

What causes the facing-the-viewer bias in biological motion?

Séamas Weech

Queen's University, Kingston, Ontario, Canada



Matthew McAdam

Queen's University, Kingston, Ontario, Canada



Sophie Kenny

Queen's University, Kingston, Ontario, Canada



Nikolaus F. Troje

Queen's University, Kingston, Ontario, Canada
Canadian Institute for Advanced Research, Toronto,
Ontario, Canada



Orthographically projected biological motion point-light displays are generally ambiguous with respect to their orientation in depth, yet observers consistently prefer the facing-the-viewer interpretation. There has been discussion as to whether this bias can be attributed to the social relevance of biological motion stimuli or relates to local, low-level stimulus properties. In the present study we address this question. In Experiment 1, we compared the facing-the-viewer bias produced by a series of four stick figures and three human silhouettes that differed in posture, gender, and the presence versus absence of walking motion. Using a paradigm in which we asked observers to indicate the spinning direction of these figures, we found no bias when participants observed silhouettes, whereas a pronounced degree of bias was elicited by most stick figures. We hypothesized that the ambiguous surface normals on the lines and dots that comprise stick figures are prone to a visual bias that assumes surfaces to be convex. The local surface orientations of the occluding contours of silhouettes are unambiguous, and as such the convexity bias does not apply. In Experiment 2, we tested the role of local features in ambiguous surface perception by adding dots to the elbows and knees of silhouettes. We found biases consistent with the facing directions implied by a convex body surface. The results unify a number of findings regarding the facing-the-viewer bias. We conclude that the facing-the-viewer bias is established at the level of surface reconstruction from local image features rather than on a semantic level.

Introduction

Heuristics and probabilistic inferences play a fundamental role in perception. Making assumptions about the world based on our experiences allows us to cope with the uncertainties of the immediate sensory stimulus and to organize it in a predictive and consistent manner. Biological motion provides an example of the ability of the visual system to organize minimal information to create a compelling percept. A few dots representing point-lights on major joints of a walking human figure create a vivid impression of an actor in motion (e.g., Johansson, 1973, 1976). Biological motion provides a wealth of information about the actor. Studies have shown that point-light walkers allow naïve observers to infer an actor's identity (Cutting & Kozlowski, 1977), the gender of the actor (Pollick, Kay, Heim, & Stringer, 2005; Troje, 2002), and details about the actor's emotional state (Michalak et al., 2009). An animal's size (Jokisch & Troje, 2003) and the weight of an object lifted by a person shown in a point-light display (Runeson & Frykholm, 1981) are also readily perceived from the motion of just a few strategically placed dots.

Point-light displays are commonly rendered as orthographic projections and presented without occlusions or other depth cues. Even if the visual system constrains the 2-D stimulus to represent a human figure, the representation is consistent with two different 3-D configurations. The two configurations are mirror-flipped versions reflected about the orthographic image plane. The mirror-flip about the projection plane has a number of perceptual consequences. For one, there is a change in perceived

Citation: Weech, S., McAdam, M., Kenny, S., & Troje, N. F. (2014). What causes the facing-the-viewer bias in biological motion? *Journal of Vision*, 14(12):10, 1–15, <http://www.journalofvision.org/content/14/12/10>, doi:10.1167/14.12.10.

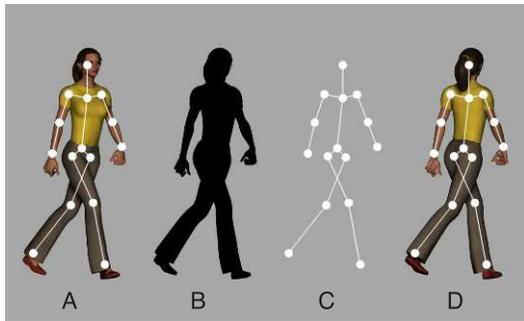


Figure 1. The figure demonstrates the depth-ambiguity of silhouettes and stick figures. Both A and D could have generated the silhouette, B. The same is true for the stick figure, C.

viewpoint with respect to the point-light display. If the display represents a fronto-parallel projection that is seen facing towards the observer, the mirror-flip configuration will face away from the observer. This reversal of facing direction following a mirror-flip also applies to any other orientation. Second, the perceived handedness of the figure undergoes a reversal, such that the right and left sides of the body are mirror-flipped and any asymmetry changes its sign. Finally, the mirror-flip about the image plane affects the perceived direction of rotation, meaning that the figure can be seen as spinning either clockwise (CW) or counter-clockwise (CCW) when set to rotate about the vertical axis.

Depth ambiguity and the perceptual switches that accompany it are not unique to point-light displays; they are also the basis for many popular illusions such as the Necker cube and the Schröder staircase. They also apply to the two classes of stimuli used in the current experiments: stick figures and silhouettes of human figures (see Figure 1).

The depth ambiguity of point-light displays and related stimuli gives rise to perceptual bistability: The two possible interpretations of such a stimulus alternate at regular intervals with observers rarely experiencing them simultaneously. However, in the case of point-light walkers, perceptual bistability is often masked by a strong bias to report a point-light walker as facing towards the observer rather than facing away. This facing-the-viewer bias was first described by Vanrie, Dekeyser, and Verfaillie (2004) who found that observers reported perceiving the facing-the-viewer interpretation of a point-light walker 80% of the time. Since then, the existence of a facing-the-viewer bias has been confirmed multiple times (Brooks et al., 2008; de Lussanet & Lappe, 2012; Jackson, Cummins, & Brady, 2008; Schouten, Davila, & Verfaillie, 2013; Schouten, Troje, Brooks, van der Zwan, & Verfaillie, 2010; Schouten, Troje, & Verfaillie, 2011; Schouten, Troje, Vroomen, & Verfaillie, 2011; Schouten & Verfaillie,

2010; Sweeny, Haroz, & Whitney, 2012; Troje, 2010; Troje & McAdam, 2010b; Vanrie & Verfaillie, 2006, 2011). Evidently, the visual system employs some kind of prior assumptions or heuristics when resolving the orientation of point-light walkers that leads to the facing-towards orientation being perceived more often.

Vanrie, Dekeyser, and Verfaillie (2004) also examined participants' perceptions of facing directions for inverted point-light walkers. These stimuli contain the low-level features of biological motion, but are less adequately perceived as representing human figures (Sumi, 1984). Vanrie, Dekeyser, and Verfaillie found much weaker facing-the-viewer biases for inverted figures and concluded that the bias might originate from the heightened social relevance attributed to approaching individuals over receding ones. At the heart of this idea is the assumption about a difference in the costs between the two possible errors the observer can make: Mistaking an approaching person for someone who is receding might have more severe consequences than the opposite mistake. This explanation of the facing-the-viewer bias also seems to support the findings of a study carried out by Brooks et al. (2008). These authors reported a strong facing-the-viewer bias when participants observed male figures, yet found the opposite, namely a pronounced facing-away bias, when female figures were observed. Brooks et al. proposed that the interaction between stimulus gender and facing-the-viewer bias might have emerged due to differences between the associated consequences of approaching males and females: An approaching male might be more threatening or aggressive than an approaching female, and therefore it may be even more costly to misperceive an approaching male as receding. Although the degree of the effect reported by Brooks et al. could not be replicated in a study by Schouten et al. (2010), these researchers did confirm the tendency for male point-light walkers to produce stronger facing-the-viewer biases than female walkers.

