating of the drawing movements on perceived naturalness of the drawing movements, controlling for pleasantness ratings and meaningfulness ratings of the *static* drawing movement outcome. First, a linear regression was performed with pleasantness rating for the videos as the dependent variable, and naturalness ratings for the videos as the independent variable, but only on videos generated using the SL and MJ (as the static images of the uniform model were exactly the

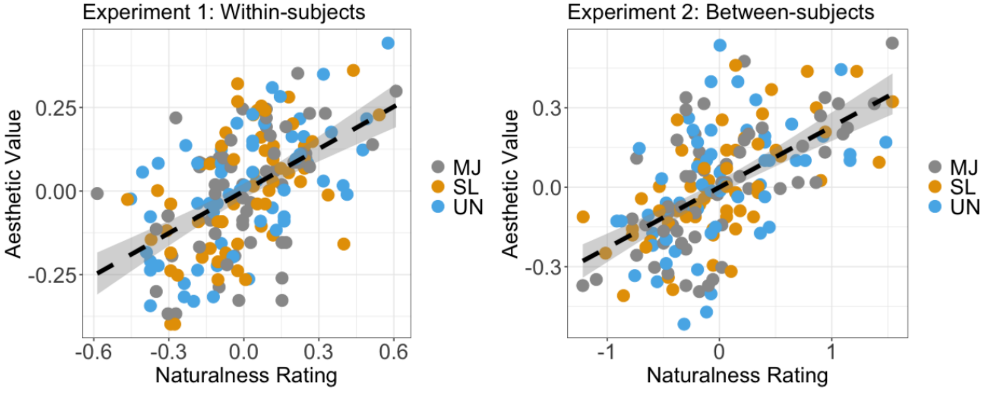

Figure 3. Correlation between by-video random intercepts for naturalness and pleasantness rating of the drawing movement videos (grey shaded area represents 95% CI around regression line) grouped by movement model in Experiment 1 (left panel) and Experiment 2 (right panel). MJ = minimum-jerk; SL = Sigma lognormal; UN = Uniform.

Table 4. Descriptive statistics for image meaningfulness and pleasantness for the static image stimuli in Experiments 1 and 2

	Pleasantness Rating: Mean (*SD*)		Meaningfulness Rating: Mean (*SD*)	
Model	Expt 1	Expt 2	Expt 1	Expt 2
SL	3.41 (1.65)	3.79 (1.79)	3.86 (1.90)	3.97 (1.71)
MJ	3.45 (1.69)	3.80 (1.78)	3.93 (1.96)	4.12 (1.73)

same as the SL). The regression model was significant, and naturalness ratings accounted for 24% of the variance in pleasantness ratings, F (1, 118) = 38.46, $p < .001$, with naturalness a significant predictor of pleasantness rating of the movement, $\beta = .50$, $p < .001$. In a second regression model, meaningfulness ratings and pleasantness ratings for the *static* images of the drawing movements were added to the naturalness ratings of the drawing movements as independent variables. In this model, 26% of the variance in pleasantness ratings was accounted for, F (3, 116) = 15.06, $p < .001$, and naturalness rating was the only significant predictor in the model, $\beta = .38$, $p < .001$, where image meaningfulness, $\beta = .09$, $p = .16$, and image pleasantness rating, $\beta = .14$, $p = .08$, were non-significant predictors. When the two regression models were directly compared, Model 2 (the full model with static image ratings) did not account for significantly more of the variance in pleasantness ratings of the videos than Model 1 (the partial model with only movement naturalness as a predictor), F (2, 116) = 2.79, $p = .07$. Therefore, we show that participants indeed perceive human-like drawing movement as more natural and pleasant. Moreover, for each stimulus, perceived naturalness was correlated with how much participants preferred that specific movement.

Interim discussion

As predicted, the first experiment revealed a link between movement naturalness and drawing aesthetics. Drawing movements generated from natural, human-like computational models of motor control (MJ and SL) were perceived as more natural and more pleasant than drawing movements resulting from a computational model that generated drawing videos with a uniform velocity profile. There was also a significant relationship between perceived naturalness and pleasantness of individual drawing trajectories. We used abstract shapes that would not trigger any specific associations with real objects or letters and our findings confirmed that perceived meaningfulness of specific preferences for certain shapes did not account for the relationship between perceived naturalness and preference for specific drawing movements.

EXPERIMENT 2. BETWEEN-SUBJECTS ANALYSIS OF PERCEIVED NATURALNESS AND PLEASANTNESS OF SL, MJ AND UNIFORM MODELS OF MOVEMENT

Experiment 1 revealed the people prefer drawing movements with a natural, human-like kinematic profile. However, it remains possible that observers explicitly linked movement naturalness and aesthetics due to the within-subjects design (using pleasantness rating in Block 1 as a proxy for naturalness judgements in Block 2), therefore we ran a between-subjects version of the experiment to eliminate this potential confound.

Method

Design

The design of Experiment 2 was the same as in Experiment 1, but used a between-subject design. One half of participants only performed naturalness judgements; the other half only performed pleasantness judgements on the drawing videos. For each group's data, we fitted a linear mixed-effects models to assess the effect of movement model on pleasantness and naturalness judgements, respectively. The final full model specification for both groups was the same as in Experiment 1: pleasantness/naturalness rating ~ movement model + (1|subject) + (1|video).

Participants

Participants were recruited voluntarily from within the student population at Goldsmiths, University of London(n = 40; 34F; $M_{\text{age}} = 23.25$, $SD_{\text{age}} = 3.94$). All participants had no prior formal training in art and design, for power calculations, see Experiment 1.

Stimuli

Stimuli in Experiment 2 were the same set as used in Experiment 1.

Procedure

In the first block, two groups of participants rated the 180 drawing movement videos for *either* pleasantness or naturalness. Participants were asked to view each 3 s drawing movement video (n 180). After each video was finished, the first group of participants rated how pleasant they found the drawing movement in the video on a Likert scale (1 = Not all pleasing; 7 = Very pleasing). The second group of participants rated how natural they found the drawing movement in the video on a Likert scale (1 = Not at all natural; 7 = Very natural). In the second block, all participants viewed the final frame of each of the drawing movements for 3 s ($n = 120$). After the image had disappeared from the screen, they rated how meaningful they found the shape of the drawing on a Likert scale (1 = Not at all meaningful; 7 = Very meaningful), in relation to the stimulus' resemblance to a recognizable letter or object. In the third block, all participants viewed the final frame of each of the drawings for 3 s ($n = 120$). After the image had disappeared from the screen, they rated how pleasant they found the shape of the drawing on a Likert scale (1 = Not all pleasing; 7 = Very pleasing); see also Figure 1 for a description of the procedure in Experiment 2.

Ethics

All experimental procedures were approved by the local ethics committee at Goldsmiths, University of London.

