Cognition 251 (2024) 105880

Contents lists available at ScienceDirect

Cognition

journal homepage: www.elsevier.com/locate/cognit

Perceptual plausibility of exaggerated realistic motion

Filipp Schmidt [a,b,*], Laura Noejovich [c], George Chakalos [c], Flip Phillips [c,d]

[a] Justus Liebig University Giessen, Germany
[b] Center for Mind, Brain and Behavior (CMBB), Universities of Marburg, Giessen, and Darmstadt, Germany
[c] Skidmore College Neuroscience & Psychology, Saratoga Springs, NY, USA
[d] Rochester Institute of Technology, Rochester, NY, USA

ARTICLE INFO

Keywords:
Motion perception
Material perception
Squash-and-stretch
Computer Animation
Cartoon Animation

ABSTRACT

The informal heuristic practices of the fine arts have much to offer to our understanding of the appearance of phenomenological reality. One interesting example is the use of *exaggeration* to enhance the illusion of liveliness in both living and nonliving subjects. This further eases the uncomfortable sense that the motion is somehow uncanny — especially with inanimate objects. We performed a series of experiments to test the effects of exaggeration on the phenomenological perception of simple animated objects — bouncing balls. A physically plausible model of a bouncing ball was augmented with a frequently used form of exaggeration known as *squash and stretch*. Observers were shown a series of animated balls, depicted using systematic parameterizations of the exaggeration model, and asked to rate their plausibility. A range of rendering styles provided varying levels of information as to the type of ball. In all cases, balls with small amounts of exaggeration were seen as plausible as those without any exaggeration (e.g., with veridical motion). Furthermore, when the type of ball was not specified, observers tolerated a large amount of exaggeration before judging them as implausible. When the type of ball was indicated, observers narrowed the range of acceptable exaggeration somewhat but still tolerated exaggeration well beyond that which would be physically possible. We contend that, in this case, exaggeration acts to bridge the so-called *uncanny valley* for artificial depictions of physical reality.

1. Introduction

Since the earliest days of animation, artists have sought to portray the so-called "Illusion of Life." Nowhere was this quest more feverish than at the studios of Walt Disney in the 1930s–50s. In those studios, observations, techniques, and heuristics were codified into the widely acknowledged and disseminated "Twelve Principles of Animation," a set of guidelines for depiction of action (Thomas & Johnston, 1981; see Table 1). It has been well observed by practicing animators that animation ignoring these rules tends to look awkward and unnatural, while respect for them gives the work life and liveliness.

Many of these rules emphasize the depiction and exaggeration of shape and motion over time.[1] Here we examine the perception of exaggeration in its most frequently depicted form, Rule 1 — the use of *squash and stretch*.

1.1. History of exaggeration in animation

Only shortly after the first live action motion pictures were produced, artists discovered that, instead of photographing real scenes in real-time, drawings that changed subtly from frame to frame could be photographed and yield the illusion of motion. This phenomenology caught the attention of the Gestaltists at the turn of the century as well, resulting in the widely studied *Phi-Phenomenon* and its special case, relevant to cinema and animation, *beta movement* (Wertheimer, 1912).

Early early animation suffered from over-drafted mechanical motion which was subsequently followed by the "rubber hose" depiction of joints and limbs as mitigation. Alas, neither of these produced particularly lifelike motion (Solomon, 1994) though it was usually still seen as entertaining and, most importantly, *plausible* if not realistic.

Animated films are especially well suited for engaging their

* Corresponding author at: Justus Liebig University Giessen, Department of Experimental Psychology, Otto-Behaghel-Str. 10F, 35394 Gießen, Germany.
E-mail addresses: Filipp.Schmidt@psychol.uni-giessen.de (F. Schmidt), lnoejovi@skidmore.edu (L. Noejovich), gchakalo@skidmore.edu (G. Chakalos), fxpppr@rit.edu (F. Phillips).

[1] The originators of these rules were, rightly so, only casual taxonomists. Therefore, there is some conceptual and pragmatic overlap between them. For example, some rules are used in the execution of others, still others are narrow interpretations of their broader cousins. Thus, we use the more generic idea of exaggeration in our work to describe its specific execution via *squash and stretch*.

https://doi.org/10.1016/j.cognition.2024.105880
Received 13 September 2023; Received in revised form 5 July 2024; Accepted 7 July 2024
Available online 16 July 2024
0010-0277/© 2024 The Author(s). Published by Elsevier B.V. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

Table 1
The Twelve Principles of Animation (Thomas & Johnston, 1981).

1.	Squash and Stretch
2.	Anticipation
3.	Staging
4.	Straight Ahead Action / Post to Pose
5.	Follow Through / Overlapping Action
6.	Slow In, Slow Out
7.	Arcs
8.	Secondary Action
9.	Timing
10.	Exaggeration
11.	Solid drawing
12.	Appeal

audiences and making impossibly abstruse situations seem especially real and easily comprehensible. There is certainly *some* suspension of disbelief at work in the appreciation of all film, but animation is especially privileged. Indeed, the notion of "cartoon physics" (O'Donnell, 1985) captures the degree to which we are willing to forego reality, as demonstrated by Rule 1:

"Any body suspended in space will remain suspended in space until made aware of its situation." (O'Donnell, 1985, p. 19).

As computer graphics became a primary tool for creating motion for animation the question of the plausibility of the depictions arose (Barzel, Hughes, & Wood, 1996). After all, the ability to computationally *create* motion and object material properties that obey all known physical laws *should*, in theory, be imperceptibly different from reality. Alternatively, *capturing* motion from reality should be an excellent compromise. Yet — as any animator will tell you — this couldn't be further from the truth.

1.2. Rotoscoping

The quest for more realistic motion led the filmmaker, animator, and inventor, Max Fleischer to create a device for transferring reference film footage of live-action motion into drawings, the *rotoscope* (Fleischer, 1917) (Fig. 1). In its essence, the device projects individual frames of film onto the back of a piece of frosted glass, where they are painstakingly traced by the animation artists onto pin-registered pieces of animation paper. Animators were already familiar with this arrangement, since a rear-illuminated glass plate was regularly used to "see through" drawing layers to facilitate frame-to-frame and foreground to background coherence in drawings. But Fleischer had the insight to create a device to allow the use of images other than other animation drawings, and, perhaps more importantly, to somewhat automate the process.

Fleischer went on to create several devices to facilitate film and animation production, including methods for synchronizing sound and images as well as other insights that have had an ongoing effect on animation, special effects, and filmmaking in general (Pointer, 2017).

In modern animation and filmmaking, computational imaging is used to capture the location and movement in space of performers as well as practical objects and synthetic objects to be inserted after practical photography. This practice, generically referred to as *motion* or *performance capture,* with its roots in biomechanics research (Adams & Spirakis, 1997; Jensen, 1978), has had a major impact on video games and film making since the early 2000s.[2] Its prevalence has resulted in specialist "CG actors" such as Aki Ross and Andy Serkis, and inevitable parodies — such as the introduction to the 2007 edition of the annual

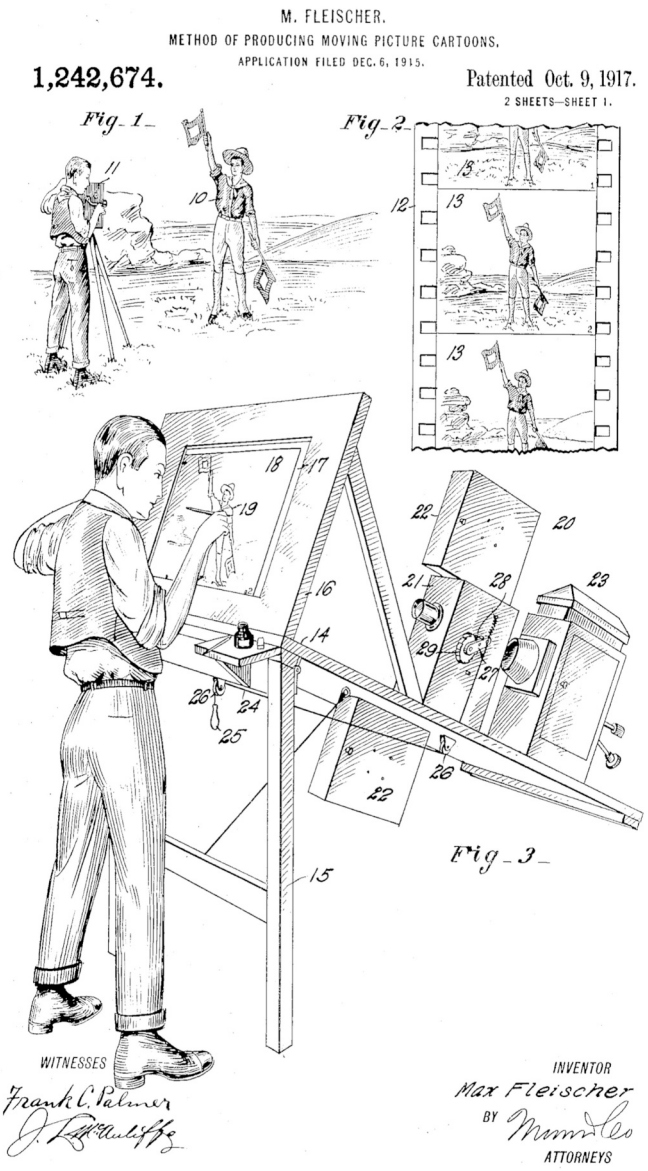

Fig. 1. Fleischer's device as depicted in his patent "Method of Producing Moving Picture Cartoons" (Fleischer, 1917). While the name is nowhere to be found in the patent, it was eventually christened the rotoscope and the process known as rotoscoping. The apparatus allows the the animator to create drawings from film footage (known as reference, 10–13) by tracing, onto paper (19), individual frames of the reference footage (13), projected onto a frosted glass plate (18). This technique is still used, 100+ years on, and is given the more high-tech moniker motion capture or performance capture. It is, essentially, the same process carried out digitally, frequently in real-time, with no film intermediate.

