Sackcloth or Silk? The Impact of Appearance vs Dynamics on the Perception of Animated Cloth

Carlos Aliaga[1,2] Carol O'Sullivan[3] Diego Gutierrez[2] Rasmus Tamstorf[1]
[1] Walt Disney Animation Studios [2] Universidad de Zaragoza [3] Disney Research Los Angeles

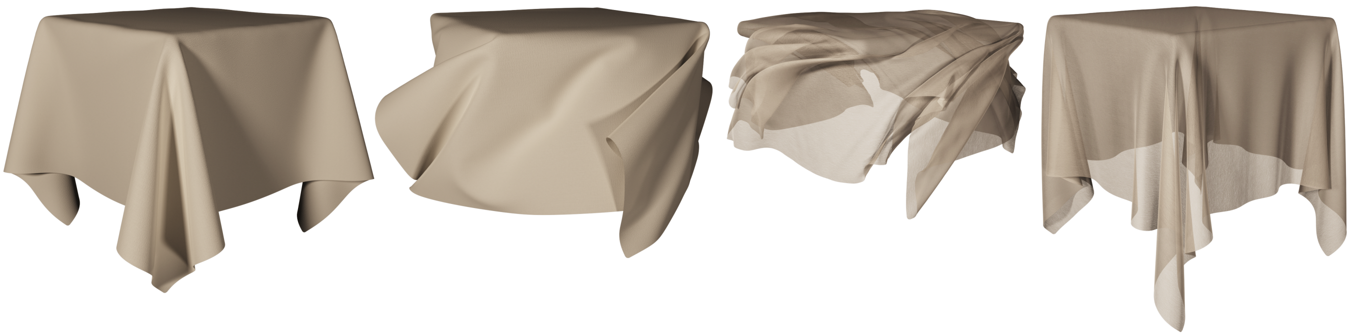

Figure 1: *Different fabrics have both different visual appearance and mechanical properties. We create replicas of several common woven fabrics, like the cotton or silk shown in the image, covering a wide range of movements in a set of video stimuli. Then, we combine the appearance of each fabric with the dynamics of the other ones and vice versa, and perform psychophysical experiments to study the relative importance of appearance and dynamics when perceiving cloth.*

Abstract

Physical simulation and rendering of cloth is widely used in 3D graphics applications to create realistic and compelling scenes. However, cloth animation can be slow to compute and difficult to specify. In this paper, we present a set of experiments in which we explore some factors that contribute to the perception of cloth, to determine how efficiency could be improved without sacrificing realism. Using real video footage of several fabrics covering a wide range of visual appearances and dynamic behaviors, and their simulated counterparts, we explore the interplay of visual appearance and dynamics in cloth animation.

CR Categories: I.3.7 [Computer Graphics]: Three-Dimensional Graphics and Realism—Animation

Keywords: Perception; Cloth Simulation; Cloth Rendering; Appearance Modelling

1 Introduction

3D animation is becoming more and more sophisticated. With the evolution of rendering algorithms, motion capture techniques and physics simulators, new productions progressively offer more complex shots and more stunning visuals. However, it is often the case that intricately modeled details and complex simulations are employed to create scene elements that may go unnoticed by the viewer, which is not a very efficient use of resources.

This leads to the following question, which we aim to investigate in this paper: *Do all elements of a simulation need to be physically correct in order to achieve realism?* Given the very large space of possible parameters, we focus here on a very common scenario where physically-based simulations are employed in current 3D application areas: the rendering and animation of photo-realistic cloth. In particular, we analyze the interplay of visual appearance and dynamics and how it affects the viewer. The goal is to analyze when (and if) a simplified simulation can be used in the presence of a very accurate shader, or vice versa. Do both appearance and dynamics need to be perfectly simulated in order to convey the desired impression? Can different strategies be employed depending on the particular types of fabric being depicted?