The hypothesis proposed by Vanrie, Dekeyser, and Verfaillie (2004) forms a reasonable and appealing description of the facing-the-viewer bias in terms of the necessity and social relevance of appropriately responding to other people. More recent results, however, seem incompatible with this theory. For instance, a series of experiments conducted by Schouten, Troje, and Verfaillie (2011) determined that judgments of point-light walker facing direction are at least partly influenced by local stimulus properties of the figures. In the first of three experiments, Schouten, Troje, and Verfaillie manipulated the structure (body type) and kinematics (motion patterns) of point-light walkers along a male-female continuum, showing that although the gender of point-light walkers was consistently identified, the degree of facing-the-viewer bias produced could not be predicted from the perceived gender

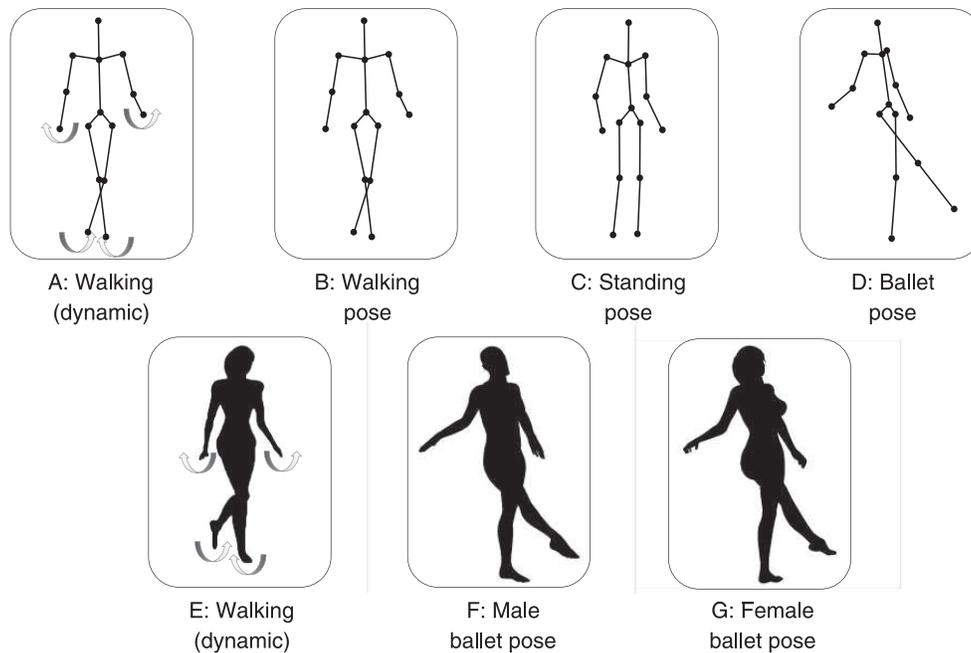


Figure 2. Stimuli used in Experiment 1: (A) walking stick figure; (B) stick figure in a static walker position; (C) stick figure in a standing position; (D) stick figure in ballet pose; (E) walking silhouette; (F) male silhouette in ballet pose; (G) female silhouette in ballet pose, similar to the Kayahara silhouette. Stick figures in our study were white on a black background. All figures were presented spinning about a vertical axis at $30^\circ/\text{s}$. Arrows indicate that figures were displayed as walking.

of the walkers. The facing-the-viewer bias was greater for male point-light walkers than for female point-light walkers if gender was conveyed by the figure's structure, yet the opposite was true if perceived gender was manipulated by changing the kinematics of the walker. These results show that the relationship between stimulus gender and facing-the-viewer bias is unlikely to be directly causal.

In a second experiment, Schouten, Troje, and Verfaillie (2011) established that the degree of facing-the-viewer bias produced by the lower half of a point-light walker in isolation is almost identical to that demonstrated for the whole figure. On the other hand, the upper half of a point-light walker in isolation produces a distinct facing-away bias. This effect was confirmed for both male and female stimuli, but it appeared to be more pronounced for female stimuli. It seems that stimulus properties that differ between the lower and upper body strongly influence the facing-the-viewer bias.

In the final experiment by Schouten, Troje, and Verfaillie (2011), the authors examined both the structural and kinematic information between male and female point-light walkers for either the full figure, or only for the upper or lower parts of the figure. The results indicated that the strong facing-the-viewer bias that was observed for female kinematics was primarily driven by the lower half of the stimulus. This result supported the conclusion that the perceived gender of

the stimulus in itself is not the crucial factor that influences facing judgments.

Taken together, these findings do not support a sociobiological interpretation of the facing-the-viewer bias, and instead underscore the importance of local visual cues that differ between the upper and lower half of a point-light figure and which appear to be correlated with some gender specific aspects of the stimulus. To identify these local visual cues, we used an investigative method that was described in a study by Troje and McAdam (2010b). These authors examined the robustness of the facing-the-viewer bias by investigating whether the facing-the-viewer bias is demonstrated with figures other than the point-light walker. The authors compared a walking stick figure to the Kayahara silhouette (Kayahara, 2003; see Figure 2G). Like point-light displays and stick figures, this rotating human silhouette displays depth-ambiguity and perceptual bistability. In contrast to the point-light walker used in the studies discussed above (e.g., Schouten, Troje, & Verfaillie, 2011), it was a female figure, constructed of the bounding occluding contours, and was displayed stationary, adopting a static ballet-like pose with the arms and one leg extended outwards (Troje & McAdam, 2010a). The authors took advantage of the capacity of both stimuli to be seen rotating either clockwise or counter-clockwise to examine perceived facing directions. Troje and McAdam (2010b) observed that the Kayahara silhouette elicited no bias in terms of

the perceived facing orientation whereas a walking stick figure was subject to the typical facing-the-viewer bias observed with point-light walkers.

The goal of the current study was to exploit the difference in the facing-the-viewer biases produced by stick figures and silhouettes in order to determine the cause of the phenomenon. In Experiment 1, we investigated the reason for the absence of facing-the-viewer bias for the Kayahara silhouette. To achieve this, we used variants of silhouettes and stick figures that isolated the various differences between the walking stick figure and the Kayahara silhouette and assessed the effect of these factors on the facing-the-viewer bias. The results of this first experiment informed a new theory about the cause of the facing-the-viewer bias. A hypothesis generated based on that theory was tested in Experiment 2.

Experiment 1

The stick figure walker and the Kayahara silhouette used by Troje and McAdam (2010b) differed in a number of attributes. Any one of them might be responsible for the fact that the stick figure elicits a strong facing-the-viewer bias and the silhouette does not.

Walking motion

The stick figure was displayed walking, whereas the Kayahara silhouette was not. Given that Troje and McAdam (2010b) used continuously rotating figures, the facing-the-viewer bias was established in terms of regular perceptual flips. The dynamic posture of the walking stick figure might have facilitated more frequent mirror-flips as the two sides of the walker changed roles over the gait cycle. On average, the walking stick figure demonstrates more bilateral symmetry over time than most individual postures. The change in handedness that comes along with a change in perceived depth might have gone unnoticed in the walking figure, but not in the static silhouette.

Posture

The Kayahara silhouette is not only static, but exhibits a ballet-like posture that is highly asymmetric. The figure stands on one leg while the other is pointed away from the body. The two arms also adopt asymmetric poses. Perhaps this specific posture is more perceptually stable on account of its pronounced asymmetry. A perceptual mirror-flip for this figure

would result in a greater magnitude of changes in configuration (e.g., the extended leg flips from being the right leg to becoming the left leg) than for the stick figure.

Gender

The Kayahara silhouette is clearly female while the stick figure has no obvious gender. Given the literature summarized above about possible effects of gender on the facing-the-viewer bias, the lack of a facing-the-viewer bias for the silhouette may be attributable to its visible gender.