CalArts Producers' Show (CalArts Animation, 2007), thus establishing it as both a critical tool and a subject of some derision among filmmakers.[3]

It would seem that, by "capturing" reality, the problem of plausible and pleasant motion would have been solved — indeed, as early as the 1900's! However, it was clear even then that there was something unusual and unsettling about the motion of these captured performers. It would seem that what was captured may not have been wholly sufficient for us to see the motion as realistic (Geller, 2008). Indeed, even direct

[2] However, the senior author had experience with its use in computer graphics and special effects, dating back to the late 1980s and proposed animation for *Total Recall*. It was considered too costly and complicated at that time since the principal actor would need to be digitized. Today, of course, that is just part of the job of acting and not considered particularly burdensome.

[3] CalArts is the preeminent traditional animation school, founded, in part, by Walt Disney.

simulation of motion via computational physical modeling frequently suffers from this. Specifically, there are certain situations in animation where a character or object will appear to not mimic physical reality very well. However, the questions are at exactly which level of life-like resemblance this "uncanny valley" (Mori, 2012) (Fig. 15) occurs, and what animators can do to avoid or attenuate uncanny valley effects. This might not be such a problem if we were not so sensitive to biological motion (Neri, Morrone, & Burr, 1998), an ability even present in infants (Fox & McDaniel, 1982). Furthermore, since we never see desk lamps moving of their own accord in real life, we may be willing to give non-biological entities a wider berth when judging the plausibility of their movement. However, early work on the physically plausible motion of real non-biological objects showed that, even with plausible physical constraints, some violation of pure physics is necessary to make the movement appear more realistic (Witkin & Kass, 1988).[4]

1.3. Exaggeration as a solution

The techniques for specifying more lifelike animated action were distilled and codified over the years, most notably by Frank Thomas and Ollie Johnston, two of Walt Disney Animation's "Nine Old Men". The aforementioned Twelve Principles (see Table 1) represent guidelines and techniques that enable perceptually plausible and visually pleasing motion and other transitions within and between scenes. This further serves the goals of presenting characters in motion as more lifelike and realistic.

Perhaps the most widely utilized exaggeration technique is *squash and stretch* (Fig. 2). *Squash and stretch* are used to emphasize the physical and material characteristics of an animated object and its behavior while in motion. This yields the visual impression of weight and flexibility to dynamic objects, whether they are as simple as a bouncing ball or more complex like the moving muscles on a face. In its most fundamental form, squash and stretch is used to change a shape, roughly horizontally ("squash") and vertically ("stretch"), relative to their motion trajectory. Most times this is done without a change in volume to keep the mass of the object roughly constant, but this conservation is sometimes violated for effect. It is important to note that this deformation is not only *implausible* in real objects, in most cases, especially with respect to stretch, it violates the laws of physics and is physically *impossible.*

Squash and stretch is recognized for its practicality and simplicity, as it can be used as little or as much as necessary to create effects with varying degrees of exaggeration. Besides weight and flexibility of animated objects, there are other factors such as acceleration that have to be considered when deciding how and where in the animation the object changes shape. In most cases, this is determined via the intuition of the animator and not necessarily with the assistance of any computational modeling. Indeed, even in situations where plausible motion is computed or captured, the resulting animation is almost always "tweaked" by an artist to make it look "more real".

[4] Some particularly interesting examples come from the senior author's experience working on the early Pixar short films. In *Tin Toy*, the motion of the plume on the toy's hat was computationally modeled to obey the physics of spring-and-weight behavior. Despite its physical accuracy, the computational motion needed to be exaggerated by the animators to make it appear more plausible. The artificial snow in the short film *Knickknack* was modeled using an extremely naïve physical model and contained no fluid dynamics, again, ultimately adjusted by the animators. Finally, in *Luxo Jr.* the cord was only animated by hand with no physics simulation used at all. In all three cases, technically inclined viewers frequently complemented the "realistic computational simulation of motion" used in the films — only to be told that little or no physical modeling was used.

1.4. Material properties

Animation techniques like *squash and stretch* are not only used to create smooth, more plausible looking motion — these deformations affect how viewers perceive material properties of objects. For example, the magnitude of *squash and stretch* and the time at which it occurs will change whether viewers perceive objects as harder or softer, as less elastic or more elastic, or as likely to break under pressure or to bend. The visual perception of materials and their properties is an emerging field in vision research (e.g., Adelson, 2001; Fleming, 2014) and many questions are still open. For example, it is not clear to what extent the perception of internal properties, such as softness, depend on visual appearance (e.g., in terms of texture or colour). Specifically, it seems that the perception of softness is driven by appearance when objects are static (e.g., depends on whether a cubic object looks like metal or velvet), but is completely dominated by motion characteristics when objects are dynamic (e.g., depends on the extent to which the same cubic object is indented by a cylinder) (Kawabe, 2020; Paulun, Schmidt, van Assen, & Fleming, 2017; Schmidt, Paulun, van Assen, & Fleming, 2017; Ujitoko & Kawabe, 2022). Consequently, it is also not clear how material properties as induced by *squash and stretch* do interact with texture and colour of the animated objects. For example, whether the perceived softness of an animated ball depends more on exaggeration or on whether it looks like a bowling ball or a tennis ball. Or, whether the uncanny valley phenomenon can be mitigated by different uses of exaggeration that depend on the visual appearance of the object.

The following experiments probe our ability to perceive distortions and exaggerations of object shape in relation to the assumed material properties of those objects. We examine the perceived plausibility of *squash and stretch* applied to a simple animated object — a bouncing ball.

2. Materials and methods

We performed a series of experiments to probe the detection and perceived plausibility of bouncing balls. We developed a physically accurate model that integrates parametrically adjustable exaggeration in a manner consistent with traditional animation practice.

2.1. Model

The basis is a simple inelastic collision of a falling body with a solid floor, each with a specified coefficient of restitution (COR). The COR is the ratio of the final to initial relative velocity after the collision. Thus, with a COR of 1.0 the resulting collision is perfectly elastic and a COR of 0.0, perfectly inelastic.

We add an exaggeration function that controls *squash and stretch* (i.e., deformation) as a function of velocity and position. With no exaggeration, the model behaves like a simple, non deforming bouncing ball. The exaggeration model consists of 10 parameters split into two classes — physically plausible and hyperrealistic (i.e., exaggerated). These parameters allow control over the timing, t_i, and the magnitude of the exaggeration (i.e., *squash and stretch*), s_i, at three different points, along with a velocity-scaled damping, d. Three time points control the timing of the exaggeration parameters, $s_{\{1,2,3\}}$, relative to the natural time of impact, t_{impact}. This allows for the changes in shape to anticipate impact (the initial physically impossible "stretch" phase), to react to the ground (the plausible but exaggerated "squash" phase) and the transition from the ground back to the natural trajectory (a physically impossible "squash-to-stretch" phase). In this way, the ball can be made to "stick" to the ground, if desired (Figure 3).

The effects of varying s (with the same magnitude at the three different points) are illustrated in Fig. 4.

Fig. 5 shows two examples of our ball model — a non-exaggerated and a moderately exaggerated animation.

We selected four different types of common balls to cover a range of

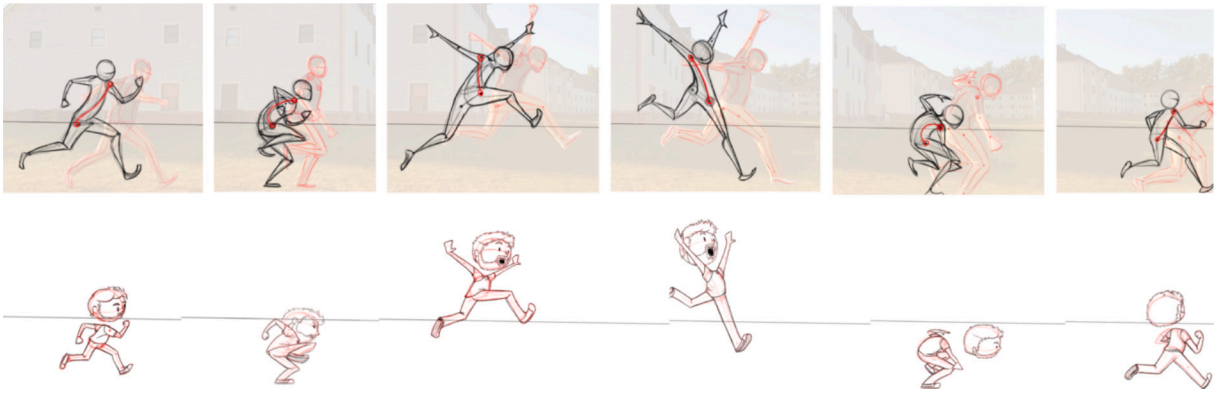

Fig. 2. An example of exaggeration in traditional animation. Here, the top row shows drawings that are "rotoscoped" from live-action reference footage. Orange lines represent the direct "draw over" of the live action, darker lines are the "pushed" drawings that exaggerate the live action using squash and stretch. The second row shows the mapping of the pushed live action onto the stylized character, where further exaggeration and interpretation takes place. (Courtesy of Elizabeth S. Vega, RIT Film and Animation.)