To answer these questions, we first captured videos of seven different real cloth samples made of different fabrics covering a wide range of visual appearances and dynamic behaviors. We also created photo-realistic synthetic versions that emulated the real cloth samples as closely as possible. Given these seven ground-truth animations, we rendered all possible combinations of appearance and dynamics, yielding a 7x7 stimulus matrix where only the diagonal elements had matching characteristics. We then conducted two perceptual experiments, where participants were asked to match these stimuli with the ground-truth filmed videos, and were also asked to identify which animation had mismatching motion and appearance properties.

To our knowledge, this is the first effort towards understanding the relative weightings of appearance and dynamics on the perception of photo-realistic animated cloth. Although we focus here on the particular case of cloth simulation, our methodology could be extended to other scenarios. Our results may be useful to guide a better distribution of resources when planning shots involving cloth simulations, or could affect how shot approvals are done. For instance, if the perception of a given fabric is strongly influenced by its visual appearance and less by its dynamics, then viewing the simulation without a reasonable depiction of the final shader to be employed, and vice versa, would not be sufficient to predict the final result.

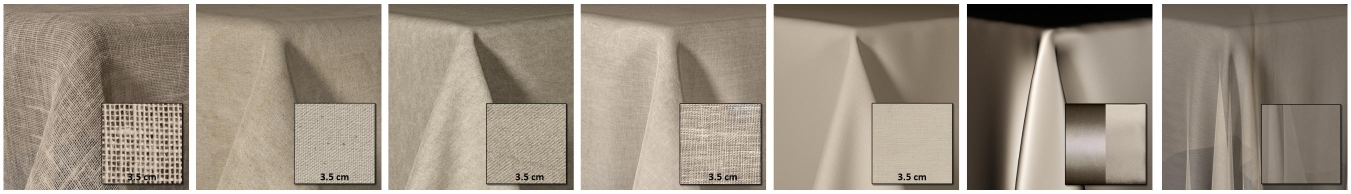

Figure 2: *Comparison between the real fabrics and the CG replicas. From left to right: burlap, canvas, denim, linen, cotton, polyester satin and sheer silk. The images show renders, the insets are close up pictures of the real fabrics in the case of the first five rows. In the case of the last two fabrics on the right (polyester satin and sheer silk), the weaving pattern is too small to notice at normal viewing distances. Thus, for polyester satin the inset shows the fabric wrapping a cylinder along the warp and weft directions to show the viewing and lighting dependent anisotropic highlights. For the sheer silk, the inset shows the real fabric draping the swivel stool.*

2 Related Work

Perceptually-based computer graphics is an active research field. The key idea is to take into account the limits of the human visual system to improve the efficiency of realistic image synthesis and animation. We refer the interested reader to the many existing surveys and courses (e.g., [O'Sullivan et al. 2004; Bartz et al. 2008; McNamara et al. 2011]), and focus here on appearance and dynamics.

Appearance Many approaches focus on generating visually plausible materials. Pellacini et al. [2000], Westlund and Meyer [2001] and Ferwerda et al. [2001] developed psychophysically-based models for gloss perception. Wills et al. [2009] performed similar experiments to derive a perceptual space of measured BRDFs. Vangorp et al. [2007] evaluated the influence of shape and illumination on surface gloss perception, showing how objects with smooth bumps provide more cues than simpler ones like spheres. Other studies include translucency and subsurface scattering [Fleming and Bülthoff 2005; Gkioulekas et al. 2013], or surface texture and reflectance [Dana et al. 1999; Filip et al. 2008; Jarabo et al. 2014] . Fleming and colleagues [2001; 2003] conducted reflectance matching experiments to demonstrate that people can recognize material properties more accurately under natural illumination than under artificial lights. Other examples focus on perceptually guided global illumination [Myszkowski 2002; Stokes et al. 2004]. Ramanarayanan and colleagues [2007; 2008] evaluated the effects of changes in environment lighting over different shapes and materials. Through several transformations in the illumination maps, such as warping or blurring, they found that many objects had the same appearance (they are visually equivalent) when illuminated by both transformed and original maps. Similar studies evaluated the effect of approximations in illumination on the perception of complex animated scenes [Jarabo et al. 2012] or materials [Křivánek et al. 2010].