Results

All data were checked for influential outliers prior to performing the analysis. No participants were excluded for failing to adequately employ the rating scales we provided. For pleasantness ratings, the full model was a marginally better fit than the null model without the fixed effect, $\chi^2(2) = 5.27, p = .07$. There was a significant effect of movement model on pleasantness ratings: The MJ model was perceived as more pleasant than the uniform model, but the SL was not (Table 5). The estimates for the random effects are shown in Table 6. For naturalness ratings of the video, the full model was not significantly better fit than the null model without the fixed effect, $\chi^2(2) = 3.24, p = .20$. There was no significant effect of movement model on naturalness ratings (Table 5). The estimates for the random effects are shown in Table 6.

Correlation between pleasantness and naturalness ratings

We performed correlations between the random intercepts of each video for naturalness and pleasantness ratings to assess whether there was a relationship between how natural the movement in each video appeared and how pleasant that movement was perceived to be (Figure 3; right panel). The correlation was r (178) = .53, $p < .001$, 95% CI of correlation [0.41, 0.63], with the magnitude of correlations equivalent in sigma-lognormal, r (178) = .53, $p < .001$, 95% CI of correlation [0.32, 0.69], minimum-jerk, r (178) = .46 $p < .001$, 95% CI of correlation [0.24, 0.64], and uniform, r (178) = .58, $p < .001$, 95% CI of correlation [0.39, 0.73], conditions.

We ran a regression of pleasantness rating of the drawing movements on perceived naturalness of the drawing movements, controlling for pleasantness ratings and meaningfulness ratings of the *static* drawing movement outcome. As in Experiment 1, linear mixed effects models were not appropriate here as the pleasantness and naturalness ratings for each stimulus video were provided in a between-subjects manner. First, a linear regression was performed with pleasantness rating for the videos as the dependent variable, and naturalness ratings for the videos as the independent variable, but only on videos generated using the SL and MJ (as the static images of the uniform model were exactly the same as the SL). The regression model was significant, and naturalness ratings accounted for 40% of the variance in pleasantness ratings, F (1, 118) = 80.22, $p < .001$, with naturalness a significant predictor of pleasantness rating of the movement, $\beta = .42$, $p < .001$. In a second regression model, meaningfulness ratings and pleasantness ratings for the *static* images of the drawing movements were added to the naturalness ratings of the drawing movements as independent variables. In this model, 50% of the variance in pleasantness ratings was accounted for, F (3, 116) = 40.06, $p < .001$, and naturalness rating was a significant predictor in the model, $\beta = .32$, $p < .001$, where image meaningfulness, $\beta = .25, p < .01$ was also a significant predictor, but image pleasantness rating, $\beta = .10, p = .15$, was a non-significant predictor. When the two regression models were directly compared, Model 2 (the full model with static image ratings) accounted for significantly more of the variance in pleasantness ratings of the videos than Model 1 (the partial model with only movement naturalness as a predictor), F (2, 116) = 2.76, $p < .001$.

Table 5. Fixed effects of movement model on pleasantness and naturalness ratings

	Predictor	Estimate	*SE*	*t*-value
Pleasantness rating	MJ vs. Uniform	.18	.09	2.09*
	SL vs. Uniform	.17	.09	1.90
Naturalness rating	MJ vs. Uniform	.23	.13	1.81
	SL vs. Uniform	.13	.13	0.99

Note. *denotes $p < 0.05$.

Table 6. Random effects of intercept (subject and stimulus) for the linear mixed effects model of pleasantness and natural ratings

	Intercept (Subject)	Intercept (Video)
Pleasantness rating	.34	.10
Naturalness rating	.61	.08

Interim discussion

Experiment 2 partly replicates the findings of Experiment 1 using a between-subject design. In Experiment 1, line drawings generated from both the SL and the MJ models were judged as more natural and pleasant than those generated from a uniform velocity model. In Experiment 2, the effect of computational model on perceived naturalness and pleasantness rating was not significant. However, for both experiments a by-stimulus correlational analysis revealed a link between perceived movement naturalness and pleasantness ratings, the magnitude of which was similar across computational models. This statistical relationship held when controlling for perceived meaningfulness (Martindale et al., 1990) and pleasantness rating of the static visual trace, suggesting that the link between pleasantness and movement naturalness is not driven by static properties of the visual trace, but is driven by drawing kinematics. Experiment 2 additionally showed that meaningfulness of the static visual trace is a significant predictor of the aesthetic appreciation of the movement, but is independent from perceived movement naturalness.

Inconsistent findings between Experiments 1 and 2 could be due to three main reasons. Firstly, a smaller sample size in each between-subject condition could have reduced statistical power in Experiment 2, especially for the application of an LMEM. Secondly, performing pleasantness judgements ahead of naturalness judgement may have led participants to explicitly search for differences in perceived naturalness in Experiment 1. Thirdly, the uniform velocity model may not be the optimal baseline model for unnatural movements; it is possible for humans to move with a constant velocity as long as the action is not constrained by gravity or curvature, so constant velocity movements may not have appeared quite unnatural enough to produce robust effects. Moreover, the uniform velocity profile differs from the SL and the MJ model not only with respect to movement naturalness, but this difference is confounded with the overall lack of changes in velocity and acceleration over the course of the movement trajectory. In Experiments 3 and 4, we address these limitations by (1) replicating our findings with new samples of participants including both novices and experts, and (2) using an Inverse Minimum Jerk (IMJ) model as the baseline model and (3) introducing an implicit task to assess movement naturalness that is based on duration estimation.

EXPERIMENT 3. DURATION AND PLEASANTNESS JUDGEMENTS OF DRAWING MOVEMENTS

Experiment 3 tested whether the association between movement dynamics and aesthetic appreciation is related to more accurate representations of duration for movements that have a natural velocity profile (Stadler et al., 2012). We used time perception as an implicit measure of movement naturalness (Orgs, Bestmann, Schuur, & Haggard, 2011; Orgs et al., 2013). To maximize differences in movement naturalness between experimental conditions, while matching drawing videos across conditions for all visual features except their velocity profile, we compared the MJ to the inverse minimum-jerk (IMJ) model (Dayan et al., 2007) rather than a uniform model (Experiments 1 and 2). Natural, human-like MJ movements speed up along straight trajectories and slow down along curved trajectories. Unnatural, IMJ movements speed up along curved trajectories and slow down along straight trajectories, thus maximizing jerk. IMJ movements are thus fully matched for changes in speed and velocity over the course of the drawing action, it is only the relationship between curvature and movement speed that is inverted in IMJ drawing actions. We predict that the duration of drawing movements with a natural movement velocity profile (MJ) will be more accurately estimated than the duration of movements with an inverted, unnatural velocity profile (IMJ) and that MJ movements will be preferred to IMJ movements.

Method

Design

Experiment 3 employed a 2 × 6 within-subject factorial design with movement model (MJ vs. IMJ) and movement/video duration (six levels, equally spaced between 1 and 2 s). For MJ, velocity along trajectories is slowest at the point of maximum curvature, whereas the IMJ follows the opposite relationship, with fastest at the point of maximum curvature. To ascertain participants' sensitivity to duration differences as a function of movement naturalness, we fitted binomial psychophysical curves based on the proportion of 'long' responses in the temporal bisection task for each participant, using the quickpsy package for R (Linares & López-Moliner, 2016). From these we derived the just noticeable difference (JND) and point of subjective equality (PSE) for each participant. The PSE refers to the temporal duration, which is perceptually identical to a reference duration. Fitting psychophysical curves rather than conducting the analyses on % long responses allows us to disambiguate between an effect of movement naturalness on duration discrimination (JND) and an effect of movement naturalness on estimating the objectively accurate duration of the drawing action (PSE). JNDs and PSEs between IMJ and MJ were then compared using t-tests. To compare pleasantness ratings, we conducted a within-subject ANOVA with the factors movement model (MJ vs IMJ) and video duration duration (six levels, equally spaced between 1 and 2 s).