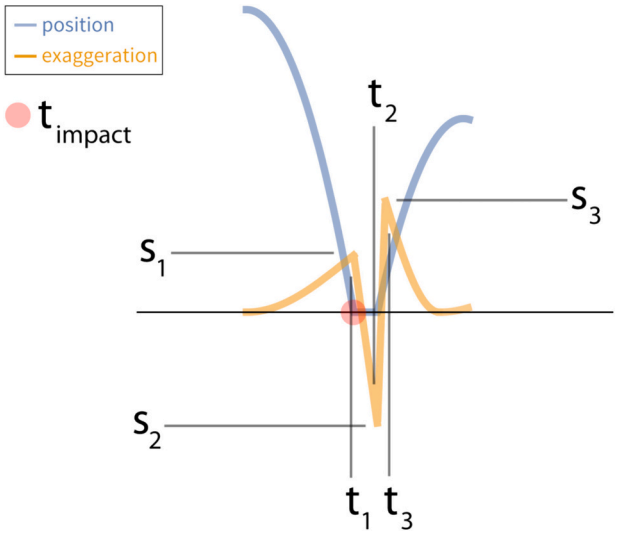

Fig. 3. Physically plausible parameters (such as gravity, coefficients of restitution, friction, etc.) control the overall position of the bouncing ball. The position (height in this 2D depiction) of the ball is shown as a light blue line, the magnitude of exaggeration of the shape of the ball is shown in orange. These three parameters specify gravity, initial position, and coefficient of restitution, g, y_0 and e, respectively. The exaggeration parameters shown here are specified as three time-scale pairs, $t_{\{1,2,3\}}$, $s_{\{1,2,3\}}$. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

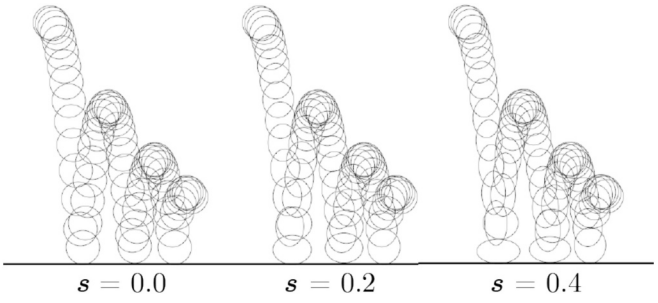

Fig. 4. Three examples of exaggeration using our model. For all three points, the magnitude of squash and stretch are equal, here represented by $s = \{0, .2, .4\}$ for each condition, timing values are also symmetric about t_{impact} at $t_{\{1,3\}} = 0.1s$. Here we use symmetric s and fixed t. Since these could be treated as two separate factors we refer to this symmetric squash and stretch simply as "exaggeration" to emphasize its composite nature. Indeed, in animation practice, squash and stretch aren't usually treated as separate transformations, but rather as a unitary.

"bounciness" (i.e., CORs, Fig. 6). For Experiments 1–3 we rendered animations using a line drawing of a circle to represent the ball and a line for the floor. Experiment 4 used a realistically rendered ball and environment. All movies were presented in ≈7° × 10° visual angle at 60 frames per second. Each stimulus depicted a 1 s static image of the background followed by 3 s of animation. In all experiments only two model parameters were varied: the COR and the magnitude of exaggeration (with s1 = s2 = s3). All other parameters were held constant and all balls were depicted at the same size, ≈1°, regardless of type.

3. Experiments

The stimuli and data for all experiments can be obtained from Schmidt, Noejovich, Chakalos, and Phillips (2024).

3.1. Experiment 1 — detection

Observers. 36 observers with normal or corrected vision participated in the experiment for financial compensation or course credits. All participants gave informed consent, were debriefed after the experiment, and treated according to the ethical guidelines of the American Psychological Association. All testing procedures were carried out in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki).

Apparatus and stimuli. Observers were seated in front of a 27″ iMac Pro at a viewing distance of approximately 50 cm and a super-resolution of 4096-by-2304, addressed as 2048-by-1152 pixels.[5] Stimulus presentation was controlled using PsychoPy (Peirce et al., 2019). The stimuli consisted of animations of unlabeled line drawings of balls. The movies were 800-by-1200 pixels with the ball depicted as 125-by-125 pixels (e.g., about 3° of visual angle). We used a range of exaggerations (0.0 to 1.0) inspired by classic examples from cartoon animations (e.g., the "Royal Cup Match" in Walt Disney's *Bedknobs and Broomsticks* (1971), "How to play football" (1944) by Walt Disney, and "Sport Chumpions" (1941) a *Merrie Melodies* film by Warner Bros.). The maximum

[5] All rendering was done at super-resolution (e.g., 4× the "addressable" screen resolution) to present the stimuli with as much detail as possible. The resolution numbers used throughout the paper are the traditional "addressable" pixel locations, but the presentation of the stimuli was done at super-resolution.

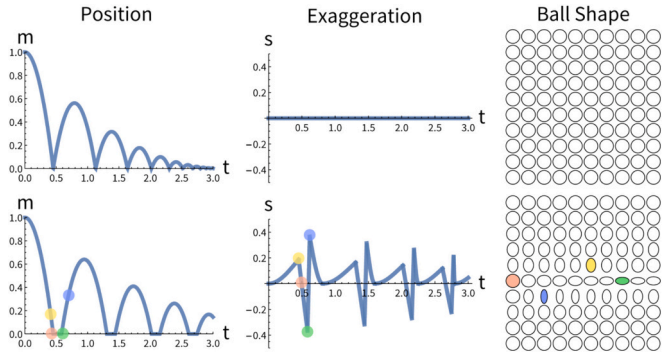

Fig. 5. Two examples of our ball model. The top row shows a non-exaggerated ball while the bottom row shows a moderately exaggerated example. The left panels show the height of the ball as a function of time. In the lower (exaggerated) panel, the colored dots correspond to locations on the subsequent panels. The middle panels show the magnitude of the exaggeration as a function of time. Positive values map to the traditional animation idea of "stretch" and negative values to "squash". The right panels show the shape of the ball over the course of one second, starting at the upper left and ending in the lower right. The physically plausible parameters are the same for both examples, with gravity, initial position, and coefficient of restitution, $e = 0.75$, $y_0 = 1.0m$ and $g = 9.8m/s^2$. The exaggeration (hyperrealistic) parameters shown here are specified as three time-scale pairs, $s_{\{1,2,3\}}$, $t_{\{1,2,3\}}$. For the non-exaggerated ball (top row), $s_{1,2,3} = \{0, 0, 0\}$, $t_{\{1,2,3\}} = \{0, 0, 0\}$ and $d = 0.0$; for the exaggerated ball (bottom row), $s_{\{1,2,3\}} = \{0.2, 0.4, 0.4\}$, $t_{\{1,2,3\}} = \{0.03, 0.1, 0.03\}$ and $d = 0.5$.

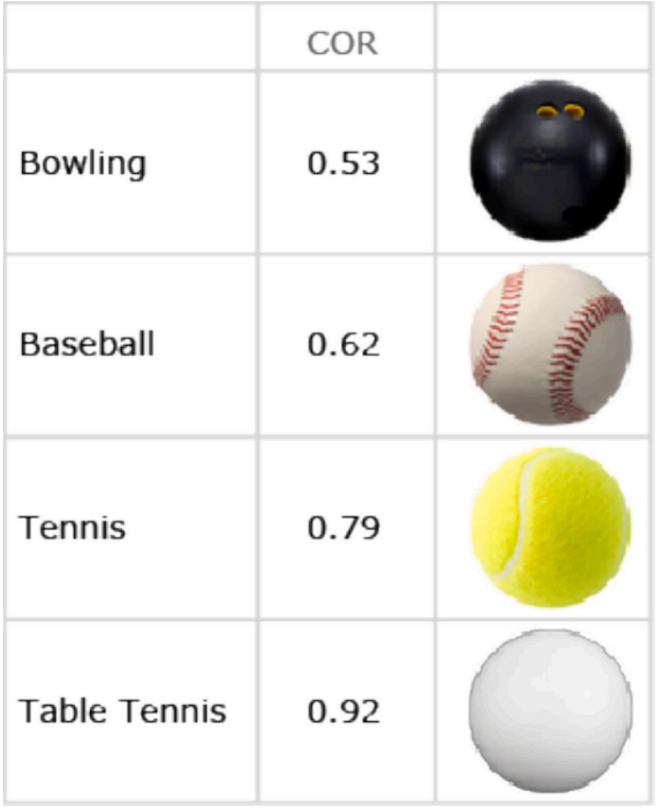

Fig. 6. Our four modeled balls, ranging from $COR = 0.53$ to 0.92. Larger CORs represent more "bounce" or energy recovery.

exaggeration produced a relative extension of horizontal and vertical axis of 1:2.

Procedure. Observers performed multiple interleaved staircases for each ball to estimate a detection threshold for the exaggeration. The individual staircases were randomized on each trial.

Results. On average, detectability was at 10% with no difference between CORs (k-sample *t*-test, $T = 1.84$, $p = .145$). Interestingly, some observers were able to reliably detect as little as 1% distortion (e.g., a few pixels of symmetric shape change, vertically and horizontally, Fig. 7).

Note that the ability to detect this distortion might be slightly overestimated if observers ignored the initial motion of the ball and focused solely on its horizontal elongation at the moment of impact. This may explain the near-floor performance of some observers suggested by the error bars in Fig. 7.

In the following experiments, we measured the perceived plausibility of the different bounciness and exaggeration conditions. Note that we decided to ask to what extent the motion is perceived as "plausible" rather than as "realistic" because the latter would have confounded the reported appearance with the perceived realism of the depiction (neither line drawings nor computer-rendered scenes will ever be considered as extremely realistic).

3.2. Experiment 2 — plausibility

Observers and Apparatus. A total of 72 observers took part using the same apparatus and conditions as in the previous experiment.

Stimuli. The stimuli consisted of animations of unlabeled line drawings of balls. The same 4 COR levels were used as in the previous experiment. Exaggeration ranged from 0 (physically accurate) to 1.0 (extremely exaggerated) in steps of 0.1. Fig. 8 shows examples of the motion and deformation afforded by the exaggeration and COR.

Procedure. On each trial the observer is presented with an animated simulated ball, dropped from a height of 1 m which disappears after 2 s. After the stimulus disappeared, observers used a 0–1 scale to rate plausibility. Each of the 4 bounciness conditions and 11 exaggeration conditions were presented 3 times for a total of 132 trials.

Results. Fig. 9 shows the rated plausibility as a function of exaggeration and COR. Observers rated stimuli with small amounts of exaggeration as being as plausible as those without. The effect is relatively independent of COR and is driven mainly by exaggeration.