Dynamics Some studies have evaluated the effects of degrading or distorting physically-based simulations on the perceived plausibility of animations, e.g., [O'Sullivan et al. 2003; Yeh et al. 2009; Han et al. 2013]. Similar studies have also been conducted in the context of cartoons [Garcia et al. 2008]. Other works focus on collisions; O'Sullivan et al. [1999] developed a model of collision perception for real-time animation, while Dingliana and O'Sullivan [2000; 2001] examined the perception of detail simplifications for LOD rigid-body physically-based animation. Some other works evaluate the perception of dynamics on animated characters. Reitsma et al. [2003] studied the visual tolerance of ballistic motion for character animation, finding that horizontal velocity errors are more detectable than vertical. Vicovaro et al. [2012] evaluated the plausibility of altered throwing motions. Finally, Hoyet et al. [2012] conducted several phsycophysical experiments to measure the perceived realism of pushing interactions, evaluating the influence of timing errors or force mismatches.

Two previous studies are relevant to our work. McDonnell et al. [2006] evaluated the perceptual impact of different geometric and image-based LOD representations of animated cloth, and guidelines for developing crowd systems with realistic clothed humans were presented. Most recently, Sigal et al. [2015] developed a perceptual control space for cloth dynamics, mapping the complex parameters from any physical simulator to a few intuitive and meaningful parameters learned from a set of perceptual experiments.

3 Stimuli Creation

In order to cover a reasonable range of different fabric appearances and dynamics, we chose seven commonly used woven cloths. In approximate order of more to less stiff, the selected fabrics are: Burlap (also commonly known as Sackcloth), Canvas, Denim, Linen, Cotton, Polyester satin and sheer Silk. We acquired real samples of all of them, cut into squares of 1x1 meters. They all are of roughly the same albedo, in order to avoid color being a confounding factor for the experiments (see Figure 2).

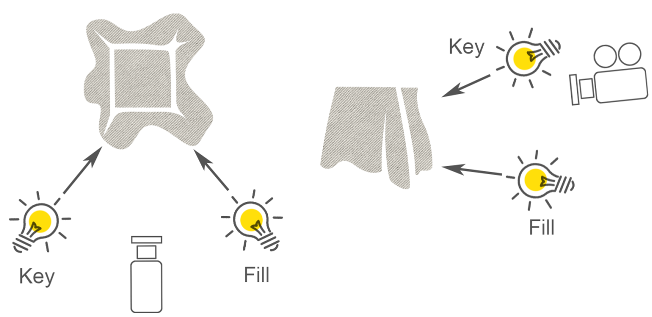

Figure 3: *Lighting studio setup for capturing the video footage of the real cloth samples, from bottom and side views.*

We then recorded videos of all the fabrics in a studio with diffuse black walls, floor, and roof, using two spot lights placed at about 45 degrees from the focal plane (Figure 3). Every piece of cloth was recorded while draping over a flat swivel stool which then spins, in order to show as many mechanical and dynamic properties of the fabric as possible (e.g., shape of the folds, angle of swing). View-dependent appearance features for each fabric are also visible in this way. We ensured that the movement was as similar as possible for each fabric.

To create computer generated replicas of the reference fabrics, we needed to emulate both the appearance and the dynamics. Note that appearance refers to the spatially varying reflected radiance of the cloths, which depends on several factors such as the texture pattern or the optical properties of the fabrics (e.g.: albedo or surface scattering). All pieces of cloth were rendered using path tracing with deferred shading [Eisenacher et al. 2013], simulating rough dielectric materials with diffuse transmittance, together with albedo, bump and opacity textures. For these, a set of close-up pictures perpendicular to the fabrics was taken to generate tileable seamless textures representing patches of 30x30 cm. The only exception was polyester satin; given its more anisotropic reflectance and color shifts, we relied on the empirical microcylinder model of Sadeghi and colleages [2013]. Figure 2, shows the appearance of the final CG replicas.