Contours versus sticks and dots

Both the stick figure and the silhouette depict a human figure with minimal features, but the features used for each figure are quite different. The silhouette consists of an occluding contour that represents the outline of the body seen from a particular viewpoint. The occluding contour is therefore not an intrinsic feature of the depicted 3-D object, but rather changes its location on the object with the viewpoint of the observer. For all points along the occluding contour, the local 3-D surface orientation is known: Normals all lie in the projection plane and are perpendicular to the 2-D contour (Koenderink, 1990; Marr, 1982; Marr & Nishihara, 1978). For the stick figure, the design consists of dots and connecting lines that are likely to be interpreted as features intrinsic to the figure—either as internal structures (bones) or as markings on the surface of the body. Unlike the occluding contour of the silhouette, these features do not change their position relative to the body. In contrast to points along the surface contour, local surface orientations for these features are not readily determined. Surface normals can either point in a direction exiting the image plane, or they can point into the mirror flipped direction into the image plane.

The amount of potentially important differences between the two stimulus classes does not allow for a full factorial design. Rather, we created a smaller set of seven different stimuli (described in detail below) that allow us to address the role of all these major differences.

We measured the facing-the-viewer bias indirectly by asking observers to indicate the perceived direction of rotation for stimuli that we presented rotating about the vertical axis, similarly to Jackson, Cummins, and Brady (2008) and Troje and McAdam (2010b). Typically, studies have examined facing-towards compared with facing-away responses for stimuli presented at fronto-parallel projection; the intention behind the

method we used was to avoid the response bias introduced by informing subjects of the two possible facing directions.

Methods

Participants

Twenty-eight participants (12 men, 16 women, M age = 22.25 years, age range: 18–36 years) took part in Experiment 1. Participants were volunteers from Queen's University and were recruited through a mailing list. No participants had significant past exposure to point-light walkers or related visual displays, such as stick figures or silhouettes. All participants had normal or corrected-to-normal vision. We obtained informed consent from all participants prior to starting the study. Approval of the study was granted by the Queen's University General Research Ethics Board.

Stimuli

We used two main classes of test stimuli, from which we selected and created several versions to be included in the experiment (Figure 2). The first test stimulus class consisted of a gender-neutral stick figure in various poses and states of motion (Troje, 2002, 2008). The sticks and dots were white on a black background. The sticks represented anatomically plausible connections between major joints and other anatomical landmarks: the ankles, knees, hips, wrists, elbows, shoulders, the center of the pelvis, the sternum, and the center of the head. In addition to a walking stick figure, we created three static versions of stick figures: one adopted the pose of a walking person, the second depicted a standing person, and the third closely mimicked the ballet-like pose of the original Kayahara silhouette.

The second test stimulus class consisted of silhouettes and included three versions: a replication of the original Kayahara silhouette; a silhouette where we replaced the female with a male figure in the same static pose as the Kayahara silhouette; and a walking female figure, animated using the same kinematics as the walking stick figure. We generated all silhouette stimuli using the 3-D animation program Poser (Smith Micro, California) and the OpenGL (Woo & Shreiner, 2003) backend for Matlab (MathWorks Inc., Natick, MA).

In order to represent and isolate the difference between the walking stick figure and the Kayahara silhouette, we used the seven stimulus versions outlined above in the following way. First we compared the walking stick figure with the Kayahara silhouette in order to replicate the difference in bias between the two stimuli that was found by Troje and McAdam (2010b).

To investigate the effect of walking motion on the facing-the-viewer bias we compared the walking stick figure to the static stick figure in a static walking pose. We also compared the walking female silhouette to the walking stick figure. Comparing responses to these stimuli allowed us to confirm whether or not motion of the figure in itself is either necessary or sufficient to produce facing-the-viewer bias. We examined the effects of posture on the facing-the-viewer bias by comparing a stick figure in the same pose as the Kayahara silhouette with a stick figure in a static, standing posture, and also with a stick figure in a static, walking pose. In order to assess the effect of the gender of the Kayahara silhouette on the facing-the-viewer bias, we compared the male silhouette to the female silhouette. Finally, by comparing stick figures and silhouettes that adopted the same posture (i.e., that of the Kayahara silhouette) we were able to examine the effect of the representation of the figure (the occluding contour vs. sticks and dots) on the facing-the-viewer bias.

In addition to the stick figures and silhouettes described above, we used a third stimulus class for practice trials. We presented 3-D cubes with unambiguous rotation directions to help familiarize participants with the task. Although some participants may have had previous exposure to the Kayahara silhouette, we did not anticipate any effects of familiarity with the silhouette on our results.

All stimuli subtended 4° of visual angle at a viewing distance of 90 cm and were presented using Matlab with the Psychophysics Toolbox extensions (Brainard, 1997) on a 19-in. LCD monitor refreshing at 60 Hz. We first generated all stimuli as 3-D objects rotating CCW at $30^\circ/s$ about the vertical axis and then projected them orthographically using a simulated camera with a horizontal optical axis. This angular velocity was chosen based on pilot studies. The chosen value reflects a practical balance between accuracy and feasibility: Faster rotation speeds amplify the effect of delays between perceptual reversals and the time a response is given compromising the accuracy with which we can determine the point at which a reversal occurred. Reducing speed produced fewer data points and would require longer trial durations.

Procedure

Participants were seated with their eyes at approximately 90 cm from the screen. They were instructed to remain still during the experiment, but were not restrained by a chin rest or bite bar. Participants looked at the on-screen figures for the duration of the trials and were not given instructions with regard to where they should fixate. We instructed participants that the stimuli would be changing rotation direction between

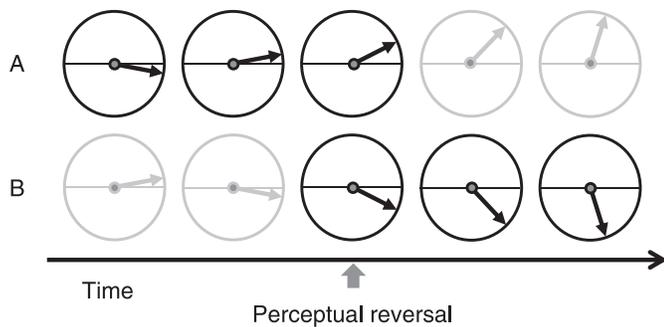


Figure 3. A depiction of a reversal towards as seen from above, with the observer at the bottom. Arrows in circles show the stimulus facing directions. Over time (left to right) percept A or B is seen to dominate the other (dark circles indicate dominant percept). A CCW percept dominates at first, then a reversal of rotation is perceived (gray arrow on the time axis) such that the facing-towards percept is reestablished. A similar case can be imagined for a reversal from a facing-towards to a facing-away interpretation of a figure, representing a reversal away.

CW and CCW at random intervals. Participants reported the perceived rotation direction of a stimulus—CW or CCW—by holding down one of two keys on a standard keyboard (S or K; key assignment was counterbalanced) at all times. If participants were holding down two keys or no keys for more than 200 ms, a beep sound was played to remind the participant to select a single direction of rotation at any time.

Each trial lasted 4 min with a 1 min interval between trials. A single practice trial consisted of participants responding to a solid cube. The rotation direction of the cube was unambiguous at any given time, but the direction changed unpredictably at an average rate of five times per minute. Immediately following the practice trial, the responses were assessed by the

experimenter to determine whether the participant understood the task. All participants completed this task satisfactorily. Next, the main experiment began. This consisted of seven trials—one for each of the conditions depicted in Figure 2. The order of the seven trials was counterbalanced across participants using a Latin Square design. The experiment lasted for approximately 45 min including introduction and debriefing.

We quantified the facing-the-viewer bias as the proportion of perceptual reversals that represented changes from a facing-away interpretation to a facing-towards interpretation of the figure and called this measure the *FTV score*. Note that an FTV score smaller than 0.5 means that observers in fact experienced a facing-away bias. A depiction of a perceptual reversal towards is presented in Figure 3, and plots showing timing and frequency of reversals for two conditions in Experiment 1 are presented in Figure 4. We discarded data from a single trial if the participant reported fewer than three reversals.