We average responses across the 3 repetitions, and performed an ART-ANOVA (Wobbrock, Findlater, Gergle, & Higgins, 2011) with the factors COR and exaggeration (Fig. 10). The score was clearly above zero for all CORs ($F(1,71) = 9736.47$, $p < .001$) and all levels of exaggeration

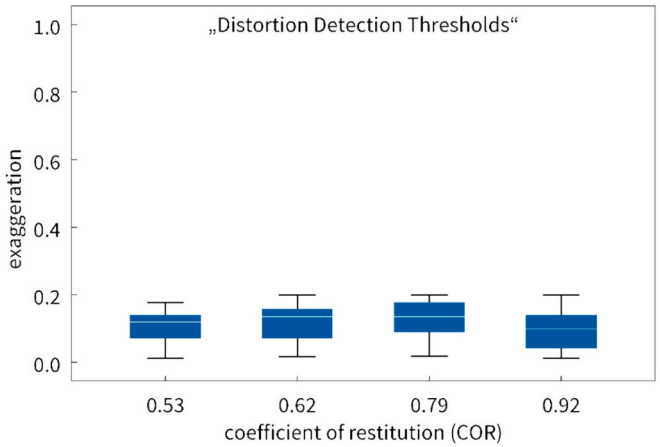

Fig. 7. Detection of distortion for the four ball types. For all four types, the range of tested exaggerations ran from 0.0 to 1.0. The white lines indicate median thresholds for all observers, the boxes indicate quantiles 25–75, and error bars denote fences. Overall, detection of distortion was very good, around 0.1 or 10%, indicating that observers could detect very fine manipulations in the shape of the balls, regardless of COR.

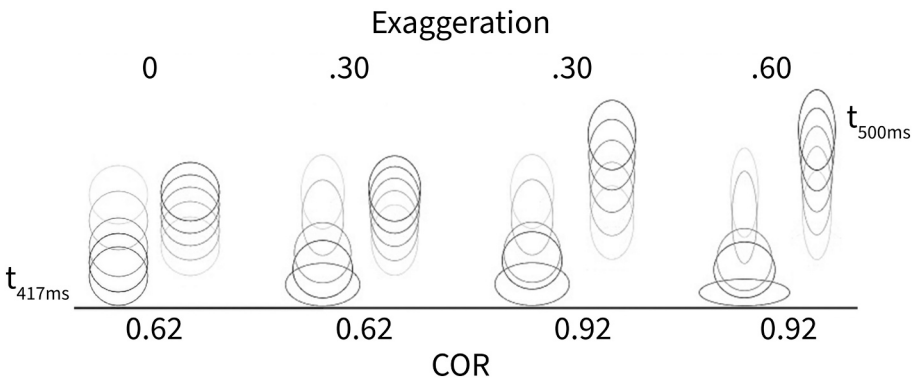

Fig. 8. Impact and rebound of two of the modeled balls (baseball and ping pong ball, COR = 0.62 and 0.92, respectively) at 0 exaggeration (e.g., physically accurate), 0.3 and 0.6. Lighter circles are prior frames over the last 83 ms to provide an idea of the shape change. Each pair shows the moment of impact at 417 ms and the position and shape after rebound 83 ms later at 500 ms. Note that, for the initial "stretch" phase to be even remotely physically possible, the atmosphere would have to provide some super-physical resistance to deform even the most pliable object in this way. Yet, this anticipation of the eventual plausible-but-exaggerated "squash" is seen as giving the ball a liveliness that the non-exaggerated but physically accurate depiction does not.

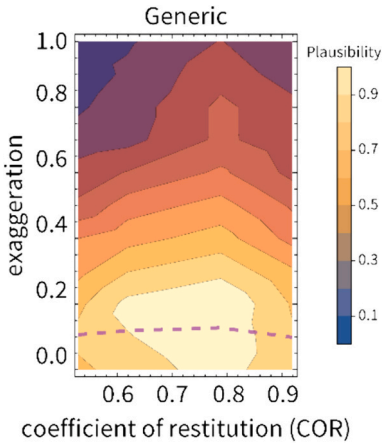

Fig. 9. Plausibility as a function of exaggeration and COR for the generic ball animations. The purple line shows the detection threshold from Experiment 1, exaggeration amounts greater than this threshold were reliably detected. For an ideal, physically plausible criterion, the preferred exaggeration should be at 0.0 for all levels of exaggeration. Peak plausibility across all four CORs was around 10% exaggeration with half of the observers finding exaggerations of up to 30% plausible. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(F(1,71) = 30.56, p < .001). Consequently, even higher levels of exaggeration were considered as plausible. The plausibility increased with COR until 0.79 and then decreased again (F(3,71) = 30.56, p < .001), and generally decreased with increasing levels of exaggeration (F(10,71) = 132.94, p < .001). The interaction between both factors was not significant.

3.3. *Experiment 3 — semantic labels*

Observers and Apparatus. A total of 67 observers took part using the same apparatus and conditions as in the previous experiment.

Stimuli and Procedure. In Experiment 3, we again presented line drawings of balls, together with a semantic label specifying the type of ball ("Bowling Ball", "Baseball", "Tennis Ball", and "Ping Pong Ball"). After the stimulus disappeared, an unlabeled rating line was shown and the observer marked the line in a location indicating the perceived plausibility of the depicted animation. Implausible-seeming depictions were marked toward the left of the scale and plausible animations to the right. Owing to the findings in Experiments 1 and 2, we used a restricted range of exaggerations (0.0 to 0.6) in steps of 0.05 to better isolate the regions of plausibility. For each of the four semantic labels, we presented the 4 bounciness conditions and 13 exaggeration conditions once, for a total of 208 trials.

As a result, higher ratings were located closer to the appropriate COR but observers still tolerated a large amount of exaggeration (Fig. 11).

Again, we performed an ART-ANOVA with the factors animation type, COR and exaggeration (Fig. 12). We found that again plausibility was clearly above zero across all conditions (all F > 41,184.30, *p* <

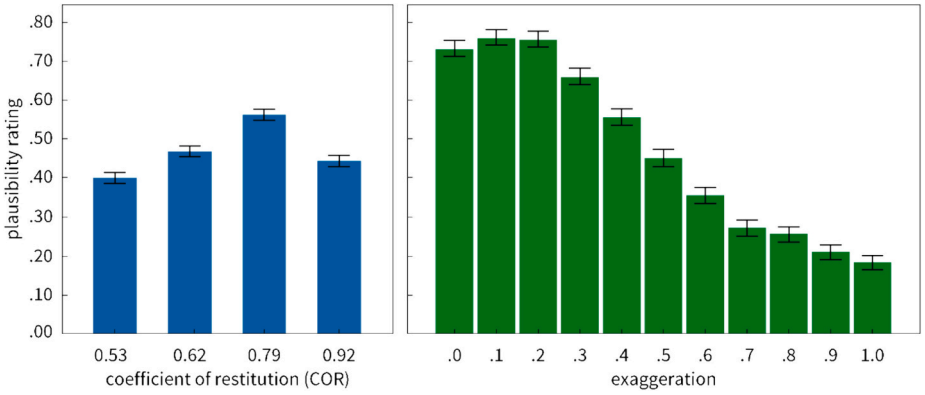

Fig. 10. Average plausibility ratings, plotted as a function of COR (blue) and exaggeration (green). Error bars denote standard errors. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

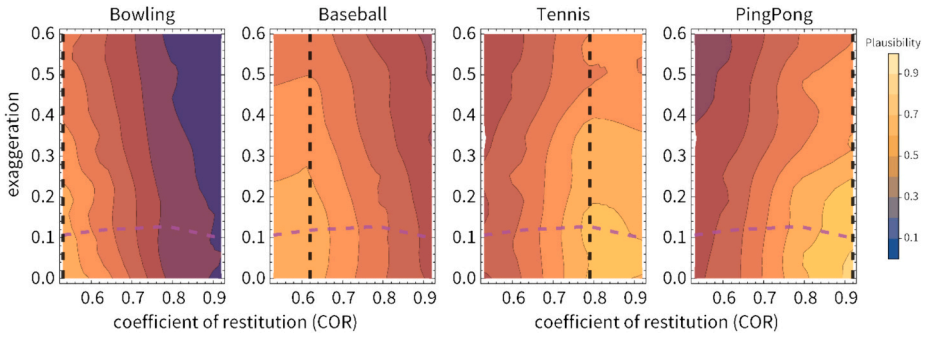

Fig. 11. Plausibility as a function of exaggeration and COR for the four semantically labeled animations (e.g., the caption "Bowling Ball" presented with each animation). The purple line shows the detection threshold from Experiment 1. For an ideal, physically plausible criterion, the preferred exaggeration should be at 0.0 for all levels of exaggeration. Plausibility generally increased when the animation depicted CORs closer to the physically correct COR (here shown with black dotted lines). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