Participants

Participants were recruited voluntarily from within the student population at Goldsmiths, University of London ($n = 32$, 15F, $M_{\text{age}} = 36.69$, $SD_{\text{age}} = 12.58$). All participants had no prior formal training in art and design.

Stimuli

A series of 240 videos were created with six different durations (1,000, 1,200, 1,400, 1,600, 1,800, and 2,000 ms), 20 uniquely shaped drawing movement trajectories, and two movement model conditions (MJ vs. IMJ).

Procedure

All experimental tasks were run using PsychoPy (Peirce, 2007) on a 13" MacBook Air. Participants first performed a temporal bisection task (Kopec & Brody, 2010; Orgs et al., 2011) followed by an pleasantness rating task. The temporal bisection task involves comparing the duration – typically in the range of milliseconds to seconds – of a given drawing video to the duration of all other videos presented throughout the experiment. Participants 'bisect' a set of durations according to whether these durations appear relatively 'short' or 'long' based on a subjective reference duration (Kopec & Brody, 2010; Wearden & Ferrara, 1996). Reference durations can be either presented on each trial, or as is the case in this study, they can be presented at the beginning of the experiment in which they are acquired by participants relatively quickly (Orgs et al., 2011, 2013). In the present experiment, reference durations were acquired during a training phase in which participants established their subjective criterion for short and long durations. At the beginning of each trial a fixation cross appeared with a random duration between 500 and 1,500 ms. This was followed by the video of the drawing movement (duration 1,000–2,000 ms), after which participants performed a button press to indicate whether the video was short ('S') or long ('L') compared to all other videos previously seen. During training only, participants were given feedback on their response accuracy; that is participants should establish a PSE at approximately 1,500 ms with a JND of 200 ms. Each training block consisted of 12 stimuli (one stimulus from each of the six video durations and each of the two experimental conditions). Participants took on average 2.44 ($SD = 1.48$) training blocks to reach a minimum of 80% accuracy. In the main experiment, stimuli from the complete set of drawing movement videos ($n = 240$) were presented in a random sequence, with each video shown only once. Videos were presented in three blocks of 80 videos, with a short break between each block. Trials were identical to those in the training block, except participants were not given trial-by-trial feedback on their performance. After completing the temporal bisection task, participants provided pleasantness ratings for all 240 stimuli. At the beginning of each trial, a fixation cross was presented with a random inter-trial-interval (ITI) between 500 and 1,500 ms. Following the presentation of the video (the image of the drawing movement was no longer onscreen), participants were asked to rate how pleasing they found the drawing movement they had just viewed by making a mouse click on a Likert Scale ranging from 1 (not at all pleasing) to 7 (extremely pleasing).

Results

Data preparation

One participant was excluded from the analysis due to chance performance on the temporal bisection task. Another participant was excluded from all analyses as their performance in both the temporal bisection and the rating task produced significant outliers.[6] In addition, we excluded all trials from the temporal bisection analysis in which the reaction time of participants was greater than two standard deviations above the mean ($M = 0.62$, $SD = 1.39$), resulting in the exclusion of 1.04% trials.

[6] *This participant's just noticeable difference (JND) in the temporal bisection task was more than three times higher than the sample mean. In the rating phase, the participant continuously rated all stimuli at <=2 on the Likert Scale, which also produced outliers in every condition. This led to the conclusion that the participant's data would have a disproportionate influence on the results of the statistical analysis (Cunningham & Wallraven, 2011).*

Temporal bisection task

Participants' mean PSE was below the true mean duration (1,500 ms) in the IMJ condition (M = 1,394.40, SD = 131.06) and slightly above the true mean duration in the MJ condition (M = 1,533.02, SD = 120.56), see Figure 4. There was a significant difference in participants' PSEs in the two conditions, $t\,(29) = 4.86, p < .001$, 95% CI of difference [80.26, 196.97], $d = .89$. Participants' PSEs in the IMJ condition were significantly shorter from the true mean duration, that is IMJ movement appeared to last longer than their objective duration, $t(29) = 4.41, p < .001$, 95% CI of mean [1,345.46, 1,443.34], $d = .81$, but their PSEs in the MJ were not significantly different from the true mean, $t\,(29) = 1.50$, $p = .14$, 95% CI of mean [1488.00, 1578.03], $d = .27$. Participants' JNDs were higher in the IMJ condition (M = 189.14, SD = 57.95) compared to the MJ condition (M = 177.80, SD = 67.77), however this difference was not significant, $t\,(29) = 1.29, p = .21$, 95% CI of difference [−6.62, 29.31], $d = .24$. Participants' reaction times were significantly faster in the MJ condition (M = 0.50, SD = 0.14) compared to the IMJ condition, M = 0.57, SD = 0.14), $t\,(29) = 7.21, p = < .001, d = .51$.

Pleasantness rating task

All rating data were checked for normality and significant outliers prior to performing the analysis. No participants were excluded for failing to adequately employ the rating scales we provided. The analysis of pleasantness ratings revealed a main effect of experimental condition, $F\,(1, 30) = 21.65$, $p < .001$, $\eta_p^2 = .42$, a non-significant effect of duration, $F\,(1.63,\ 48.87) = 1.27$, $p = .29$, $\eta_p^2 = .04$, and a non-significant interaction between