The dynamics of the different fabrics were simulated by modeling the cloth as a triangular mesh, along with proximity forces to prevent primitives near each other from colliding, as proposed by Baraff and Witkin [1998]. Similarly, we use additional constraints for cloth-object collisions. If continuous time collisions remain after the initial solve, we rely on the robust collision algorithm from Bridson et al. [2002], augmented by a fail-safe that cancels impact while maintaining sliding motion [Harmon et al. 2008]. We relied on physical parameters given by the manufacturer when available (such as density and thickness, e.g., burlap weighs $207g/m^2$ with 0.69mm thickness, while the values for silk are $207g/m^2$ and 0.69mm); all the remaining parameters were manually adjusted to obtain a result as close as possible to the real cloth properties (see Figure 4).

We then rendered all possible combinations of appearance and dynamics, yielding 7x7=49 videos (six seconds each) replicating the movement in the recorded video. Thus for each row (column) of the matrix, only one rendered video matches the appearance with the correct dynamics. In addition, to study the effect of viewing distance on the perception of mismatched properties, we rendered all of the stimuli at three different camera distances, resulting in resolutions of 1728x1123, 1000x650 and 520x338 from close to far viewing distances respectively. A selection from this full set of 49x3=147 videos is included in this submission as supplementary material (the full set exceeds the upload limit). Note that we rendered all videos with the swivel stool rotating in the opposite direction from the real videos, to avoid that participants would base their judgments on exact visual matching.

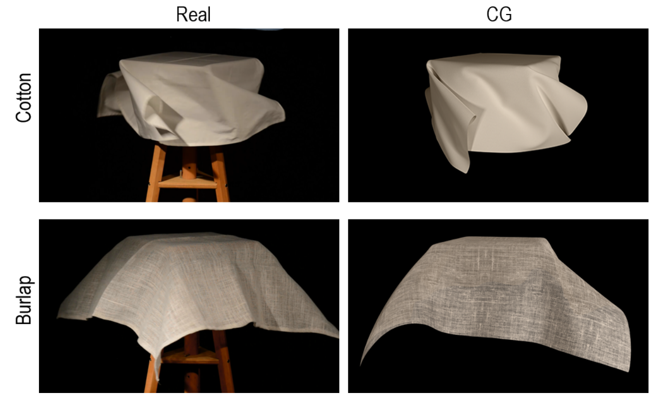

Figure 4: *Comparison between the movements of the real cloth smaples and the CG replicas. The first row shows the cotton rotating at the maximum speed. The second row shows the burlap at the frame just before starting to stabilize. Note that the real and CG samples are rotating in the same direction in these images just for comparison, but do so in opposite directions during the experiments to avoid exact image matching. To emulate the cloth motion, we paid special attention to the number, size and shape of the folds created (both at static and dynamic frames), the amount of bouncing, the effect of air forces, and the maximum height and width reached when rotating. For further comparisons, a selection of the videos are included in the supplementary material.*

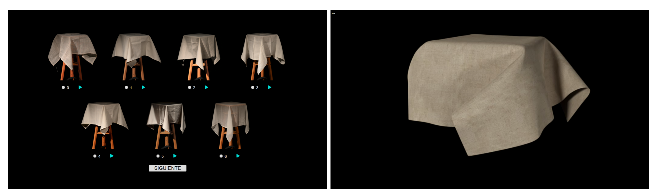

Figure 5: *Two screen layout for the experiment 1. On the left, the navigation screen with the seven real (ground truth) reference fabrics. Each thumbnail has a radio button for selection and a replay button. On the right, the CG cloth that is currently being displayed.*

4 Experiments

To answer the questions set out in our introduction, we conducted two perception experiments with 63 naive participants (34F/29M, aged 18–27) with varying levels of experience in computer graphics. We counterbalanced the order in which they performed Experiment 1 and Experiment 2, to avoid ordering effects.

4.1 Experiment One: Ground Truth comparison

The goal of the first experiment is twofold: firstly, to evaluate how effective the simulations were at capturing the appearance and dynamics of the real stimuli; and secondly, to determine whether either dynamics or appearance were more important when animating photo-realistic cloth.