Results and discussion

The FTV scores for all seven stimulus conditions are depicted in Figure 5. We conducted a one-way repeated measures analysis of variance (ANOVA) on the FTV scores and found a significant main effect, $F(6, 48) = 6.14, p < 0.001, \text{partial } \eta^2 = 0.43$. In a follow-up analysis, we conducted seven paired sample *t* tests using Bonferroni adjusted alpha levels of 0.0071 (0.05/7) in order to compare conditions based on the attributes identified above as factors that might influence the facing-the-viewer bias. We also used a Bonferroni adjusted alpha level of 0.0071 (0.05/7) for one-sample *t*

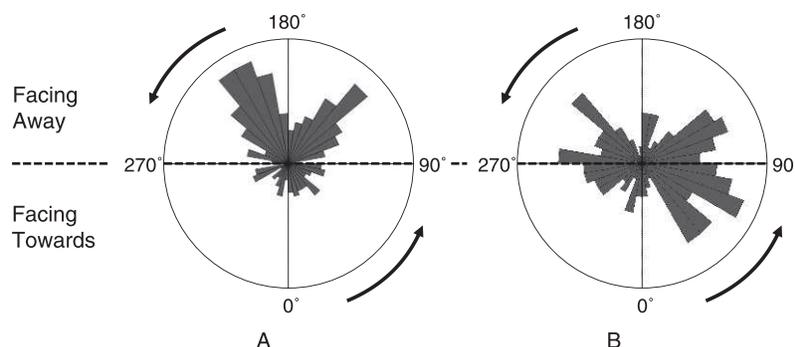


Figure 4. A rose plot depicting the distribution of reversals for the walking stick figure (A) and the female ballet pose silhouette (B) as seen from above with the observer situated at 0°. For the purpose of this plot, data were normalized such as if observers always perceived the figure spinning counter-clockwise. That means that a reversal at 90° is one that occurs when the figure is seen in sagittal view and is about to rotate into the facing-away part of the circle. Likewise, a reversal at 270° is one in which it rotates from the facing-away direction into the facing-towards part of the circle. Data are pooled across all participants in Experiment 1. The distance from the center of the plot represents the number of reversals in each 10° bin. The depiction shows that observers most often perceived reversals that led to a facing-towards interpretation for stick figures, but not for silhouettes.

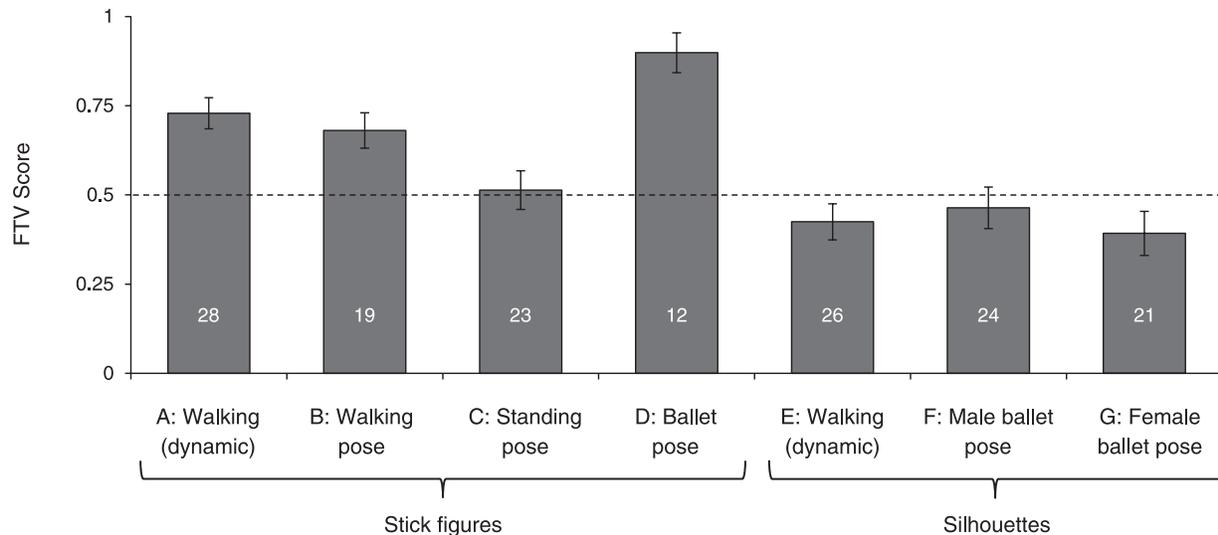


Figure 5. Mean FTV scores in each condition for Experiment 1. Dashed line corresponds to the level to be expected if no bias was present. Numbers on the bars indicate the number of data points available for that condition. These vary as we discarded trials with fewer than three reversals. Error bars indicate standard errors of the mean. Corresponding representations of each stimulus can be found in Figure 2 (A–G).

tests to compare scores for the seven conditions with the 0.5 level that was to be expected if no bias was present. Results of comparisons that examine the influence of each of these attributes are outlined below.

We also looked at a possible connection between the frequency of perceptual reversals and FTV scores, but we did not find any indication of such a relation. When all stimuli were taken together, there was no correlation between the frequency of perceptual reversals and FTV scores between subjects, $r(147) = 0.06$, $p = 0.48$. We observed that the frequency of perceptual reversals when participants observed the dynamic stick figure and silhouette stimuli (reversals for walking stick figure: $M = 17.36$; reversals for walking silhouette: $M = 18.96$) was higher than that of all other stimuli (reversals for other conditions pooled: $M = 7.56$, $SD = 3.06$). Perception of the ballet pose stick figure, in particular, appeared to be highly stable—many subjects experienced fewer than three perceptual reversals while observing this stimulus, and as such there were notably fewer data-points for this condition than for others.

Comparing FTV scores between conditions, we began by verifying previous research that found a difference in facing-the-viewer biases for the walking stick figure (Figure 2A) and Kayahara silhouette (Figure 2G). We replicated Troje and McAdam's (2010b) results by finding a significant difference between the two conditions, $t(20) = 4.01$, $p < 0.001$, Cohen's $d = 1.01$. The walking stick figure elicited a significant facing-the-viewer bias, $M = 0.73$, $SD = 0.23$; one sample t test compared with 0.5, $t(27) = 5.30$, $p < 0.001$, Cohen's $d = 0.99$, whereas the silhouette evoked a nonsignificant tendency to be seen facing-away, $M =$

0.39, $SD = 0.28$; one sample t test compared with 0.5, $t(20) = 1.80$, $p = 0.09$, Cohen's $d = 0.38$. This result is depicted in Figure 4, which we used above to explain how we derived the FTV score. Variances in the degree of the facing-the-viewer bias in the different stick figure conditions are discussed below. Within the three silhouette stimuli there were no such differences. With all three we observed a very slight, yet nonsignificant tendency to be perceived as facing away.

Walking motion

We compared the walking and static walker-pose stick figures, Figure 2B; $M = 0.68$, $SD = 0.22$; one sample t test compared with 0.5, $t(18) = 3.57$, $p = 0.002$, Cohen's $d = 0.83$, and found no difference in the FTV scores produced, $t(18) = 0.70$, $p = 0.95$, Cohen's $d = 0.13$. Both stimuli produced significant FTV scores that indicated facing-the-viewer biases. The fact that we found no difference between these stimuli suggests that dynamic walking motion is not necessary to produce a facing-the-viewer bias for depth-ambiguous figures.