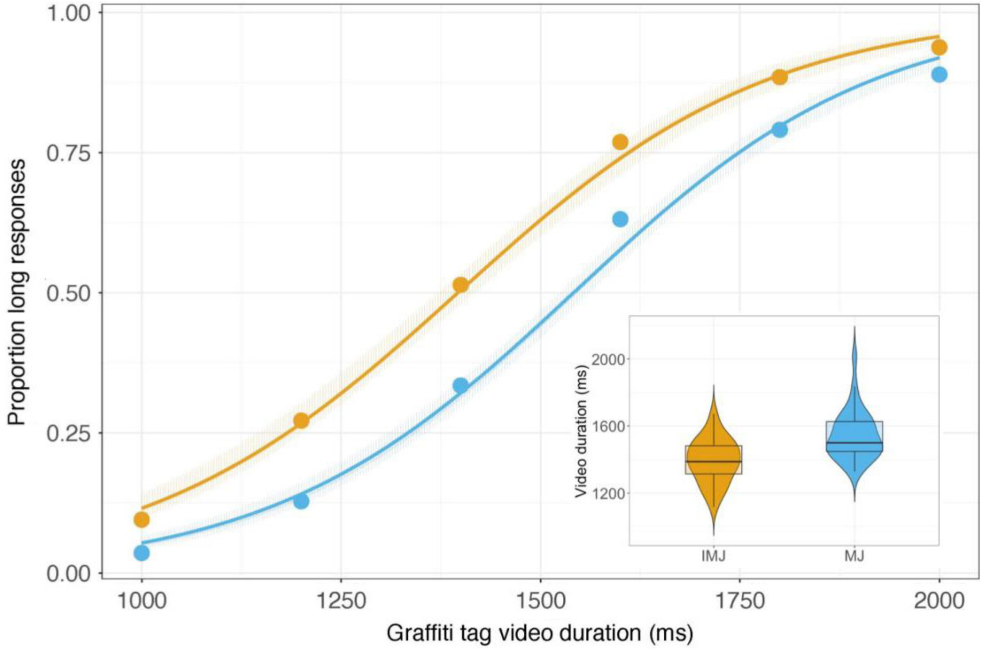

Figure 4. Psychophysical curve with 95% CI for mean proportion long responses across all participants (n = 30) and participant PSEs for IMJ/unnatural and MJ/natural drawing movements (inset panel boxplot and violin plot).

condition and duration, $F\,(3.71,\ 111.27) = 2.16$, $p = .08$, $\eta_p^2 = .07$. Participants found the drawing movements generated using the MJ more pleasant than those generated using the inverse MJ (Figure 5).

Interim discussion

As was the case in Experiment 1 and – partly – in Experiment 2, Experiment 3, replicates the finding that natural drawing movements are preferred to unnatural drawing movements, here movements with an IMJ velocity profile. Natural drawing movements are also associated with more accurate estimations of movement duration, suggesting that seeing natural drawing kinematics leads to more accurate representations of the drawing actions (Stadler et al., 2012): participants' duration estimation of natural drawing movements matched the actual duration of the drawing movement. In contrast, the duration of unnatural drawing movements was overestimated. Importantly, biased duration estimation for unnatural drawing actions were not the result of poorer discriminability of temporal durations in the IMJ condition, as participants' JNDs for the two experimental conditions were not significantly different. Accordingly, participants in our study not only prefer natural movements but also establish a more accurate representation of the duration of these drawing movement. Moreover, biased durations for IMJ drawing actions cannot be explained by differences in visual surface features between the two conditions, as stimuli only differed with respect to the curvature/speed relationship, either minimizing or maximizing movement jerk. Preferences for human-like drawing movements thus occur if the difference between natural and unnatural movements is salient enough, and without any explicit judgements of movement naturalness. Experiments 1 to 3 thus clearly show that people prefer drawing actions that comply with the biological constraints of human movement. Yet the strength of this effect seems to depend on the saliency of movement *un*naturalness, that is it is more robust when natural movements are contrasted with IMJ as compared with uniform velocity

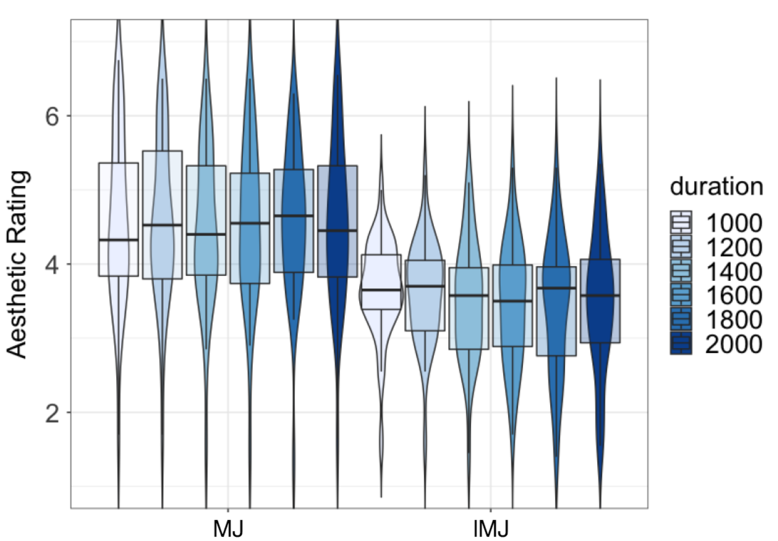

Figure 5. Pleasantness ratings for drawing movements videos with normal and inverted velocity profiles across six durations (ms).

movements. This suggests that drawing expertise could increase sensitivity to the naturalness of drawings actions, as experts may use more subtle cues to detect movement naturalness and make aesthetic judgements compared to novices. This question was explored in Experiment 4 by measuring experts and non-expert aesthetic judgements of static line drawings.

EXPERIMENT 4. PLEASANTNESS JUDGEMENT OF LINE DRAWINGS AND NATURALNESS OF DRAWING MOVEMENTS

Experiments 1–3 focussed on the aesthetics of drawing actions, assessing the pleasantness of drawing movements while controlling for the aesthetics of the static shape of the drawing. In Experiment 4, we investigated whether the preference for natural drawing movements translates to the aesthetics of the line drawing itself, that is when the thickness of the line reveals the naturalness of the drawing movement. When drawing with a pen, faster, straight drawing movements result in thinner lines than slower, curved drawings. We predict that line drawings that exhibit a natural line thickness/curvature relationship will be preferred to line drawings with an unnatural line thickness/curvature relationship. Furthermore, we predicted that experts should be more aesthetically sensitive to these subtle differences in movement outcome, due to their greater experience with performing and perceiving drawing actions.

Method

Design

Experiment 4 used a mixed design with one between-subject (drawing expertise, two levels) and one within subject factor (movement model, two levels MJ vs. IMJ). All analyses were conducted on drawing videos as well as the last frame of each video, that is the final line drawing. We conducted linear mixed-effects models using the package lme4 in R (Bates et al., 2015) on the effect of movement model (MJ/IMJ) and expertise on pleasantness for static images and naturalness for videos. As fixed effects, we added movement model, expertise (artist/non-artist) and their interaction. As random effects, we added intercepts of subject and image/video, as well as by-subject effects of movement model, following guidance on maximal random effects structure justified by design (Barr, 2013). p-values were obtained by likelihood ratio tests of the full model with the effect in question against the model without the effect in question. Finally, to test if there was a stimulus-specific link between the naturalness of the drawing action and preference for the resulting line drawing, we correlated the intercepts of naturalness ratings for each drawing action with the intercepts of pleasantness ratings for each line drawing.

Participants

Participants were recruited voluntarily from within the student population at Goldsmiths, University of London ($n = 61$, 35F; 29 art students (with at least 3 years graduate training in a visual art field); $M_{\text{age}} = 27.33$, $SD_{\text{age}} = 7.04$).

Stimuli

We manipulated characteristics of static drawing movement outcomes to give the impression of MJ and IMJ velocity profiles, using modulations of line thickness to represent changes in velocity (Figure 6). These manipulations of line thickness correspond to the way in which paint or ink accumulates on the surface when the artist performs a drawing movement: faster movements produce thinner lines; the location of areas of line thickness then corresponds to the contrasting velocity profiles of the MJ and IMJ models. We created videos and static outcome images of these drawing movements (n = 80; Figure 6).