We chose an experimental design where each participant only watches a subset of the stimuli, in order to avoid fatigue effects. Thus, the stimuli are distributed among participants ensuring that each video is seen by 45 different people, and each person sees 105 different samples of the total set of 147.

Two equally calibrated screens of the same model were used for the experiment (Dell U2311H IPS FullHD 23”). On the right screen, one of the 147 rendered videos is shown, and the participant is asked the question: ’Which of the reference cloths on the left best matches the one on the right?’. The participant can answer by choosing any of the seven reference cloths shown in thumbnails on the left (Figure 5). She can replay any of these reference ground truth videos again, as many times as needed until an answer is given (there is no time limit). Each time a reference video is replayed at full resolution on the left, the current CG replica that is being evaluated is played on the right for comparison purposes. Both videos are synchronized, but the cloths rotate in opposite directions to discourage exact visual pattern matching.

At the start of the experiment, we ensure all participants have familiarized themselves with all real stimuli. All participants are shown a representative frame of every one of the seven reference videos as a thumbnail on the left screen. They view all of the videos by clicking on each of these thumbnails, and the corresponding six-second video is played on the right screen. They can repeat each one as many times as needed. The experiment took between 25 and 45 minutes, separated in two halves by a 5-minute break.

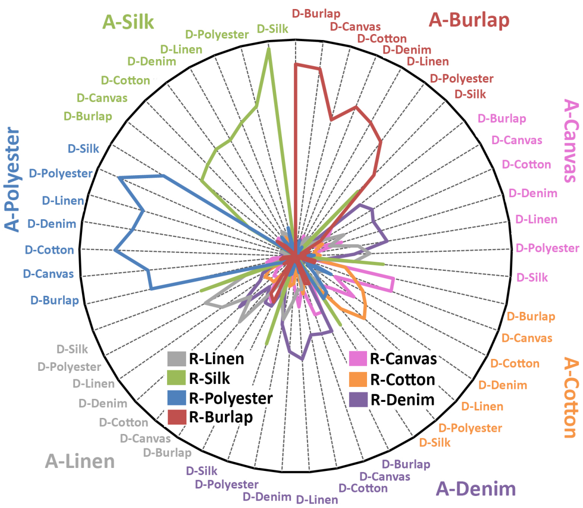

Figure 6: *Experiment 1 results, summarized as a radar graph and collapsed over distance (which had no effect). The colored areas in the graph represent how often each Response was given for the Appearance/Dynamics combinations depicted on the perimeter.*

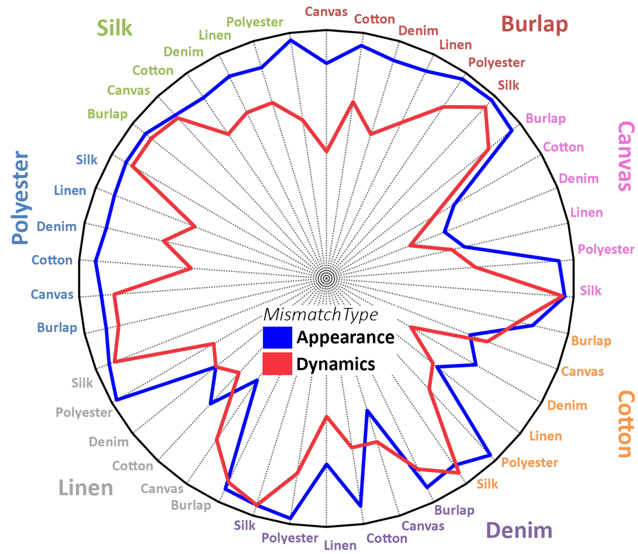

Figure 7: *Experiment 2 results, summarized as a radar graph and collapsed over distance (which had no effect). The outermost labels on the perimeter indicate the "correct" fabric, while the innermost ones show the mis-matched one. The two line graphs indicate the percentage of mismatches accurately detected for the two types of mismatch: appearance or dynamics.*

Experiment One: Results. Because of the way we designed our experiment, we were able to cross-tabulate all participant responses by summarizing them in a *Multi-way Frequency Table*. The variable combinations for which frequency counts were calculated were: (1) *Distance* x 3 (close, medium, far), (2) *Appearance* x 7 (denoted A-Burlap, A-Canvas, A-Cotton, A-Denim, A-Linen, A-Polyester, A-Silk), (3) *Dynamics* x 7 (D-Burlap – D-Silk) and (4) *Response* x 7 (R-Burlap – R-Silk). The results are shown in Figure 6.