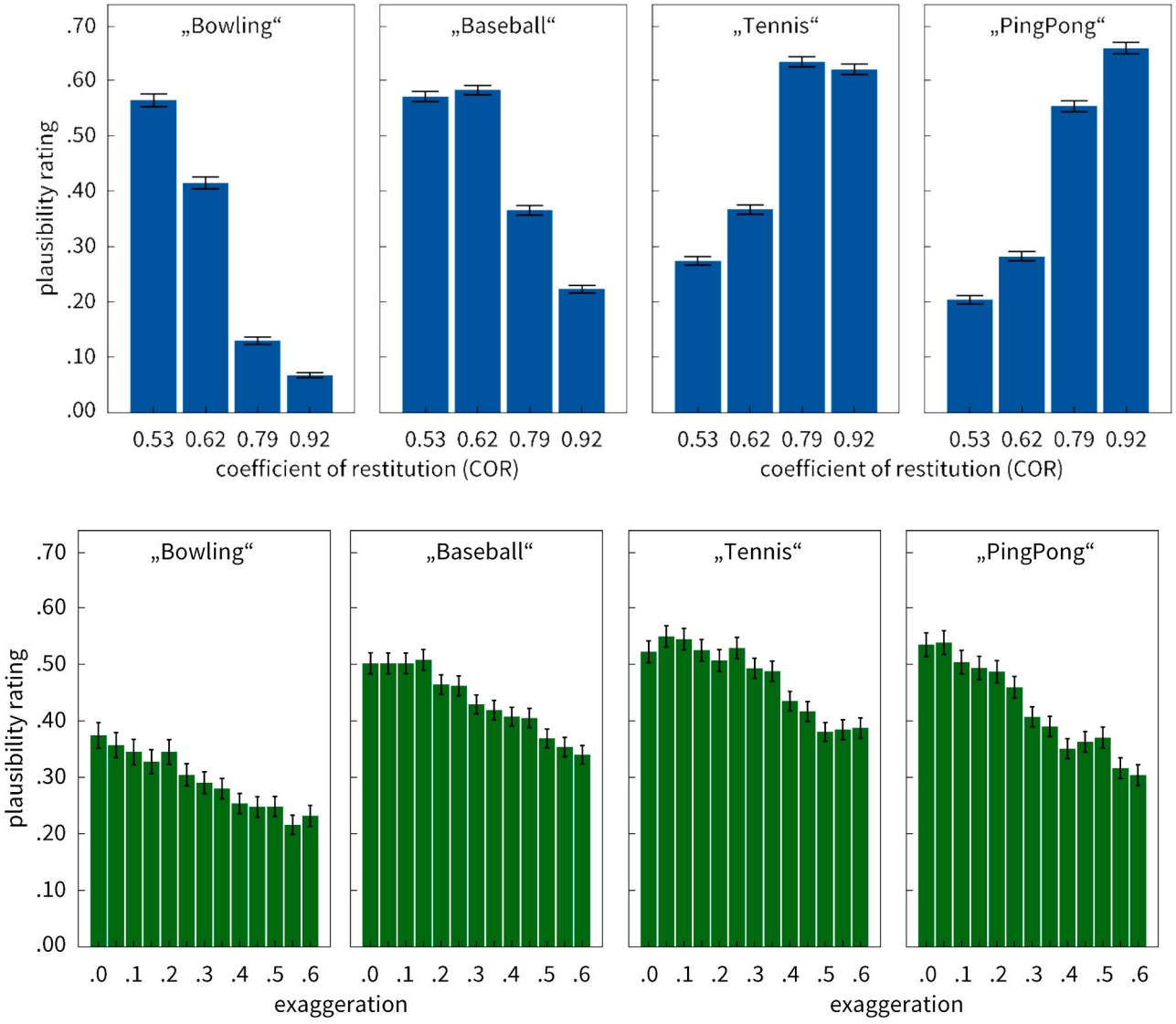

Fig. 12. Average plausibility ratings, plotted as a function of COR (blue) and exaggeration (green), separately for the four semantically labeled animations. Error bars denote standard errors. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

.001), and different for different animation types ($F(3,66) = 358.44$, $p < .001$), CORs ($F(3,66) = 6.22$, $p < .001$), and levels of exaggerations ($F(12,66) = 73.19$, $p < .001$). However, we also see a marked interaction between animation type and COR ($F(9,66) = 769.72$, $p < .001$), where plausibility is decreasing with COR for "Bowling Ball" and "Baseball" animations, and increasing with COR for "Tennis Ball" and "Ping Pong Ball" animations. The interaction between animation type and exaggeration ($F(36,66) = 1.91$, $p < .001$) is significant but much weaker and

less clear. The interaction of COR and exaggeration was not significant.

3.4. Experiment 4 — renderings

Observers and Apparatus. A total of 67 observers took part using the same apparatus and conditions as in the previous experiment.

Stimuli and Procedure. For Experiment 4, stimuli were depicted photorealistically instead of schematically. Physically based materials were used to depict the surface characteristics of the objects ("Bowling Ball", "Baseball", "Tennis Ball", and "Ping Pong Ball"). As with the previous experiments, these were rendered at the super-resolution of the monitor to avoid any pictorial artifacts. Again, we used a restricted range of exaggerations (0.0 to 0.6) in steps of 0.05 for each of the four renderings and presented the 4 bounciness conditions and 13 exaggeration conditions once, for a total of 208 trials. As in Experiment 3, plausibility continued to shrink around the veridical COR, and there is again a distinct interaction between the parameters (Fig. 13).

Again, we performed an ART-ANOVA with factors animation type, COR and exaggeration (Fig. 14). We found that plausibility was clearly above zero across all conditions (all $F > 41{,}685.11$, $p < .001$), and different for different animation types ($F(3,66) = 169.85$, $p < .001$), CORs ($F(3,66) = 7.52$, $p < .001$), and levels of exaggerations ($F(12,66) = 63.24$, $p < .001$). Again, we see a marked interaction between animation type and COR ($F(9,66) = 477.52$, $p < .001$), where plausibility is decreasing with COR for "Bowling Ball" and "Baseball" animations, and again increasing with COR for "Tennis Ball" and "Ping Pong Ball" animations. This time, neither the interaction between animation type and exaggeration nor between COR and exaggeration was significant.

4. Discussion

Since the earliest days of animation, artists have sought to depict the Illusion of Life. One of the most important rules resulting from this challenge is *squash and stretch* — an animation technique in which moving objects change shape horizontally and vertically, relative to their motion trajectory, without changing in volume. *Squash and stretch* exaggerates animated motion but also gives weight and flexibility to objects. Here, we tested the effects of *squash and stretch* unto the judged plausibility of a simple visual scene — a bouncing ball. We hypothesized that small levels of *squash and stretch* would yield as high or even higher plausibility estimations compared to physically more veridical scenes without *squash and stretch*. Notably, we were not interested in whether people perceived the ball motion as exaggerated, but rather whether they perceived it as *plausible*.

It is well-known among animators that the motion of non-human characters, especially inanimate objects, frequently "reads" better when that motion is based on or biased toward human motion. After all, this sort of motion is what we humans are most familiar with. The luxury of animating the inanimate is that no one knows what a "hopping lamp" should look like, so making it look plausible is most easily done by making it look like a human or animal would move (Beaudine & Jackson, 1956; Lasseter, 1987; Learoyd, 2019; Thomas & Johnston, 1981). The oft-noticed work of Heider and Simmel (1944) makes this point experimentally and phenomenologically — constructed stories about the moving polygons are almost always anthropomorphic, ascribing conscious intentionality to the motion. Note that a bias toward anthropomorphism has been accepted wisdom, passed down across generations of animators, and a subject that would make for a very interesting study on its own merits.

It has been shown that animation techniques can be used to make it easier for people to understand graphical user interfaces (Thomas & Calder, 2001) or to predict what a robot will do (Takayama, Dooley, & Ju, 2011). The standard animation test for all beginning artists is to draw a bouncing ball due to its simplistic and variable nature and has been surprisingly rewarding in terms of what could be learned.[6] Since a ball is an incredibly simple object, and therefore easy to animate, it could be manipulated in several different ways. Through many tests and alterations, animators quickly learned the mechanics of animating a scene. Two of the most significant aspects associated with bouncing ball animations are the amount of *squash and stretch*, or the level of exaggeration, and the coefficients of restitution, or the bounciness of the ball. Other aspects include ball texture and weight, but also characteristics of the surface it is hitting (e.g., its material, shape), all of which result in variations in ball animations. Experimentation with bouncing ball animations also gave rise to several other animation techniques beyond *squash and stretch* such as *timing*, *anticipation*, and *staging* (Thomas & Johnston, 1981). Animators were then able to implement these techniques into their cartoon characters, creating more realistic depictions of how human replicas should move, act, and respond to their surroundings.

Indeed, here we show that observers judge scenes with small, but perceptible, levels of *squash and stretch* as just as plausible compared to scenes with no *squash and stretch* at all — even though the latter best mimic physical reality. This overall finding is essentially the same whether or not the ball is depicted as a simple line drawing (Exp. 2), whether the observers are informed about the material identity of that ball (Exp. 3), or whether the ball is rendered with a photorealistic appearance (Exp. 4). To the best of our knowledge, we provide the first empirical test of the contribution of *squash and stretch* to perceived plausibility of a simple visual scene.

4.1. The uncanny valley in the illusion of life

Modern practical (e.g., non-animated live action) film making techniques have evolved to allow for virtually unlimited cinematographic and editorial freedom. This means that changes can often appear very quickly, sometimes taxing the viewer's experience. This is especially true with static representations of places and things, as the lack of motion from one scene to the next can make it difficult to remember the context of each moment within a scene (Cutting, 2019). Fortunately, animation, and, by extension, animators themselves, excel at curating a visual experience by selecting the right information for the audience to make sense of the depiction. Specifically, animation techniques are essential for creating smooth transitions between scenes, as they simplify the information presented in the scene that must be processed by the viewer. They also enable drawn depictions to represent reality better than animations with no animation techniques present. However, when a cartoon does not contain any of these animation techniques, the depiction can elicit feelings of uncertainty and doubt.

We propose to interpret this effect and our findings in the context of mitigating the uncanny valley in depicting the Illusion of Life. The "Uncanny Valley" is a phenomenological observation made by roboticist Masahiro Mori, which refers to the hypothetical changes in robot eeriness with regard to their resemblance to people (Lissauer, 2014; Mori, 2012) where at a certain level of human likeness of robots, the human replicas start to look much more eerie ("uncanny valley") and emotional reactions only recover once the resemblance of human replicas becomes even higher (Sasaki, Ihaya, & Yamada, 2017; Yamada, Kawabe, & Ihaya, 2012). The uncanny valley is present in still objects; however, the relationship greatly increases when motion is added to objects or characters (Fig. 15).

While the uncanny valley originated in the field of robotics, we propose that it can be applied to other fields of study such as animation and material perception in vision science. In the field of animation,

[6] Alternately, or in advanced cases, a "sack of flour" is used, again, for the same reasons.