Procedure

Participants first aesthetically rated a complete stimulus set of videos. In each trial, a static drawing movement outcome was presented onscreen for 2,000 ms. Following presentation of the image, participants were asked to rate how pleasant they found the image they had just seen by making a mouse click on a Likert Scale ranging from 1 (not at all pleasing) to 7 (very pleasing). In a second block of trials, participants rated the naturalness of the same set of drawing movements seen in block 1, presented as videos. Following the presentation of each video, participants were asked to rate how natural they found the drawing movement they had just viewed by making a mouse click on a Likert Scale ranging from 1 (not at all natural) to 7 (very natural). The order of presentation of the images and videos was fully randomized within blocks. The task order was not counterbalanced across participants, to avoid biasing participants' ratings of the static stimuli by prior judgements of movement naturalness (Orlandi et al., 2020).

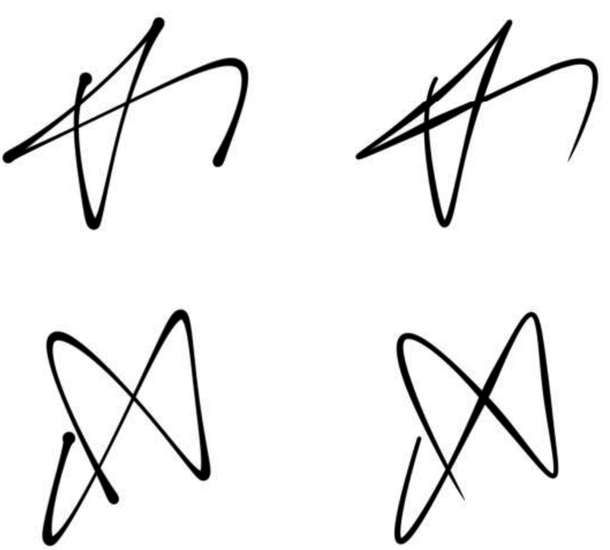

Figure 6. Two examples of line drawings generated with natural, MJ (left column) and unnatural IMJ (right column) movement models. For all stimuli, drawing speed determines line thickness, producing either a natural (MJ) or an unnatural (IMJ) static trace of the drawing action.

Pleasantness rating of line drawings

All rating data were checked for significant outliers prior to performing the analysis. No participants were excluded for failing to adequately employ the rating scales we provided. For pleasantness ratings, the full model was a better fit than the null model without the fixed effect, $\chi^2(3) = 9.42, p = .02$. There was a significant interaction between expertise and movement model (Table 7). As can be seen in Figure 7, artists rated the MJ model generated images higher than the IMJ images, whereas there was no difference between the two models for the non-artist group. For naturalness ratings of the video, the full model was also a better fit than the null model without the fixed effect, $\chi^2(3) = 19.39, p < .001$. The fixed effect of movement model was significant (Table 7). Both groups of participants rated the drawing movements as more natural in the MJ condition (Figure 7). The estimates for the random effects are shown in Table 8.

Data analysis: Correlation between pleasantness ratings of line drawings and naturalness ratings of drawing movements

A correlation revealed a strong link between naturalness of drawing movements and aesthetic appreciation of the static drawing movement outcome, $r\,(78) = .62, p < .001$, 95% CI of correlation coefficient [0.46, 0.74] (Figure 8). The magnitude of the correlation was similar in experts, $r\,(78) = .54$, $p < .001$, 95% CI of correlation coefficient [0.36, 0.68], and non-experts, $r\,(78) = .62$, $p < .001$, 95% CI of correlation coefficient [0.46, 0.74].

Interim discussion

Experiment 4 is consistent with findings from Experiment 1 and 2 in showing that that MJ drawing movements are perceived as more natural than unnatural uniform velocity (Experiments 1) or IMJ (Experiment 3) movements. However, only expert observers take into account the *performed* naturalness of drawing movements when judging the completed line drawings, as evident in a realistic relationship between line thickness and drawing speed. Experts show relatively higher ratings for the MJ movement and relatively lower ratings of the IMJ movements to the non-expert group. However, for both expert and novice observers the pleasantness of specific line drawings correlates with the *perceived* naturalness of the drawing actions that generated these drawings.

Table 7. Fixed effects of expertise and movement model on pleasantness and naturalness ratings

	Predictor	Estimate	*SE*	*t*-value
Pleasantness rating	Expertise	.23	.21	1.09
	Movement model	.23	.13	1.77
	Expertise*Movement model	.27	.11	2.40*
Naturalness rating	Expertise	.05	.20	0.23
	Movement model	.59	.14	4.33**
	Expertise*Movement model	.20	.15	1.35

Note. *denotes $p < 0.05$, **$p < 0.001$.

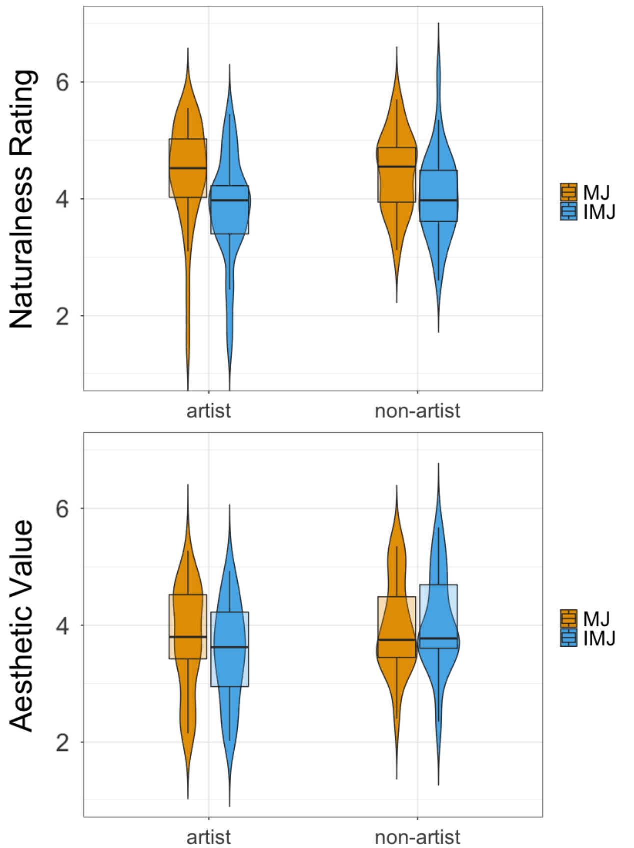

Figure 7. Pleasantness ratings for line drawings (upper panel) and naturalness ratings for drawing movements (lower panel) in Experiment 4.