Additionally, we compared the walking stick figure with the walking silhouette, Figure 2E; $M = 0.42$, $SD = 0.26$; one sample t test compared with 0.5, $t(25) = 1.57$, $p = 0.13$, Cohen's $d = 0.29$, and found that the stick figure elicited higher FTV scores, $t(25) = 4.16$, $p < 0.001$, Cohen's $d = 0.82$. The walking silhouette, in contrast, produced an FTV score that did not differ from 0.5. These results suggest that dynamic motion is not sufficient in itself to produce facing-the-viewer bias for depth-ambiguous figures and confirm that the difference between the Kayahara silhouette and the

walking stick figure with respect to the facing-the-viewer bias is unlikely to be caused by the dynamic motion of the stick figure.

Posture

The static ballet pose stick figure produced a significant FTV score consistent with a strong facing-the-viewer bias, Figure 2D; $M = 0.90$, $SD = 0.19$; one sample t test compared with 0.5, $t(11) = 7.30$, $p < 0.001$, Cohen's $d = 2.06$, whereas the standing stick figure did not produce facing-the-viewer bias, Figure 2C; $M = 0.51$, $SD = 0.26$; one sample t test compared with 0.5, $t(22) = 0.18$, $p = 0.86$, Cohen's $d = 0.05$. The difference between these conditions was significant, $t(11) = 5.13$, $p < 0.001$, Cohen's $d = 1.13$. We also found a significant difference between the FTV scores for the ballet pose stick figure and the static walker-pose stick figure, $t(10) = 4.46$, $p = 0.001$, Cohen's $d = 0.94$. Together, these results suggest that the posture of the Kayahara silhouette is not responsible for the fact that the stimulus does not produce a facing-the-viewer bias. Originally, we had proposed that the bilateral asymmetry of the ballet-pose silhouette might reduce the facing-the-viewer bias, but this clearly is not the case: The highly symmetric standing stick figure generated nonsignificant FTV scores, whereas the asymmetric ballet-pose stick figure produced a very strong facing-the-viewer bias. We can therefore conclude that the difference between the ballet-pose silhouette and the dynamic walking stick figure does not result from the difference in the degree of bilateral symmetry portrayed by each figure.

While posture per se cannot explain the difference between FTV biases elicited by the walking stick figure and the Kayahara silhouette, we still find pronounced posture-dependent differences among the static stick figures—a result that we discuss further below.

Gender

Despite the considerable research on gender-related effects on the facing-the-viewer bias (e.g., Brooks et al., 2008; Schouten et al., 2010), we did not find any difference in FTV scores when we changed the gender of the silhouette from female to male. We compared the degree of facing-the-viewer bias produced by male, Figure 2F; $M = 0.46$, $SD = 0.29$; one sample t test compared with 0.5, $t(23) = 0.68$, $p = 0.51$, Cohen's $d = 0.13$, and female ballet pose silhouettes and found no difference, $t(19) = 0.94$, $p = 0.36$, Cohen's $d = 0.24$. Both the male and female ballet-pose silhouettes produced neutral FTV scores. This result indicates that the difference in facing-the-viewer bias between the walking stick figure and the Kayahara silhouette is not related to the visible gender of the silhouette.

Contours versus sticks and dots

The significant difference in FTV scores between stick figures and silhouettes remained even when the posture was the same. The ballet pose stick figure elicited a large degree of facing-the-viewer bias, while for the female ballet pose silhouette we observed no bias, $t(10) = 4.91$, $p < 0.001$, Cohen's $d = 1.69$. In this case, the main difference between the stimuli was the nature of the features representing the figure (the occluding contour of the silhouette versus the sticks and dots of the stick figure). The pronounced difference in FTV scores for the two stimuli therefore provides evidence for the influence of the stimulus representation on facing-the-viewer bias. We conclude that the difference in FTV scores obtained between the Kayahara silhouette and the walking stick figure is driven by the difference in representation. Indeed, we did not find significant biases for any silhouette-based stimuli, yet participants displayed a facing-the-viewer bias (FTV score > 0.5 , $ps < 0.02$) in the following conditions that involved stick figure stimuli: the ballet pose stick figure, static walker pose stick figure, and dynamic walking stick figure. As mentioned above, the only stick figure that did not elicit a significant facing-the-viewer bias was the standing stick figure.

The results of Experiment 1 confirmed a difference in terms of facing-the-viewer bias between the walking stick figure and the Kayahara silhouette. This result is commensurate with research demonstrating that the facing-the-viewer bias is not a necessary attribute of a depth-ambiguous human figure (e.g., Schouten, Troje, & Verfaillie, 2011; Troje & McAdam, 2010b; Vanrie & Verfaillie, 2006). The lack of a facing-the-viewer bias for the original Kayahara silhouette, for its walking version, and for its male equivalent, makes it very difficult to explain the facing-the-viewer bias as caused by differential gains and losses associated with the two potential errors that an observer can make when making judgments of facing directions. However, we found that both the representation and the posture of the stimuli affected the degree of facing-the-viewer bias. Every stick figure stimulus evoked a facing-the-viewer bias except for the standing stick figure. One difference between the standing stick figure and the other stimuli was that the standing stick figure lacked depth perpendicular to the fronto-parallel plane.

Our theory is the following: The seemingly inconclusive results can be explained by linking our observations on the facing-the-viewer bias to another well described perceptual bias: The tendency to perceive a depth-ambiguous surface as convex rather than concave (Hill & Bruce, 1994; Langer & Bülthoff, 2000; Liu & Todd, 2004; Mamassian & Landy, 1998; Reichel & Todd, 1990). Adams and Mamassian (2004) point out that surfaces of objects are more often convex than concave. In addition, visual structures located on

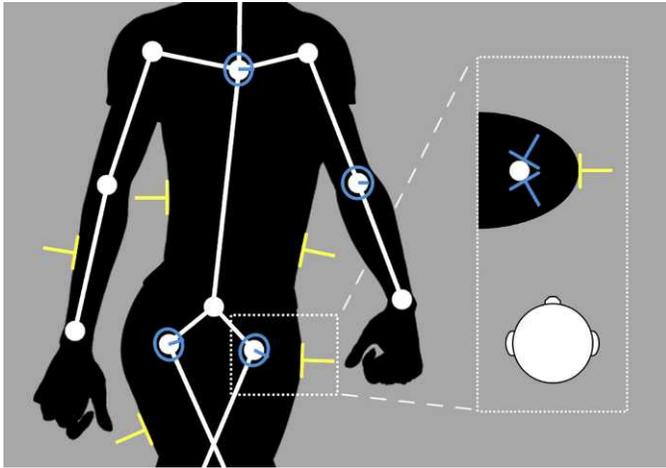


Figure 6. Depiction of a few local surface orientations in silhouette and stick figure stimuli. For the silhouette, local surface orientations (yellow probes, consisting of a base plate that is oriented tangential to the surface and a pin that indicates orientation of the surface normal) are unambiguously defined. Normals lie in the image plane and are orthogonal to the contour. For the stick figure, the direction of the orientations (blue probes) are ambiguous. The inset shows a depiction of this ambiguity as seen from above—normals can be oriented towards or away from the observer.

concave surfaces are more likely to become obstructed from the observer's view by other parts of the same surface (Troje, 2013). This generates a bias to perceive ambiguous surfaces as convex, as demonstrated by the well-known hollow potato illusion (Hill & Bruce, 1994).

The convexity bias explains why among the different stick figure stimuli that we used only the standing figure did not exhibit a facing-the-viewer bias. Both in the static and in the walking version of the figure, the knees are features with potentially significant curvature and the visual system has to reach a decision as to whether they are concave or convex. The same is true for the outstretched leg in the ballet pose stick figure. The surface normal associated with its most distal point either points towards the viewer forming a strong convexity, or it points away from the viewer forming an equally strong concavity. A convex interpretation of these features results in a facing-the-viewer bias. The standing stick figure, in contrast, has no pronounced curvatures that could become subject to the convexity bias.