We then analyzed these data using Log-Linear Analysis, which allows us to find the best model to fit the observed data. In the case of Figure 6, the best model was (2,4), (3,4), meaning that there was a main effect of both Appearance(2) and Dynamics (3) on the Response (4) given. However, the distance from the camera had no effect on the responses. From Figure 6 we can see that appearance dominated the responses for three fabrics: Burlap, Silk and Polyester. There was more confusion between the other materials. We also looked at how often Dynamics affected the choices, and the only material where dynamics was very influential was for Silk, where the green line in the figure shows how the response was always silk when the dynamics were silk, and silk was also often picked when the appearance was a different material (e.g., see the green spike for A-Burlap).

4.2 Experiment Two: Identifying Mismatches

The main goal of this experiment is to determine how accurate participants were at identifying mismatches between the appearance and dynamics of photo-realistic cloth animations. First, as in Experiment One, participants are shown the seven real videos at the beginning and are allowed to replay them until they become familiar with them. Once the test begins, one of the recorded videos is shown on the left screen while two CG videos from our stimuli matrix are shown side-by-side on the right screen. One of the CG videos is always the corresponding replica of the real video shown, with matching appearance and dynamics, while the other one has been rendered with either the appearance or the dynamics from a different cloth. The order is randomized for each pair of stimuli. This leads to 252 combinations in total: 7 fabrics x 12 mismatched options (6 each for appearance and dynamics) x 3 viewing distances. The participant is asked which of the two simulated cloths on the right is most similar to the ground-truth cloth video shown on the left. There is no time limit, and the participant is allowed to replay the videos as often as necessary.

As in the previous experiment, we opted for an experimental design where each participant only watches a subset of the stimuli in order to avoid fatigue effects. Thus, the stimuli are distributed so as to ensure that each stimulus pair is seen by 45 different people, and each person sees 180 different samples of the total set of 252.
This experiment lasted between 50 and 70 minutes, again divided in two parts by a break of 5–10 minutes. The experiment was performed using the same screens and controlled settings as in Experiment One.

Experiment Two: Results. As in the previous experiment, we were able to cross-tabulate all participant data by summarizing the percentage of correctly identified mismatches in a multi-way frequency table, and statistically analyzed them using Log-Linear Analysis. Again, distance had no effect on the results, but both Appearance, Dynamics, and their interaction did. The results are shown in Figure 7. We can again see that appearance mismatches were most easily detected for most, but not all, fabrics, whereas participants were more confused about the dynamics mismatches.

5 Conclusions

In this paper, we have presented the results of two perceptual experiments where we explored the interactions of appearance and dynamics of seven common woven fabrics. We demonstrate how appearance dominates over dynamics, except for the few cases where dynamics are very characteristic, such as in the case of silk. We also found that these effects are robust across different viewing distances.

As future work, it would be interesting to consider some other factors that may have an effect on the perception of moving cloth (e.g. different illumination conditions such as environment lighting), or to explore more deeply the influence of the most important factors of cloth simulation considered here (e.g. BRDF and spatial frequency of the textures in the case of the appearance, dynamics parameters in the case of motion synthesis). Finally, performing a similar study with animated characters wearing clothes made from these fabrics would allow us to confirm our findings in more ecologically valid and familiar scenarios.

Acknowledgements

Thanks to all the participants in our experiments and to the anonymous reviewers for their feedback. We also wish to acknowledge additional funding from national project Lightslice and the Gobierno de Aragón.

References

BARAFF, D., AND WITKIN, A. 1998. Large steps in cloth simulation. In *Proc. SIGGRAPH'98*, 43–54.