Table 8. Random effects of intercept (subject and stimulus) and slope (subject) for the linear mixed effects model of pleasantness and natural ratings

	Intercept (Subject)	Intercept (Image/Video)	Slope (Subject)
Pleasantness rating	.81	.44	.33
Naturalness rating	.76	.38	.48

GENERAL DISCUSSION

Embodied accounts of aesthetic experience posit that the appreciation of static visual art, such as painting, graffiti, and drawing depends on the observer simulating the artist's movements. Using computational models of drawing movements, we show that *drawing actions* are preferred if they exhibit a human-like, natural velocity profile. Importantly, this aesthetic value transfers to the aesthetics of the *drawing outcome*. Computer-generated drawing movements and drawings are preferred and represented more precisely if they appear to comply with the kinematics of human writing. However, in contrast with the dominant view of embodied aesthetics (Freedberg & Gallese, 2007), we

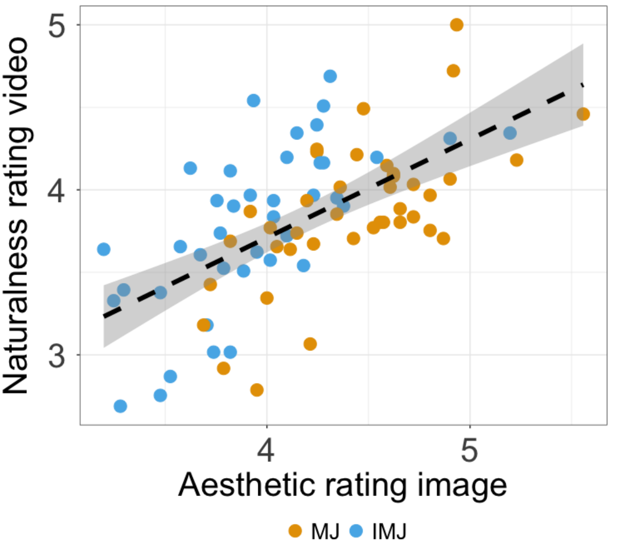

Figure 8. Correlation between pleasantness ratings for line drawings and naturalness ratings for drawing movements for MJ and IMJ stimuli.

show that this link depends (1) on the saliency of movement naturalness between experimental conditions and (2) the observers' artistic expertise; pleasantness judgements are *only* influenced by drawing kinematics to the extent that participants have extensive experience with drawing, and the natural contingency between line thickness and drawing speed. In other words, the importance of action for the aesthetics of static visual art will depend on the observer's expertise with the artist's actions. People who do not paint themselves might judge an 'action painting' by Jackson Pollock purely based on the static visual properties of the painting alone, without automatically relating the visual features of the painting to the artist's actions. However, if the observer knows how to paint, this knowledge will more strongly influence their aesthetic judgment of the painting.

Experiment 1 shows that observers prefer drawing movements generated from two competing models of human motor control (Flash & Hogan, 1985; Plamondon, 1995). Drawing movements resulting from these models were also perceived as more natural than a control model with a uniform velocity profile. However, this result was not replicated in Experiment 2, where the model was not a good fit for the data. Additionally, in Experiments 1 and 2, we found a strong correlation between pleasantness rating of each unique drawing movement stimulus and its perceived naturalness in both within and between-subjects' designs. This finding suggests that *perceived* naturalness may at times be a more powerful cue to aesthetic judgment than *performed* naturalness of movement dynamics, at least for people without artistic expertise and in the presence of subtle movement cues. Similar findings have been found in the domain of perceptual processing fluency and its link to stimulus liking (Reber et al., 2004) as perceived fluency has been found to be a stronger predictor of aesthetic judgements than objectively manipulated fluency (Forster, Leder, & Ansorge, 2013). Across Experiments 1 and 2, the perceived differences between the movement models were very subtle, informing the development of a more appropriate movement control model in Experiments 3 and 4, and the later inclusion of an expert participant sample.

In Experiment 3, we studied whether preference for natural drawing movements is linked to unbiased perception of movement duration. Prior research in action perception has shown actions with human kinematics are perceived and predicted more accurately than non-human actions (Orgs et al., 2013; Stadler et al., 2012). This findings is consistent with processing fluency theory of aesthetic appreciation (Reber et al., 2004) which posits that people prefer stimuli that are more easily recognizable or memorable. By fitting psychophysical curves, we show that fluent processing of natural movements relates specifically to the unbiased perception of objective movement duration (significant effects on the PSE), but not to better discriminability between duration differences (no effect on JND). The preference for natural drawing movements can thus be interpreted as a special case of processing fluency for the social perception of other humans (Pitcher & Ungerleider, 2021). Consistent with this interpretation, participants showed a consistent preference for MJ movements, but no preference for specific movement durations; it does not matter whether the same drawing movements are performed faster or slower, it only matters that drawing movements exhibit a natural relationship between drawing speed and line curvature. Previous studies have shown temporal dilations due to the speed or trajectory of movement, that is faster stimulus motion can produce both longer (Brown, 1995) or shorter perceived durations (Orgs et al., 2011). Importantly however, MJ and IMJ videos in our study did not differ with respect to changes in stimulus speed or acceleration, but only with respect to the relationship between drawing speed and line curvature. Therefore, we argue that the processing advantage for perceiving the correct duration of natural drawing movements is linked to the dedicated psychological and brain mechanisms for perceiving the actions of other people (Dayan et al., 2007).

In Experiment 4, we show that preferences for natural movements extend to preference for their static outcomes in expert participants. This finding qualifies embodied accounts of aesthetics, which posit that the aesthetic appeal of artworks is dependent on the observer's prior experiences with actions depicted through the content or medium. In support, we show that drawing movements that were rated as more natural in their dynamic form, were also preferred in their static form. However, our findings diverge from the dominant account of embodied aesthetics (Freedberg & Gallese, 2007) as they show that prior experience with artistic actions determine whether they inform aesthetic judgements. Only participants with graduate artistic experience showed a preference difference for line drawings generated using MJ in comparison to IMJ, indicating that only expert observers are aesthetically sensitive to the natural contingency between line thickness and drawing speed. This mirrors similar findings in dance aesthetics, where only expert dancers are able to infer emotional expressions from the subtle differences in kinematics of ballet (Christensen, Gomila, Gaigg, Sivarajah, & Calvo-Merino, 2016). In sum, our study shows that actions indeed influence the visual aesthetics of visual art. Such an influence is far from automatic but depends on the saliency of natural kinematic features as well as the observer's familiarity with these features.

Our findings suggest a preference for artworks with kinematics that signal the presence of a human agent. This corroborates the findings of a previous study (Chamberlain, Mullin, Scheerlinck, & Wagemans, 2018), in which observers preferred drawings made by robots that they reported as being more 'human-like'. A similar observation was made by Cross et al. (2016), who found that observers reported videos of actions to be smoother (more natural) and more pleasurable to watch when they had been told that they originated from human motion capture techniques, rather than from computer-generated animation. Here, we show for the first time that bottom-up kinematic properties (as opposed to top-down knowledge/beliefs of the observer) that correspond to human action are sufficient to enhance the aesthetic appeal of the computer-generated drawing in expert observers.

To conclude, across four experiments, we present evidence that the aesthetics of drawings are linked to the aesthetics of drawing actions. In contrast to popular notions of automated simulation of observed actions, we show that these associations are instead developed during the acquisition of expertise and depend on the saliency of human-like movement features. We therefore show that artistic expertise changes the way artists respond to visual stimuli as a function of both their perceptual and sensorimotor experience (Chamberlain et al., 2019). Thus, a complete account of the role of embodiment in visual aesthetics must consider both the process by which artworks are created, the finished artworks and the relevant expertise of the observer performing an aesthetic judgement.