The reason why we do not see orientation biases in the silhouettes is because the stimulus does not contain any discrete image features to which local surface orientation can be assigned except for the occluding contour. For the occluding contour, however, this assignment is straightforward and unambiguous: All surface normals lie in the image plane and are perpendicular to the contour. Also, there is no

ambiguity about which side of the contour belongs to the figure and which belongs to the contour. The unambiguous solution for the contour points, however, does not help to disambiguate the perception of the figure itself. The silhouette displays full depth-ambiguity and no facing-the-viewer bias is observed. The manner in which local surface assignment differs between stick figures and silhouettes is depicted in Figure 6.

Note that this interpretation assumes a sequence of processing that starts with the identification of 2-D features, then assigns surface orientation to them (the 2½-D view), and finally fits a 3-D surface to the features by integrating over local surface orientations. This is the sequence of events that David Marr (1982) suggested. The silhouette remains flat after this procedure is applied. The perceived three-dimensionality of the rotating figure is probably achieved through other processes that do not involve the assignment of local surface orientation.

We hypothesized that the facing-the-viewer bias in biological motion perception is driven by a bias for convex surfaces, and that both surface curvature and features with ambiguous surface normals are prerequisites for producing facing-the-viewer bias. In Experiment 2 we tested this hypothesis by examining whether silhouettes are subject to the facing-the-viewer bias when accompanied by identifiable structures other than the occluding contour.

Experiment 2

The aim of Experiment 2 was to test the hypothesis that the facing-the-viewer bias is based on a convexity bias and relies on the presence of local image features on curved surfaces. To achieve this, we generated silhouette-based stimuli showing a person in a crouching pose with pronounced curvature of both elbows and knees (Figure 7). If seen from the front, the knees form a distinct convexity and the elbows a distinct concavity. The situation reverses if the figure is seen from behind. According to our hypothesis, these implied convexities and concavities should not affect perceived orientation as the silhouette does not contain any features other than the outline with which they could be associated.

We then created other conditions where we introduced additional features in the form of individual dots that we positioned on knees and/or elbows. If the facing-the-viewer bias is linked to the assignment of surface orientations to identifiable structures, then the addition of such structures on silhouettes should generate systematic orientation biases. When situated on the knees, such landmarks should generate a

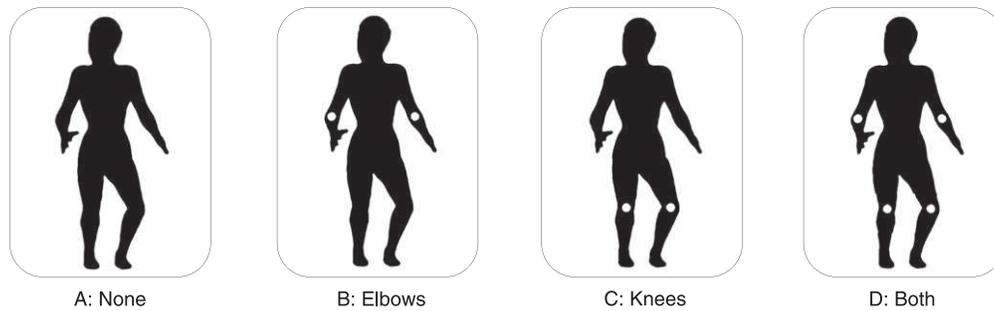


Figure 7. Depictions of stimuli used in Experiment 2. (A) Crouching silhouette. Crouching silhouettes with marker on (B) elbows only, (C) knees only, (D) both elbows and knees. All silhouettes were presented spinning about a vertical axis at 30°/s.

facing-the-viewer bias, whereas the same landmarks on the elbows should generate a facing-away bias. The layout of figures with point-light landmarks on both the upper and lower body should provide conflicting cues in terms of the facing direction of the figures, and are expected to cancel each other—at least to some degree. Similarly, if features with ambiguous surface normals are required, a crouching stimulus with no point-light landmarks should not produce orientation biases.

Methods

Participants and procedure

Participants in Experiment 2 were the same as those who took part in Experiment 1 with the addition of one more individual ($N = 29$, 12 men, 17 women, M age = 22.17 years, age range: 18–36 years). The procedure was nearly identical to that of Experiment 1. There were five trials in total: The first was a practice trial identical to the practice trial we used in Experiment 1 in which a rotating cube with an unambiguous direction of rotation was presented. The practice trial was followed by four experimental trials—one for each stimulus. We counterbalanced the presentation order across subjects using a Latin Square design. The experiment lasted approximately 30 min including introduction and debriefing.

Stimuli

We presented four silhouette stimuli. These were composed using the same human model from Poser that we used in Experiment 1 for the female silhouettes. The crouching posture was bilaterally symmetric. The whole figure subtended 4° of visual angle at a viewing distance of 90 cm and the dots on the figure subtended 0.15° of visual angle. As in Experiment 1, the stimuli appeared to rotate at 30°/s about the vertical axis. The four stimuli are depicted in Figure 7.

Results and discussion

Results are depicted in Figure 8. We conducted a one-way repeated measures ANOVA on the FTV scores and found a significant main effect of stimulus condition, $F(3, 63) = 11.58$, $p < 0.001$, partial $\eta^2 = 0.36$. In a follow up analysis we conducted paired sample t tests using Bonferroni adjusted alpha levels of 0.025 (0.05/2) for the two planned comparisons. We also used Bonferroni adjusted alpha levels of 0.013 (0.05/4) for one-sample t tests to compare scores for the four conditions with the 0.5 level that was to be expected if no bias was present. We found no difference, $t(22) = 1.02$, $p = 0.32$, Cohen's $d = 0.19$, between the condition with no markers, Figure 7A; $M = 0.69$, $SD = 0.23$, one sample t test compared with 0.5, $t(23) = 4.05$, $p = 0.001$, Cohen's $d = 0.82$, and the condition with both elbow and knee markers, Figure 7D; $M = 0.63$, $SD = 0.24$; one sample t test compared with 0.5, $t(26) = 2.81$, $p = 0.009$, Cohen's $d = 0.54$. Both stimuli produced significant FTV scores consistent with facing-the-viewer bias. The knee marker condition elicited FTV scores significantly larger than 0.5, Figure 7C; $M = 0.80$, $SD = 0.21$; one sample t test compared with 0.5, $t(27) = 7.56$, $p < 0.001$, Cohen's $d = 1.39$, and differed significantly from the elbow marker condition, $t(23) = 5.33$, $p < 0.001$, Cohen's $d = 1.13$, where stimuli tended to generate FTV scores that were smaller than 0.5, Figure 7B; $M = 0.37$, $SD = 0.30$; one sample t test compared with 0.5, $t(23) = 2.12$, $p = 0.039$, Cohen's $d = 0.45$, although this latter difference cannot be considered significant given our Bonferroni adjusted alpha level. As in Experiment 1, we found no correlation between the average frequency of reversals and the FTV score between subjects, $r(102) = 0.05$, $p = 0.62$.