BARTZ, D., CUNNINGHAM, D., FISCHER, J., AND WALLRAVEN, C. 2008. The role of perception for computer graphics. In *Eurographics State-of-the-Art Reports*, 65–86.

BRIDSON, R., FEDKIW, R., AND ANDERSON, J. 2002. Robust treatment of collisions, contact and friction for cloth animation. *ACM Trans. Graph. 21*, 3, 594–603.

DANA, K. J., VAN GINNEKEN, B., NAYAR, S. K., AND KOENDERINK, J. J. 1999. Reflectance and texture of real-world surfaces. *ACM Trans. Graph. 18*, 1, 1–34.

DINGLIANA, J., AND O'SULLIVAN, C. 2000. Graceful degradation of collision handling in physically based animation. *Comp. Graph. Forum 19*, 3, 239–248.

EISENACHER, C., NICHOLS, G., SELLE, A., AND BURLEY, B. 2013. Sorted deferred shading for production path tracing. *Comp. Graph. Forum 32*, 4, 125–132.

FERWERDA, J. A., PELLACINI, F., AND GREENBERG, D. P. 2001. Psychophysically based model of surface gloss perception. In *Proc. Photonics West–Electronic Imaging*, 291–301.

FILIP, J., CHANTLER, M. J., GREEN, P. R., AND HAINDL, M. 2008. A psychophysically validated metric for bidirectional texture data reduction. *ACM Trans. Graph. 27*, 5, 138:1–138:11.

FLEMING, R. W., AND BÜLTHOFF, H. H. 2005. Low-level image cues in the perception of translucent materials. *ACM Trans. Applied Perception 2*, 3, 346–382.

FLEMING, R. W., DROR, R. O., AND ADELSON, E. H. 2001. How do humans determine reflectance properties under unknown illumination? In *Proc. IEEE Workshop on Identifying Objects across Variations in Lighting: Psychophysics and Computation*.

FLEMING, R. W., DROR, R. O., AND ADELSON, E. H. 2003. Real-world illumination and the perception of surface reflectance properties. *Journal of Vision 3*, 5, 347–368.

GARCIA, M., DINGLIANA, J., AND O'SULLIVAN, C. 2008. Perceptual evaluation of cartoon physics: accuracy, attention, appeal. In *Proc. Symp. on Applied Perception in Graph. and Visualization*, 107–114.

GKIOULEKAS, I., XIAO, B., ZHAO, S., ADELSON, E. H., ZICKLER, T., AND BALA, K. 2013. Understanding the role of phase function in translucent appearance. *ACM Trans. Graph. 32*, 5, 147:1–147:19.

HAN, D., HSU, S.-W., MCNAMARA, A., AND KEYSER, J. 2013. Believability in simplifications of large scale physically based simulation. In *Proc. ACM Symp. on Applied Perception*, 99–106.

HARMON, D., VOUGA, E., TAMSTORF, R., AND GRINSPUN, E. 2008. Robust treatment of simultaneous collisions. *ACM Trans. Graph. 27*, 3, 23:1–23:4.

HOYET, L., MCDONNELL, R., AND O'SULLIVAN, C. 2012. Push it real: perceiving causality in virtual interactions. *ACM Trans. Graph. 31*, 4, 90:1–90:9.

JARABO, A., EYCK, T. V., SUNDSTEDT, V., BALA, K., GUTIERREZ, D., AND O'SULLIVAN, C. 2012. Crowd light: Evaluating the perceived fidelity of illuminated dynamic scenes. *Comp. Graph. Forum 31*, 2pt3, 565–574.

JARABO, A., WU, H., DORSEY, J., RUSHMEIER, H., AND GUTIERREZ, D. 2014. Effects of approximate filtering on the appearance of bidirectional texture functions. *IEEE Trans. Visualization and Comp. Graph. 20*, 6, 880–892.

KŘIVÁNEK, J., FERWERDA, J. A., AND BALA, K. 2010. Effects of global illumination approximations on material appearance. *ACM Trans. Graph. 29*, 4, 112:1–112:10.