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Author Contribution

Rebecca Chamberlain: Conceptualization (equal); Data curation (equal); Formal analysis (equal); Methodology (equal); Project administration (equal); Resources (equal); Supervision (equal); Validation (equal); Visualization (equal); Writing – original draft (equal); Writing – review & editing (equal). Daniel Berio: Investigation (equal); Methodology (equal); Resources (equal); Software (equal). Veronika Mayer: Formal analysis (equal); Methodology (equal). Kirren Chana: Formal analysis (equal); Methodology (equal). Frederic Fol Leymarie:Software (equal); Supervision (equal); Writing – review & editing (equal). Guido Orgs: Conceptualization (equal); Methodology (equal); Supervision (equal); Writing – original draft (equal); Writing – review & editing (equal).

Conflicts of interest

All authors declare no conflict of interest.

Data Availability Statements

Data available from the lead author on request.

References

Barr, D. J. (2013). Random effects structure for testing interactions in linear mixed-effects models. *Frontiers in Psychology*, *4*, 328. https://doi.org/10.3389/fpsyg.2013.00328

Bates, D., Mächler, M., Bolker, B., & Walker, S. (2015). Fitting linear mixed-effects models using lme4. *Journal of Statistical Software*, *67*(1), 1–48. https://doi.org/10.18637/jss.v067.i01

Berio, D., Calinon, S., & Leymarie, F. F. (2017). Dynamic graffiti stylisation with stochastic optimal control. *Proceedings of the 4th International Conference on Movement Computing*, 18, 1–8.

New York, NY, USA: Association for Computing Machinery. https://doi.org/10.1145/3077981.3078044

Berio, D., Fol Leymarie, F., & Plamondon, R. (2018). Expressive curve editing with the sigma lognormal model. *Proceedings of Eurographics* (pp. 1–4). Eurographics Association. https://doi.org/10.2312/egs.20181038

Berio, D., & Leymarie, F. F. (2015). Computational models for the analysis and synthesis of graffiti tag strokes. *Proceedings of the Workshop on Computational Aesthetics* (pp. 35–47). Eurographics Association. https://dl.acm.org/doi/10.5555/2811239.2811242

Bidet-Ildei, C., Orliaguet, J.-P., Sokolov, A. N., & Pavlova, M. (2006). Perception of elliptic biological motion. *Perception*, *35*, 1137–1147. https://doi.org/10.1068/p5482

Brown, S. W. (1995). Time, change, and motion: The effects of stimulus movement on temporal perception. *Perception and Psychophysics*, *57*, 105–116. https://doi.org/10.3758/BF03211853

Chamberlain, R., Kozbelt, A., Drake, J. E., & Wagemans, J. (2019). Learning to see by learning to draw: A longitudinal analysis of the relationship between representational drawing training and visuospatial skill. *Psychology of Aesthetics, Creativity, and the Arts*, *15*(1), 76–90. https://doi.org/10.1037/aca0000243

Chamberlain, R., Mullin, C., Scheerlinck, B., & Wagemans, J. (2018). Putting the art in artificial: Aesthetic responses to computer-generated art. *Psychology of Aesthetics, Creativity, and the Arts*, *12*(2), 177–192. https://doi.org/10.1037/aca0000136

Champely, S. (2018). *pwr: Basic functions for power analysis (R package version 1.2-2)*. [Computer software]. Retreived from https://CRAN.R-project.org/package=pwr

Christensen, J. F., Gomila, A., Gaigg, S. B., Sivarajah, N., & Calvo-Merino, B. (2016). Dance expertise modulates behavioral and psychophysiological responses to affective body movement. *Journal of Experimental Psychology: Human Perception and Performance*, *42*, 1139–1147. https://doi.org/10.1037/xhp0000176

Cross, E. S., Ramsey, R., Liepelt, R., Prinz, W., de Hamilton, A. F., & Hamilton, A. F. d. C. (2016). The shaping of social perception by stimulus and knowledge cues to human animacy. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *371*, 20150075. https://doi.org/10.1098/rstb.2015.0075

Cunningham, D. W., & Wallraven, C. (2011). *Experimental design: From user studies to psychophysics*. Boca Raton, FL: CRC Press.

Dayan, E., Casile, A., Levit-Binnun, N., Giese, M. A., Hendler, T., & Flash, T. (2007). Neural representations of kinematic laws of motion: Evidence for action-perception coupling. *Proceedings of the National Academy of Sciences of the United States of America*, *104*, 20582–20587. https://doi.org/10.1073/pnas.0710033104

De Preester, H., & Tsakiris, M. (2014). Sensitivity to differences in the motor origin of drawings: From human to robot. *PLoS One*, *9*(7), e102318. https://doi.org/10.1371/journal.pone.0102318

de'Sperati, C., & Viviani, P. (1997). The relationship between curvature and velocity in two-dimensional smooth pursuit eye movements. *Journal of Neuroscience*, *17*, 3932–3945. https://doi.org/10.1523/JNEUROSCI.17-10-03932.1997

Edelman, S., & Flash, T. (1987). A model of handwriting. *Biological Cybernetics*, *57*(1–2), 25–36. https://doi.org/10.1523/JNEUROSCI.17-10-03932.1997

Flash, T., & Hogan, N. (1985). The coordination of arm movements: An experimentally confirmed mathematical model. *Journal of Neuroscience*, *5*, 1688–1703. https://doi.org/10.1523/JNEUROSCI.05-07-01688.1985

Forster, M., Leder, H., & Ansorge, U. (2013). It felt fluent, and I liked it: Subjective feeling of fluency rather than objective fluency determines liking. *Emotion*, *13*(2), 280–289. https://doi.org/10.1037/a0030115

Freedberg, D., & Gallese, V. (2007). Motion, emotion and empathy in esthetic experience. *Trends in Cognitive Sciences*, *11*, 197–203. https://doi.org/10.1016/j.tics.2007.02.003

Grafton, S. T., & de Hamilton, A. F. (2007). Evidence for a distributed hierarchy of action representation in the brain. *Human Movement Science*, *26*, 590–616. https://doi.org/10.1016/j.humov.2007.05.009

Humphries, S., Rick, J., Weintraub, D., & Chatterjee, A. (2021). Movement in aesthetic experiences: What we can learn from Parkinson disease. *Journal of Cognitive Neuroscience*, *33*, 1329–1342. https://doi.org/10.1162/jocn_a_01718

Kirsch, L. P., Dawson, K., & Cross, E. S. (2015). Dance experience sculpts aesthetic perception and related brain circuits: Dance experience, aesthetics, and the brain. *Annals of the New York Academy of Sciences*, *1337*(1), 130–139. https://doi.org/10.1111/nyas.12634

Kirsch, L. P., Drommelschmidt, K. A., & Cross, E. S. (2013). The impact of sensorimotor experience on affective evaluation of dance. *Frontiers in Human Neuroscience*, *7*, 521. https://doi.org/10.3389/fnhum.2013.00521