The results of Experiment 2 support the hypothesis that stimulus features with ambiguous surface orientations play a key role in the cause of the facing-the-viewer bias. The addition of markers on elbows and knees induced shifts in the facing-the-viewer bias in the predicted directions. When placed on the knees, 80% of the reported reversals corresponded to changes from a

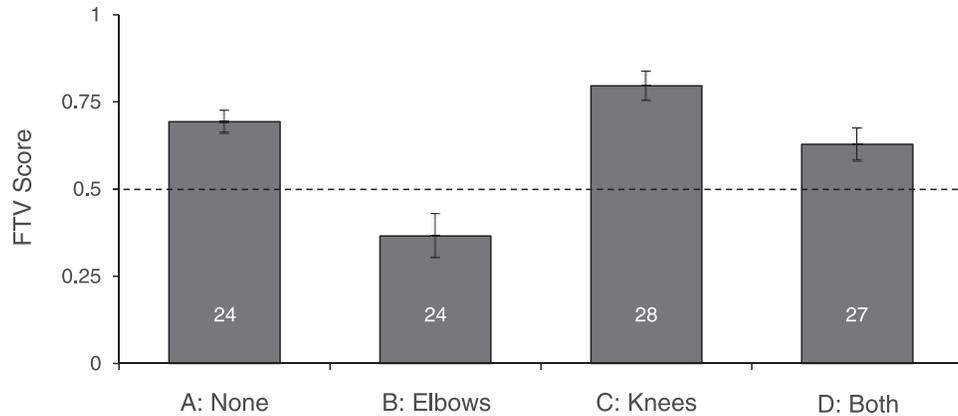


Figure 8. Mean FTV scores in each condition for Experiment 2. Dashed line corresponds to the level to be expected if no bias was present. Numbers on the bars indicate the number of data points available for that condition. These vary as we discarded trials with fewer than three reversals. Error bars indicate standard errors of the mean. Corresponding representations of each stimulus can be found in Figure 7 (A–D).

facing-away orientation to a facing-the-viewer orientation. When the markers were placed on the elbows, only 37% of the reversals were in that direction while the majority of reversals were towards a percept in which the figure was facing away from the observer. These findings are in line with our prediction that a perceptual bias that is based on a preference for convex over concave surfaces forms the basis of the facing-the-viewer bias.

However, another result is not readily predicted by our theory. When averaged across all conditions in Experiment 2, FTV scores were significantly higher than 0.5, $M = 0.62$, $SD = 0.25$, one-sample t test compared with 0.5, $t(25) = 2.45$, $p = 0.022$, Cohen's $d = 0.49$. The facing-the-viewer bias for the silhouette with knee markers only was larger than the facing-away bias for the silhouette with elbow markers only and moderate facing-the-viewer biases were observed for both the silhouette with no markers and for the one with markers on both knees and elbows.

In Experiment 2 we had given the silhouette a posture that exaggerated the concavities and convexities at elbows and knees that we hypothesized to be important. Adding markers to these structures clearly had the effect predicted by assuming that the convexity bias operates on the level of the assignment of surface orientations to local features, and therefore before recognition and semantic attribution. Given the previously observed priority of the lower body over the upper body, a net facing-the-viewer bias for the silhouette with both knee and elbow markers can also be reasonably understood. However, the facing-the-viewer bias for the marker-less figure seems to be in conflict with the fact that we did not observe any such bias for the silhouettes used in Experiment 1.

We can only speculate, here, that given the very pronounced curvatures around elbows and knees in the

stimuli used in Experiment 2, a weaker version of the convexity prior becomes visible that acts on the recovered surfaces at a later stage in the reconstruction process. The convexity bias is a ubiquitous phenomenon that has been observed in a number of different contexts (see General discussion below). There is no reason to assume that it is restricted to the visual processing level at which local surface orientation is determined, even though this seems to be the processing level that dominates the phenomenology of the facing-the-viewer bias.

At this point, we should also discuss a possible limitation of the interpretation of the results of Experiment 2. Looking at the experiment in isolation, an alternative explanation could account for the results: The dots placed on knees and elbows allocated attention to these particular areas. The convexity bias that had been canceled out between the convexities and concavities of knees and elbows in the normal silhouette with no dots attached is now dominated by the attended location. Note, however, that this theory ignores the results of Experiment 1 and the logic that led to Experiment 2. Adopting the theory that changes in the allocation of attention is responsible for the results of Experiment 2, we would still need to explain why stick figures (and point-light displays, for that matter) generate a pronounced facing-the-viewer bias, but silhouettes do not.

General discussion

The aim of this research was to understand the cause for the facing-the-viewer bias. In Experiment 1 we examined the degree of facing-the-viewer bias induced when we isolated the differences between a stimulus that

typically induces a facing-the-viewer bias (the walking stick figure) and a stimulus that does not (the Kayahara silhouette). We found that human silhouettes did not elicit a facing-the-viewer bias as large as the one typically associated with stick figures, regardless of the posture, gender, or walking motion of the silhouette. The stick figure of a person standing upright with straight legs and arms did not elicit a facing-the-viewer bias either.

We conclude that there is little evidence for a sociobiological explanation of the facing-the-viewer bias. While perceptual depth reversal for the standing stick figure and for the different silhouettes imposes the same change in the social significance of the stimulus as for the other stick figure displays, we still do not find the same, pronounced facing-the-viewer bias.

Based on the results of Experiment 1, we developed a framework that helps to explain a multitude of previous, seemingly inconsistent findings. We proposed that the facing-the-viewer bias is caused by a bias for convex surfaces that the visual system applies when assigning local surface orientations to stimulus features as part of the process of 3-D reconstruction from 2-D images (Marr, 1982). This hypothesis generated the prediction that silhouettes to which visible landmarks were added would be subject to facing biases, and that the direction of the biases would depend upon the location of the landmarks on the silhouette figure. Results were consistent with our predictions in terms of the direction of biases induced by each condition. Our findings support the theory that a convexity bias applied to features with ambiguous surface orientation drives the facing-the-viewer bias in biological motion perception.

Our explanation for the facing-the-viewer bias parsimoniously accounts for a number of other findings produced in prior experiments. Vanrie and Verfaillie (2006) found that point-light representations with the limbs extended perpendicular to the body tend to elicit a strong facing-the-viewer bias, whereas figures with laterally extended limbs do not. These results are expected given that convexity assumptions cannot be applied to a surface that is devoid of curvature along the line of sight. As well, the convexity bias account is consistent with the perceptual differences between upper and lower body figures that were reported by Schouten, Troje, and Verfaillie (2011). Our theory generates the prediction that the lower body of a point-light walker would be interpreted as facing-the-viewer due to the surface curvature of the knees. Similarly, we would predict that the upper body produces a bias for the figure to be seen as facing away, since the elbows only bend such that they would appear convex to an observer who is looking at a person from behind. Moreover, it is notable that facing-the-viewer bias was often absent for participants who observed female point-light walkers in the study by Schouten, Troje, and Verfaillie, whereas the

majority of male walkers produced strong facing-the-viewer bias. A major difference between male and female walkers in the stimuli that were used in those experiments is the posture of the elbows (see Troje, 2002). For the female walker, the elbows tend to point backwards. For the male walker, however, at least in its exaggerated form, the elbows point laterally, away from the midline of the body. In a fronto-parallel projection, the elbows of the male stimulus provide little curvature in the direction of the line of sight. For all other viewpoints, the curvature along the line of sight of the left elbow has the opposite sign to the curvature of the right elbow.

This fact explains the dependency of the facing-the-viewer bias on stimulus gender that was identified by Brooks et al. (2008) and Schouten et al. (2010). It also explains why a gender effect on the facing-the-viewer bias is only observed if gender is conveyed by the structure of the walker, but not by its kinematics (Schouten, Troje, & Verfaillie, 2011).

The idea that a convexity bias guides our perception of ambiguous figures has first been expressed in the context of figure-ground segregation in the 2-D image plane (Kanizsa & Gerbino, 1976; Koffka, 1935; Rubin, 1958) and also with respect to biasing 3-D shape perception (e.g., Adams & Mamassian, 2004; Hill & Bruce, 1994; Langer & Bühlhoff, 2000; Mamassian & Landy, 1998). It has been proposed that the heuristic is formed through experiences with the natural world, where object surfaces tend to be most often convex (Mamassian & Landy, 1998). The bias is also linked to the idea of self-occlusion: A concave surface would be more likely to self-occlude a landmark from view than would a convex surface exhibiting a similar landmark (Troje, 2013).