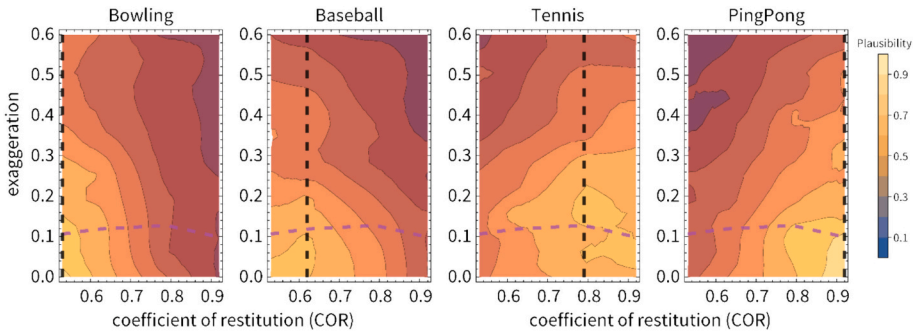

Fig. 13. Plausibility as a function of exaggeration and COR for the four photorealistically rendered animations (e.g., the generic ball rendered as "Bowling Ball", see Fig. 6). The purple line shows the detection threshold from Experiment 1. For an ideal, physically plausible criterion, the preferred exaggeration should be at 0.0 for all levels of exaggeration. Plausibility increased when the animation depicted CORs closer to the physically correct COR (here shown with black dotted lines). Compared to semantically labeled animations, the accepted range of plausibility shrinks slightly. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

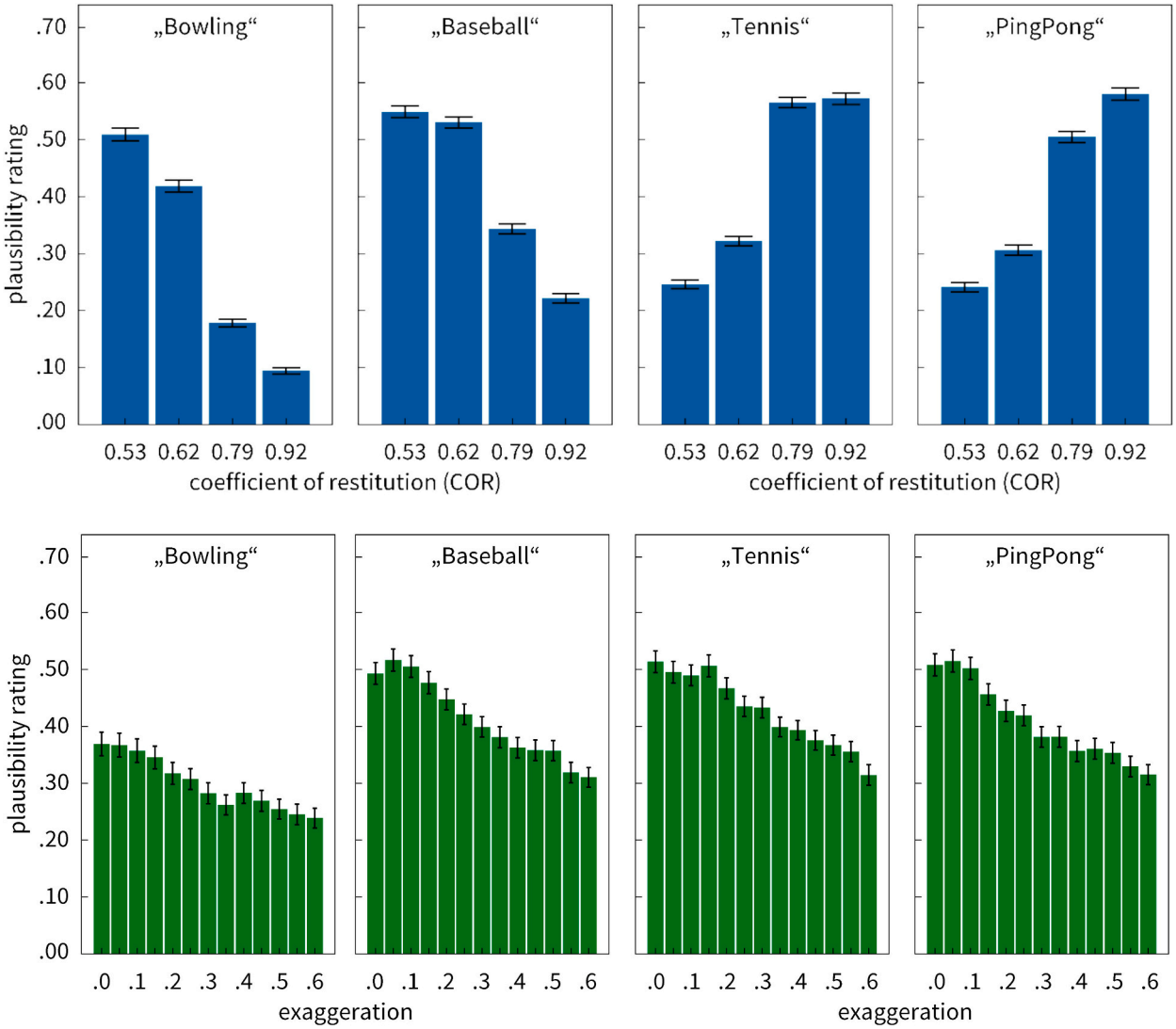

Fig. 14. Average plausibility ratings, plotted as a function of COR (blue) and exaggeration (green), separately for the four photorealistically rendered animations. Error bars denote standard errors. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

animators try to get out of this chasm through the use of animation techniques. Just like in robots, there are certain situations in animation where an object or character appears to not mimic physical reality very well, and the questions are at exactly which level of life-like resemblance this "uncanny valley" occurs, and what animators can do to avoid or attenuate uncanny valley effects.

Following this line of argument, the Twelve Principles of Animation are essential to animators because they allow their creations to avoid

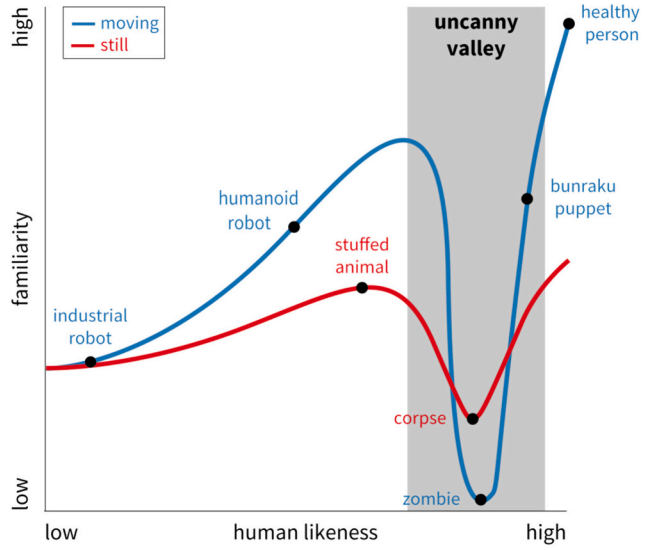

Fig. 15. A graphical depiction of the "Uncanny Valley" phenomenon. The x-axis represents the relative likeness to a living human and the y-axis represents phenomenological familiarity. As human likeness increases, so does familiarity to the point where it plummets into the uncanny valley (gray area). This version is adapted from the original to include the notion of animate versus inanimate objects (Mori, 2012). Note that animation exaggerates the effect of likeness on familiarity.

reaching the uncanny valley and generating feelings of discomfort or eeriness. In the context of this paper, the uncanny valley therefore refers to how much *squash and stretch* is helping to make a bouncing ball look plausible, without the ball appearing to behave weird. Participants might perceive physical reality (with no deformation at all) as somewhat uncanny, which might be why they consider some level of *squash and stretch* as appearing most plausible. Accordingly, animation techniques such as *squash and stretch,* that were developed for bridging the uncanny valley in animation, might also proof relevant for other fields of study where uncanny valleys occur.

4.2. Automating squash and stretch

Previous studies in computer science described algorithms to produce *squash and stretch* in computer animations (Chenney, Pingel, Iverson, & Szymanski, 2002; Lasseter, 1987; Wang, Drucker, Agrawala, & Cohen, 2006) or video footage (Collomosse & Hall, 2005; Collomosse, Rowntree, & Hall, 2005; Lee, Kwon, & Lee, 2012) with minimal human intervention. More recent algorithms were developed to apply *squash and stretch* deformations to motion capture data, for example, of human actors or faces (Kwon & Lee, 2007; Kwon & Lee, 2008; Lees, 2006; Ruhland, Prasad, & McDonnell, 2017) — which due to technological advances is increasingly easy to generate (e.g., Xiao, Zhuang, Yang, & Wu, 2006), and is a promising route to ease up the laborious task of producing cartoon animations. All of these developments are driven by the principal idea that animation techniques like *squash and stretch* make it easier for observers to follow the depicted scenes and increase their appeal. Accordingly, *squash and stretch* is discussed to improve user interactions with computers, by (i) making it easier to understand interface behavior, (ii) conveying feelings of substance in the graphical objects that users are manipulating, and, (iii) making the user's experience more pleasant and engaging (Thomas & Calder, 2005; Chang & Ungar, 1993). Other animation techniques, such as anticipation, are even used to improve user interactions with robots (Ribeiro & Paiva, 2012; Takayama et al., 2011). However, what are the detailed effects of *squash and stretch* on observers?

4.3. Squash and stretch in cognition

In fact, the empirical evaluation of *squash and stretch* from a cognitive and vision science perspective is extremely limited. To the best of our knowledge, only a single study tested its effects on cognition. (Garcia, Dingliana, & O'Sullivan, 2008) simulated scenes of balls with different elasticities bouncing off from two platforms before falling into oblivion; and in different trials participants were asked at different time points of the simulation to move a platform to catch the ball. By comparing scenes based on a physical simulation engine versus the same engine bolstered by *squash and stretch*, they showed that participants were better in anticipating the ball's trajectory with the animation technique. In a different experiment, (Garcia et al., 2008) demonstrated that participants judged a simple game in which they controlled a spaceship to avoid bugs bouncing around in a rectangular 2D box as more appealing when the bugs were animated using *squash and stretch*. In contrast, they did not find any effects of the animation technique in an experiment where participants simultaneously watched four scenes in which balls were falling and interacting with moving obstacles, and had to read words appearing on the balls at random intervals — indicating that participants' attention was not directed more to scenes featuring *squash and stretch*. These findings do support previous beliefs about why animation techniques are useful: they make it easier for observers to follow animations by allowing them to better anticipate upcoming events, and make animations more appealing. Here, we take a different stance by arguing that *squash and stretch* is also effective because it increases the perceived plausibility of depicted events.