Kopec, C. D., & Brody, C. D. (2010). Human performance on the temporal bisection task. *Brain and Cognition*, *74*(3), 262–272. https://doi.org/10.1016/j.bandc.2010.08.006

Kuznetsova, A., Brockhoff, P. B., & Christensen, R. H. (2017). lmerTest package: Tests in linear mixed effects models. *Journal of Statistical Software*, *82*(13), 1–26. http://dx.doi.org/10.18637/jss.v082.i13

Lacquaniti, F., Terzuolo, C., & Viviani, P. (1983). The law relating the kinematic and figural aspects of drawing movements. *Acta Psychologica*, *54*(1–3), 115–130. https://doi.org/10.1016/0001-6918(83)90027-6

Leder, H., Bär, S., & Topolinski, S. (2012). Covert painting simulations influence aesthetic appreciation of artworks. *Psychological Science*, *23*(12), 1479–1481. https://doi.org/10.1177/0956797612452866

Linares, D., & López-Moliner, J. (2016). quickpsy: An R package to fit psychometric functions for multiple groups. *The R Journal*, *8*(1), 122–131. https://doi.org/10.32614/RJ-2016-008

Martindale, C., Moore, K., & Borkum, J. (1990). Aesthetic preference: Anomalous findings for berlyne's psychobiological theory. *The American Journal of Psychology*, *103*(1), 53. https://doi.org/10.2307/1423259

Meary, D., Chary, C., Palluel-Germain, R., & Orliaguet, J.-P. (2005). Visual perception of writing and pointing movements. *Perception*, *34*, 1061–1067. https://doi.org/10.1068/p3388

Moscatelli, A., Polito, L., & Lacquaniti, F. (2011). Time perception of action photographs is more precise than that of still photographs. *Experimental Brain Research*, *210*(1), 25–32. https://doi.org/10.1007/s00221-011-2598-y

Orgs, G., Bestmann, S., Schuur, F., & Haggard, P. (2011). From body form to biological motion: The apparent velocity of human movement biases subjective time. *Psychological Science*, *22*(6), 712–717. https://doi.org/10.1177/0956797611406446

Orgs, G., Kirsch, L., & Haggard, P. (2013). Time perception during apparent biological motion reflects subjective speed of movement, not objective rate of visual stimulation. *Experimental Brain Research*, *227*(2), 223–229. https://doi.org/10.1007/s00221-013-3502-8

Orlandi, A., Cross, E. S., & Orgs, G. (2020). Timing is everything: Dance aesthetics depend on the complexity of movement kinematics. *Cognition*, *205*, 104446. https://doi.org/10.1016/j.cognition.2020.104446

Peirce, J. W. (2007). PsychoPy—Psychophysics software in Python. *Journal of Neuroscience Methods*, *162*(1–2), 8–13. https://doi.org/10.1016/j.jneumeth.2006.11.017

Pelphrey, K. A., Morris, J. P., & Mccarthy, G. (2004). Grasping the intentions of others: The perceived intentionality of an action influences activity in the superior temporal sulcus during social perception. *Journal of Cognitive Neuroscience*, *16*, 1706–1716. https://doi.org/10.1162/0898929042947900

Pengcheng, L., Liu, J., & Koestler, D. (2017). *pwr2: Power and sample size analysis for one-way and two-way ANOVA modles (R package version 1.0) [Computer software]*. Retreived from https://CRAN.R-project.org/package=pwr2

Pitcher, D., & Ungerleider, L. (2021). Evidence for a third visual pathway specialized for social perception. *Trends in Cognitive Sciences*, *25*(2), 100–110. https://doi.org/10.1016/j.tics.2020.11.006

Plamondon, R. (1995). A kinematic theory of rapid human movements. *Biological Cybernetics*, *72*, 295–307. https://doi.org/10.1007/BF00202785

Plamondon, R., O'Reilly, C., Rémi, C., & Duval, T. (2013). The lognormal handwriter: Learning, performing, and declining. *Frontiers in Psychology*, *4*, 945. https://doi.org/10.3389/fpsyg.2013.00945

Reber, R., Schwarz, N., & Winkielman, P. (2004). Processing fluency and aesthetic pleasure: Is beauty in the perceiver's processing experience? *Personality and Social Psychology Review*, *8* (4), 364–382. https://doi.org/10.1207/s15327957pspr0804_3

Rosenberg, H. (1952). The American action painters. *Art News*, *51*, 22. https://doi.org/10.12987/9780300185720-026

Stadler, W., Springer, A., Parkinson, J., & Prinz, W. (2012). Movement kinematics affect action prediction: Comparing human to non-human point-light actions. *Psychological Research Psychologische Forschung*, *76*(4), 395–406. https://doi.org/10.1007/s00426-012-0431-2

Taylor, J. E. J., Witt, J. K., & Grimaldi, P. J. (2012). Uncovering the connection between artist and audience: Viewing painted brushstrokes evokes corresponding action representations in the observer. *Cognition*, *125*(1), 26–36. https://doi.org/10.1016/j.cognition.2012.06.012

Ticini, L. F., Rachman, L., Pelletier, J., & Dubal, S. (2014). Enhancing aesthetic appreciation by priming canvases with actions that match the artist's painting style. *Frontiers in Human Neuroscience*, *8*, 391. https://doi.org/10.3389/fnhum.2014.00391

Todorov, E., & Jordan, M. I. (1998). Smoothness maximization along a predefined path accurately predicts the speed profiles of complex arm movements. *Journal of Neurophysiology*, *80*, 696–714. https://doi.org/10.1152/jn.1998.80.2.696

Topolinski, S. (2010). Moving the eye of the beholder: Motor components in vision determine aesthetic preference. *Psychological Science*, *21*, 1220–1224. https://doi.org/10.1177/0956797610378308

Troje, N. F., & Westhoff, C. (2006). The inversion effect in biological motion perception: Evidence for a "Life Detector"? *Current Biology*, *16*(8), 821–824. https://doi.org/10.1016/j.cub.2006.03.022

Viviani, P., & Flash, T. (1995). Minimum-jerk, two-thirds power law, and isochrony: Converging approaches to movement planning. *Journal of Experimental Psychology: Human Perception and Performance*, *21*(1), 32. https://doi/10.1037/0096-1523.21.1.32

Viviani, P., & Schneider, R. (1991). A developmental study of the relationship between geometry and kinematics in drawing movements. *Journal of Experimental Psychology: Human Perception and Performance*, *17*(1), 198. https://doi/10.1037/0096-1523.17.1.198

Wacławek, A. (2011). *Graffiti and street art*. New York, NY, USA: Thames and Hudson.

Wang, L., & Jiang, Y. (2012). Life motion signals lengthen perceived temporal duration. *Proceedings of the National Academy of Sciences of the United States of America*, *109*(11), E673–E677. https://doi.org/10.1073/pnas.1115515109

Wearden, J. H., & Ferrara, A. (1996). Stimulus range effects in temporal bisection by humans. *The Quarterly Journal of Experimental Psychology*, *49*(1), 24–44. https://doi.org/10.1080/713932615

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