MCDONNELL, R., DOBBYN, S., COLLINS, S., AND O'SULLIVAN, C. 2006. Perceptual evaluation of lod clothing for virtual humans. In *Proc. ACM SIGGRAPH/Eurographics Symp. Computer Animation*, 117–126.

MCNAMARA, A., MANIA, K., AND GUTIERREZ, D. 2011. Perception in graphics, visualization, virtual environments and animation. In *SIGGRAPH Asia 2011 Courses*, 17:1–17:137.

MYSZKOWSKI, K. 2002. Perception-based global illumination, rendering, and animation techniques. In *Proc. Spring Conf. on Comp. Graph.*, 13–24.

O'SULLIVAN, C., AND DINGLIANA, J. 2001. Collisions and perception. *ACM Trans. Graph. 20*, 3, 151–168.

O'SULLIVAN, C., RADACH, R., AND COLLINS, S. 1999. A model of collision perception for real-time animation. In *Proc. Eurographics Workshop on Comp. Anim. and Sim.*, 67–76.

O'SULLIVAN, C., DINGLIANA, J., GIANG, T., AND KAISER, M. K. 2003. Evaluating the visual fidelity of physically based animations. *ACM Trans. Graph. 22*, 3, 527–536.

O'SULLIVAN, C., HOWLETT, S., MORVAN, Y., MCDONNELL, R., AND OCONOR, K. 2004. Perceptually adaptive graphics. In *Eurographics State-of-the-Art Reports*, vol. 4.

PELLACINI, F., FERWERDA, J. A., AND GREENBERG, D. P. 2000. Toward a psychophysically-based light reflection model for image synthesis. In *Proc. SIGGRAPH'00*, 55–64.

RAMANARAYANAN, G., FERWERDA, J., WALTER, B., AND BALA, K. 2007. Visual equivalence: towards a new standard for image fidelity. *ACM Trans. Graph. 26*, 3, 76.

RAMANARAYANAN, G., BALA, K., AND FERWERDA, J. A. 2008. Perception of complex aggregates. *ACM Trans. Graph. 27*, 3, 60:1–60:10.

REITSMA, P. S., AND POLLARD, N. S. 2003. Perceptual metrics for character animation: sensitivity to errors in ballistic motion. *ACM Trans. Graph. 22*, 3, 537–542.

SADEGHI, I., BISKER, O., DE DEKEN, J., AND JENSEN, H. W. 2013. A practical microcylinder appearance model for cloth rendering. *ACM Trans. Graph. 32*, 2, 14:1–14:12.

SIGAL, L., MAHLER, M., DIAZ, S., MCINTOSH, K., CARTER, E., RICHARDS, T., AND HODGINS, J. 2015. A perceptual control space for garment simulation. *ACM Trans. Graph.*.

STOKES, W. A., FERWERDA, J. A., WALTER, B., AND GREENBERG, D. P. 2004. Perceptual illumination components: a new approach to efficient, high quality global illumination rendering. *ACM Trans. Graph. 23*, 3, 742–749.

VANGORP, P., LAURIJSSEN, J., AND DUTRÉ, P. 2007. The influence of shape on the perception of material reflectance. *ACM Trans. Graph. 26*, 3, 77.

VICOVARO, M., HOYET, L., BURIGANA, L., AND O'SULLIVAN, C. 2012. Evaluating the plausibility of edited throwing animations. In *Proc. ACM SIGGRAPH/Eurographics Symp. on Comp. Anim.*, 175–182.

WESTLUND, H. B., AND MEYER, G. W. 2001. Applying appearance standards to light reflection models. In *Proc. SIGGRAPH'01*, 501–51.

WILLS, J., AGARWAL, S., KRIEGMAN, D., AND BELONGIE, S. 2009. Toward a perceptual space for gloss. *ACM Trans. Graph. 28*, 4, 103:1–103:15.

YEH, T. Y., REINMAN, G., PATEL, S. J., AND FALOUTSOS, P. 2009. Fool me twice: Exploring and exploiting error tolerance in physics-based animation. *ACM Trans. Graph. 29*, 1, 5:1–5:11.