4.4. Squash and stretch in the perception of plausibility

Even though a physically veridical scene would not express any *squash and stretch* (for exceptions see below), some level of non-physical deformation might actually be perceived as more plausible than the actual physical reality. This argument, which is supported by our findings, is adding an altogether different point to the list of pros for using animation techniques: their field of application might not be restricted to the domain of animation (such as exaggeration in cartoons) but might also give realistic scenes a more plausible feel. Why should this be the case?

First, there are real instances of *squash and stretch* deformations in real world scenes. For example, if examining interactions between objects at high temporal resolution, deformations are often much stronger than what we would expect — as can be experienced, for example, when looking at strobe images of a tennis ball being hit by a racket or a golf ball being hit by a club. However, it is not clear why and how we should incorporate these deformations into our representations of plausible material behavior given that the temporal resolution of our visual system is not high enough to see them.

Second, there is the peculiar case of things made of living flesh that are also often changing shape in line with *squash and stretch* principles. For example, when bending your arm, your biceps will swell (i.e., it will squash and stretch) while conserving the volume of the muscle. However, again, it is not clear why this should affect our representations of plausible material behavior for much more rigid objects, for which we never experience such deformation behavior. Even though it is reasonable to assume that from these and other deformations of soft material objects we learn that volume tends to be not affected by deformation — in line with a basic principle of *squash and stretch* — a bouncing ball from soft material will *not* show, for example, elongation when falling with high speed.

Third, our findings might be explained by previous exposure of participants to animations and cartoons — as participants were typically American or German students aged 20–25 years. However, their exposure to live action movies was presumably even higher. Also, we did not refer to animations or cartoons in our instructions but rather explicitly asked them to judge the plausibility of the ball behavior with respect to

an event in the real world.

Fourth, the basic pattern of our findings was the same for Experiments 3 and 4, even though the scenes in the latter were of realistic visual appearance (note, however, that we cannot rule out that semantic knowledge also played a role in Experiment 4, as participants could infer the identity of the balls from their appearance).

Finally, cinematographic photography and projection samples action in time over a given shutter's exposure window. This results in what is colloquially described as "motion blur" as part of that process. Higher frame rates and shorter shutter speeds reduce this blur. Some studies suggest that viewers find a slight amount of blur more visually pleasing or convincing in some contexts (Cutting, 2002; Pan, Bingham, & Bingham, 2013). In other contexts, (Eschner, Mindek, & Waldner, 2023) there is little effect, such as blur in molecular visualization videos. This discrepancy is likely due to the particular information available in a given animated presentation, however. This along with previous exposure to these techniques, as posited above, might explain the observers' plausibility ratings as a function of aesthetic preference for blur.

We suggest that some combination of the above is responsible for the preference of distortion among our participants. Animators boost or attenuate features of physically accurate motion to clarify and direct attention toward specific aspects of the animated object, such as material properties. Maybe naive observers do the same: they prefer conditions under which material properties are exaggerated, and therefore more salient (just as in machine algorithms for *motion magnification*; Oh et al., 2018).

4.5. Squash and stretch in material perception

Finally, our findings also have implications for the field of material perception. As described in the introduction section, *squash and stretch* can be used to emulate different materials, for example, moving objects exhibiting high levels of *squash and stretch* will be perceived as being soft and elastic and consequently, will be expected to rather bend than break under pressure. These effects of *squash and stretch* and other classical principles of animation are not yet studied systematically, and they might well affect the perception of a whole range of internal object properties, such as mass, fragility, stickiness, etc. (Schmid & Doerschner, 2018). It is also not clear to what extent the perception of material properties and plausibility do interact as previous studies showed that material properties are often judged based on simple heuristics related to specific visual features (e.g., Kawabe, 2019; Nishida, 2019). For example, the mass of two moving, colliding objects might be judged based on relative speed of objects after collision (Todd & Warren, 1982), the elasticity of a bouncing ball on the height of subsequent bounces (Warren, Kim, & Husney, 1987), or the softness of objects on their deformation (Paulun et al., 2017; Schmidt et al., 2017). Here, we demonstrate that a specific type of deformation — *squash and stretch* — let observers judge events as being more plausible than would be warranted if our judgments were based on physical accuracy. However, would the decrease in plausibility with high deformation values also diminish judgments about perceived softness or elasticity? If not, as suggested by the vivid impressions of softness and elasticity from massive exaggerations in cartoons, to what extent are they independent? *Squash and stretch* and other animation techniques can be used to investigate these and related questions.

Here, we also tested for the first time how *squash and stretch* is interacting with visual appearance of objects, in terms of texture or colour, in shaping plausible percepts. Indeed, it seems that appearance (i.e., the different type of ball renderings in Experiment 4) is interacting with levels of *squash and stretch* and COR. However, distortion and exaggeration are tolerated — even with compelling photorealistic depictions of the bouncing balls. This observation is in line with a preference of observers for depictions of objects with enhanced relevant features, potentially to allow them to better estimate the objects' material properties.

4.6. Limitations and future directions

Squash and stretch is the first of the Twelve Principles of Animation (Table 1) and some of the other principles can be considered its variants (e.g., Principle 6: slowing (or easing) in and out; Principle 9: timing) so that they can also be investigated within our paradigm. Here, we varied only a few selected parameters but not others, such as the time at which the deformation occurred, the time interval in which the deformation was manifesting ("ease-in") or going away ("ease-out"), or the time interval in which the ball was "sticking" to the ground between bounces.

Note that we tested the situation in which the ball is deforming before and after ground contact, which is physically less plausible compared to a deformation *only after* contact (both variants of *squash and stretch* are used in animations) — by which we potentially underestimated *squash and stretch* effects.

Also note that we explicitly measured the *plausibility* of the perceived *squash and stretch* motion rather than its *realism*. This is because we did not want participants to focus on spurious aspects, such as the realism of the rendering. Also, they might have been prompted to report their knowledge of whether *squash and stretch* is occurring in the real world, without much consideration of whether the motion in our stimuli looks visually convincing and plausible. Of course, investigating to what extent participants believe *squash and stretch* to be a physical phenomenon (e.g., by asking for the realism of single video frames), is a very interesting question in itself but not the goal of this work.

For the sake of simplicity, we did not yet test interactions between objects. Future studies might investigate to what extent plausibility, but also internal properties of objects, are affected by different *squash and stretch* behavior of two (or more) interacting objects.

Finally, there are other cognitive effects of *squash and stretch* where systematic investigation is still pending, such as perceived animacy (Kawabe, 2017) and evoked as well as perceived emotions (Thomas & Johnston, 1981).

4.7. Conclusion

Observers welcomed distortions in the generic condition regardless of the ball's physical properties. More specific depiction constrained ratings but observers still tolerated significant exaggeration. More realistic depiction limited but did not eliminate exaggeration effects. Accordingly, we propose there is an animator in all of us that prefers depictions of objects where relevant features are enhanced, similar to caricature-based distortions (e.g., Rhodes, Byatt, Tremewan, & Kennedy, 1997), potentially allowing us easier access to material properties.

CRediT authorship contribution statement

Filipp Schmidt: Writing – review & editing, Writing – original draft, Visualization, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Laura Noejovich:** Writing – review & editing, Investigation, Conceptualization. **George Chakalos:** Writing – review & editing, Investigation, Conceptualization. **Flip Phillips:** Writing – review & editing, Writing – original draft, Visualization, Software, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The stimuli and data for all experiments can be obtained from https://zenodo.org/doi/10.5281/zenodo.12666464.

Acknowledgments

This research was funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation), project number 222641018–SFB/TRR 135 TP C1, a grant to FP from the Fulbright Foundation, and award #2238180 to FP from the National Science Foundation. GC and LN were supported with a Skidmore Summer Collaborative Research Grant. We wish to thank Jasmin Kleis for help in data collection, Jacob Cheeseman, Pete Docter, Elizabeth Vega, Kevin Bauer and Roland W. Fleming for helpful comments and discussions.

The stimuli and data for all experiments can be obtained from https://zenodo.org/doi/10.5281/zenodo.12666464.

References

Adams, L. P., & Spirakis, A. (1997). Stereo photogrammetry. In J. F. Orr, & J. C. Shelton (Eds.), *Optical measurement methods in biomechanics* (pp. 17–38). Springer. https://doi.org/10.1007/978-0-585-35228-2_2.

Adelson, E. H. (2001). On seeing stuff: The perception of materials by humans and machines. In B. E. Rogowitz, & T. N. Pappas (Eds.), *Human vision and electronic imaging*. SPIE. https://doi.org/10.1117/12.429489.

CalArts Animation. (2007). *CalArts producers' show intro*. Retrieved from https://www.youtube.com/watch?v=YA7V6fwzJtI.

Barzel, R., Hughes, J. R., & Wood, D. N. (1996). Plausible motion simulation for computer graphics animation. In R. Boulic, & G. Hégron (Eds.), *Computer animation and simulation* (pp. 183–197). Springer. https://doi.org/10.1007/978-3-7091-7486-9_13.

Beaudine, W., & Jackson, W. (1956). *The plausible impossible*.

Chang, B.-W., & Ungar, D. (1993). Animation: From cartoons to the user Interface. In *Proceedings of the 6th annual ACM symposium on user interface software and technology*. https://doi.org/10.1145/168642.168647. ACM Press.

Chenney, S., Pingel, M., Iverson, R., & Szymanski, M. (2002). Simulating cartoon style animation. In *Proceedings of the second international symposium on non-photorealistic animation and rendering*. https://doi.org/10.1145/508530.508553. ACM Press.

Collomosse, J. P., & Hall, P. M. (2005). Video paintbox: The fine art of video painting. *Computers & Graphics, 29*(6), 862–870. https://doi.org/10.1016/j.cag.2005.09.003

Collomosse, J. P., Rowntree, D., & Hall, P. M. (2005). Rendering cartoon-style motion cues in post-production video. *Graphical Models, 67*(6), 549–564. https://doi.org/10.1016/j.gmod.2004.12.002

Cutting, J. E. (2002). Representing motion in a static image: Constraints and parallels in art science, and popular culture. *Perception, 31*(10), 1165–1193. https://doi.org/10.1068/p3318

Cutting, J. E. (2019). Sequences in popular cinema generate inconsistent event segmentation. *Attention, Perception, & Psychophysics, 81*, 2014–2025.

Eschner, J., Mindek, P., & Waldner, M. (2023). Illustrative motion smoothing for attention guidance in dynamic visualizations. In *Eurographics conference on visualization*. https://doi.org/10.48550/arXiv.2305.16030

Fleischer, M. (1917). Method of producing moving-picture cartoons. US patent. Retrieved from https://patents.google.com/patent/US1242674A/en?inventor=Fleischer+Max.

Fleming, R. W. (2014). Visual perception of materials and their properties. *Vision Research, 94*, 62–75. https://doi.org/10.1016/j.visres.2013.11.004

Fox, R., & McDaniel, C. (1982). The perception of biological motion by human infants. *Science, 218*(4571), 4486–4487. https://doi.org/10.1126/science.7123249

Garcia, M., Dingliana, J., & O'Sullivan, C. (2008). Perceptual evaluation of cartoon physics. In *Proceedings of the 5th symposium on applied perception in graphics and visualization*. https://doi.org/10.1145/1394281.1394301. ACM Press.

Geller, T. (2008). Overcoming the uncanny valley. *IEEE Computer Graphics and Applications, 28*(4), 11–17. https://doi.org/10.1109/MCG.2008.79

Heider, F., & Simmel, M. (1944). An experimental study of apparent behavior. *The American Journal of Psychology, 57*(2), 243. https://doi.org/10.2307/1416950

Jensen, R. K. (1978). Estimation of the biomechanical properties of three body types using a photogrammetric method. *Journal of Biomechanics, 11*(8–9), 349–358. https://doi.org/10.1016/0021-9290(78)90069-6

Kawabe, T. (2017). Perceiving animacy from deformation and translation. *i-Perception, 8*(3), Article 204166951770776. https://doi.org/10.1177/2041669517707767

Kawabe, T. (2019). Visual assessment of causality in the Poisson effect. *Scientific Reports, 9*(1), 14993. https://doi.org/10.1038/s41598-019-51509-x

Kawabe, T. (2020). Mid-air action contributes to pseudo-haptic stiffness effects. *IEEE Transactions on Haptics, 13*(1), 18–24. https://doi.org/10.1109/toh.2019.2961883

Kwon, J.-Y., & Lee, I.-K. (2007). Rubber-like exaggeration for character animation. In *Pacific conference on computer graphics and applications*. https://doi.org/10.1109/pg.2007.25. IEEE.

Kwon, J.-Y., & Lee, I.-K. (2008). Exaggerating character motions using sub-joint hierarchy. *Computer Graphics Forum, 27*(6), 1677–1686. https://doi.org/10.1111/j.1467-8659.2008.01177.x

Lasseter, J. (1987). Principles of traditional animation applied to 3D computer animation. In *Proceedings of the annual conference on computer graphics and interactive techniques*. https://doi.org/10.1145/37401.37407. ACM Press.

Learoyd, J. (2019). Animating the inanimate | anthropomorphism in object animation. HeadStuff. Retrieved from https://headstuff.org/culture/visual-arts/animating-the-inanimate-anthropomorphism-in-object-animation/.

Lee, S.-Y., Yoon, J.-C., Kwon, J.-Y., & Lee, I.-K. (2012). CartoonModes: Cartoon stylization of video objects through modal analysis. *Graphical Models, 74*(2), 51–60. https://doi.org/10.1016/j.gmod.2012.02.001

Lees, A. (2006). Learned deformable skeletons for motion capture based animation. In *Proceedings of the international conference on computer graphics and interactive techniques in australasia and southeast asia*. https://doi.org/10.1145/1174429.1174440. ACM Press.

Lissauer, G. (2014). *The tropes of fantasy fiction*. McFarland Publishers.

Mori, M. (2012). The uncanny valley. *IEEE Robotics and Automation Magazine, 19*(2), 98–100. https://doi.org/10.1109/mra.2012.2192811

Neri, P., Morrone, M. C., & Burr, D. C. (1998). Seeing biological motion. *Nature, 395*(6705), 894–896. https://doi.org/10.1038/27661

Nishida, S. (2019). Image statistics for material perception. *Current Opinion in Behavioral Sciences, 30*, 94–99. https://doi.org/10.1016/j.cobeha.2019.07.003

O'Donnell, M. (1985). Elementary education: An easy alternative to actual learning. In *In 19. a borzoi book*. Knopf.

Oh, T.-H., Jaroensri, R., Kim, C., Elgharib, M., Durand, F., Freeman, W., & Matusik, W. (2018). Learning-based video motion magnification. In *European conference on computer vision* (pp. 663–679). Springer. https://doi.org/10.1007/978-3-030-01225-0_39.

Pan, J. S., Bingham, N., & Bingham, G. P. (2013). Embodied memory: Effective and stable perception by combining optic flow and image structure. *Journal of Experimental Psychology: Human Perception and Performance, 39*(6), 1638–1651. https://doi.org/10.1037/a0032070

Paulun, V. C., Schmidt, F., van Assen, J. J. R., & Fleming, R. W. (2017). Shape motion, and optical cues to stiffness of elastic objects. *Journal of Vision, 17*(1), 20. https://doi.org/10.1167/17.1.20

Peirce, J., Gray, J. R., Simpson, S., MacAskill, M., Höchenberger, R., Sogo, H., … Lindeløv, J. K. (2019). PsychoPy2: Experiments in behavior made easy. *Behavior Research Methods, 51*(1), 195–203. https://doi.org/10.3758/s13428-018-01193-y

Pointer, R. (2017). *The art and inventions of max fleischer: American animation pioneer*. McFarland Publishers.

Rhodes, G., Byatt, G., Tremewan, T., & Kennedy, A. (1997). Facial distinctiveness and the power of caricatures. *Perception, 26*, 207–223. https://doi.org/10.1068/p260207

Ribeiro, T., & Paiva, A. (2012). The illusion of robotic life. In *Proceedings of the annual acm/ieee international conference on human-robot interaction*. https://doi.org/10.1145/2157689.2157814. ACM Press.

Ruhland, K., Prasad, M., & McDonnell, R. (2017). Data-driven approach to synthesizing facial Animation using motion capture. *IEEE Computer Graphics and Applications, 37*(4), 30–41. https://doi.org/10.1109/mcg.2017.3271467

Sasaki, K., Ihaya, K., & Yamada, Y. (2017). Avoidance of novelty contributes to the uncanny valley. *Frontiers in Psychology, 8*. https://doi.org/10.3389/fpsyg.2017.01792

Schmid, A. C., & Doerschner, K. (2018). Shatter and splatter: The contribution of mechanical and optical properties to the perception of soft and hard breaking materials. *Journal of Vision, 18*(1), 14. https://doi.org/10.1167/18.1.14

Schmidt, F., Noejovich, L., Chakalos, G., & Phillips, F. (2024). Dataset for perceptual plausibility of exaggerated realistic motion. *Zenodo*. https://doi.org/10.5281/zenodo.12666464

Schmidt, F., Paulun, V. C., van Assen, J. J. R., & Fleming, R. W. (2017). Inferring the stiffness of unfamiliar objects from optical shape, and motion cues. *Journal of Vision, 17*(3), 18. https://doi.org/10.1167/17.3.18

Solomon, C. (1994). *Enchanted drawings: The history of animation*. Wings Books.

Takayama, L., Dooley, D., & Ju, W. (2011). Expressing thought. In *Proceedings of the international conference on human-robot interaction*. https://doi.org/10.1145/1957656.1957674. ACM press.

Thomas, B. H., & Calder, P. (2001). Applying cartoon animation techniques to graphical user interfaces. *ACM Transactions on Computer-Human Interaction, 8*(3), 198–222. https://doi.org/10.1145/502907.502909

Thomas, B. H., & Calder, P. (2005). Supporting cartoon animation techniques in direct manipulation graphical user interfaces. *Information and Software Technology, 47*(5), 339–355. https://doi.org/10.1016/j.infsof.2004.09.003

Thomas, F., & Johnston, O. (1981). *The illusion of life: Disney animation*. Abbeville Press.

Todd, J. T., & Warren, W. H. (1982). Visual perception of relative mass in dynamic events. *Perception, 11*(3), 325–335. https://doi.org/10.1068/p110325

Ujitoko, Y., & Kawabe, T. (2022). Perceptual judgments for the softness of materials under indentation. *Scientific Reports, 12*(1), 1761. https://doi.org/10.1038/s41598-022-05864-x

Wang, J., Drucker, S. M., Agrawala, M., & Cohen, M. F. (2006). The cartoon animation filter. In *ACM SIGGRAPH*. https://doi.org/10.1145/1179352.1142010. ACM Press.

Warren, W. H., Kim, E. E., & Husney, R. (1987). The way the ball bounces: Visual and auditory perception of elasticity and control of the bounce pass. *Perception, 16*(3), 309–336. https://doi.org/10.1068/p160309

Wertheimer, M. (1912). Experimentelle studien über das sehen von bewegung. *Zeitschrift für Psychologie, 61*.

Witkin, A., & Kass, M. (1988). Spacetime constraints. *ACM SIGGRAPH Computer Graphics, 22*(4), 159–168. https://doi.org/10.1145/378456.378507

Wobbrock, J. O., Findlater, L., Gergle, D., & Higgins, J. J. (2011). The aligned rank transform for nonparametric factorial analyses using only ANOVA procedures. In

Proceedings of the ACM conference on human factors in computing systems (pp. 143–146). ACM Press https://doi.org/10.1145/1978942.1978963.

Xiao, J., Zhuang, Y., Yang, T., & Wu, F. (2006). An efficient keyframe extraction from motion capture data. *Advances in Computer Graphics*, 494–501. https://doi.org/10.1007/11784203_44

Yamada, Y., Kawabe, T., & Ihaya, K. (2012). Categorization difficulty is associated with negative evaluation in the uncanny valley phenomenon. *Japanese Psychological Research, 55*(1), 20–32. https://doi.org/10.1111/j.1468-5884.2012.00538.x