The fact that large parts of the phenomenology of the facing-the-viewer bias can be explained by means of a convexity bias operating on the level of Marr's 2½-D representation does not mean that other mechanisms may not play a role at all. We discussed already the possibility that a convexity bias may also play a role at later processing stages—even though weaker and therefore only visible in the presence of the pronounced surface curvatures inherent to the crouching figure used in Experiment 2.

Recently, Heenan and Troje (2014) presented data that support the theory that the facing-the-viewer bias is at least in parts modified by the social relevance of biological motion stimuli. The authors show that individuals with high anxiety levels demonstrate a higher degree of facing-the-viewer bias than individuals with low levels of anxiety. It is argued that more anxious individuals prefer to adopt the most threatening interpretation of an ambiguous stimulus, and as such the percept involving a stimulus oriented towards the viewer tends to dominate.

Another finding remains difficult to align with our current theory: Inverted point-light walkers do not seem to elicit the same degree of facing-the-viewer bias as do upright stimuli (Vanrie, Dekeyser, & Verfaillie, 2004). This appears to contradict the low-level, convexity bias explanation because the projected images of the upright and inverted stimuli are equivalent except for the 180° rotation of the figure. Inverted stimuli should therefore evoke a similar convexity impression as upright stimuli. However, it might be that observers do not succeed in adequately representing the sticks and dots of inverted figures as a three-dimensional structure on account of the unfamiliar orientation of the figure. If the walker is interpreted as a collection of two-dimensional lines and dots, the percept does not have the potential to be convex or concave with respect to the line of sight. Another possible explanation of the inversion effect may have to do with the observation that the lower part of the figure seems to dominate perceived orientation in depth (Schouten, Troje, & Verfaillie, 2011). For the inverted figure, the lower part is now characterized by the outward bending elbows rather than the knees.

The account of the facing-the-viewer bias put forward in this study predicts that we would find similar response patterns when participants observe nonhuman stimuli that display visible markers with ambiguous surface orientations as opposed to occluding contours. By examining visual interpretations of inanimate objects presented as silhouettes with and without additional markers on key positions, we would be able to further verify the role of the convexity bias in explaining the pronounced facing-the-viewer preference observed for biological motion stimuli.

Conclusions

We conducted two experiments where we examined facing-the-viewer bias for multiple configurations of human stick figures and silhouettes. The findings of Experiment 1 indicated that stick figures with surface curvature typically produce strong facing-the-viewer biases, whereas manipulations of posture, gender, and the degree of walking motion were insufficient to generate facing-the-viewer biases for silhouettes. We hypothesized that this result was driven by the different nature of image features of silhouettes and stick figures. The local surface orientations for the dots and lines of the stick figure are potentially ambiguous. In contrast, local surface orientations of points along the occluding contours that form the silhouette are determined unambiguously. The facing-the-viewer bias, seen in this light, can be reduced to a convexity bias: In the ambiguous case, we prefer to assign local surface

orientation such that the structure is convex with respect to the observer's viewpoint. We tested this hypothesis in Experiment 2 and found that minimal point-light landmarks on curved surfaces were sufficient to produce a facing-the-viewer bias for silhouettes and manipulate it predictably. Our findings also help to interpret and unify various observations regarding the facing-the-viewer bias, including the figure-part effect (Schouten, Troje, & Verfaillie, 2011) and the stimulus gender dependency (Brooks et al., 2008; Schouten et al., 2010). Our findings implicate Marr's 2½-D sketch stage of internal representations (Marr, 1982; Marr & Nishihara, 1978) as the main—even though possibly not the only—processing level at which the facing-the-viewer bias manifests. Overall our results suggest that the facing-the-viewer bias typically observed for point-light displays can be reduced to a convexity bias and does not necessarily require sociobiological interpretations to understand and explain it.

Keywords: biological motion, visual perception, facing-the-viewer bias, convexity bias

Acknowledgments

The authors thank Stephen Scovil for invaluable technical help. This research was supported by grants from the Natural Sciences and Engineering Research Council of Canada (NSERC) and Canadian Institute for Advanced Research (CIFAR) awarded to Nikolaus F. Troje.

Commercial relationships: none.

Corresponding author: Nikolaus F. Troje.

Email: troje@queensu.ca.

Address: Department of Psychology, Queen's University, Kingston, Ontario, Canada.

References

- Adams, W. J., & Mamassian, P. (2004). Bayesian combination of ambiguous shape cues. *Journal of Vision*, 4(10):7, 921–929, <http://www.journalofvision.org/content/4/10/7>, doi:10.1167/4.10.7. [PubMed] [Article]
- Brainard, D. H. (1997). The Psychophysics Toolbox. *Spatial Vision*, 10, 433–436.
- Brooks, A., Schouten, B., Troje, N. F., Verfaillie, K., Blanke, O., & van der Zwan, R. (2008). Correlated changes in perceptions of the gender and orientation of ambiguous biological motion figures. *Current Biology*, 18, R728–R729.

- Cutting, J. E., & Kozlowski, L. T. (1977). Recognizing friends by their walk: Gait perception without familiarity cues. *Bulletin of the Psychonomic Society*, 9, 353–356.
- de Lussanet, M. H., & Lappe, M. (2012). Depth perception from point-light biological motion displays. *Journal of Vision*, 12(11):14, 1–12, <http://www.journalofvision.org/content/12/11/14>, doi:10.1167/12.11.14. [PubMed] [Article]
- Heenan, A., & Troje, N. F. (2014). Both physical exercise and progressive muscle relaxation reduce the facing-the-viewer bias in biological motion perception. *PLoS One*, 9, e99902.
- Hill, H., & Bruce, V. (1994). A comparison between the hollow-face and ‘hollow-potato’ illusions. *Perception*, 23, 1335–1337.
- Jackson, S., Cummins, F., & Brady, N. (2008). Rapid perceptual switching of a reversible biological figure. *PloS One*, 3, e3982.
- Johansson, G. (1973). Visual perception of biological motion and a model for its analysis. *Attention, Perception and Psychophysics*, 14, 201–211.
- Johansson, G. (1976). Spatio-temporal differentiation and integration in visual motion perception. *Psychological Research*, 38, 379–393.
- Jokisch, D., & Troje, N. F. (2003). Biological motion as a cue for the perception of size. *Journal of Vision*, 3(4):1, 252–264, <http://www.journalofvision.org/content/3/4/1>, doi:10.1167/3.4.1. [PubMed] [Article]
- Kanizsa, G., & Gerbino, W. (1976). Convexity and symmetry in figure-ground organization. In M. Henle (Ed.), *Vision and artifact* (pp. 25–32). New York: Springer.
- Kayahara, N. (2003). *Silhouette illusion*. Retrieved from <http://procreo.jp/labo/silhouette.swf>
- Koenderink, J. J. (1990). *Solid shape (Vol. 2)*. Cambridge, MA: MIT press.
- Koffka, K. (1935). *Principles of Gestalt psychology*. Oxford: Harcourt, Brace.
- Langer, M. S., & Bülthoff, H. H. (2000). A prior for global convexity in local shape-from-shading. *Max Planck Institute for Biological Cybernetics Technical Report No. 081*, 30, 403–410.
- Liu, B., & Todd, J. T. (2004). Perceptual biases in the interpretation of 3D shape from shading. *Vision Research*, 44, 2135–2146.
- Mamassian, P., & Landy, M. S. (1998). Observer biases in the 3D interpretation of line drawings. *Vision Research*, 38, 2817–2832.
- Marr, D. (1982). *Vision: A computational investigation into the human representation and processing of visual information*. New York: Freeman.
- Marr, D., & Nishihara, H. K. (1978). Representation and recognition of the spatial organization of three-dimensional shapes. *Proceedings of the Royal Society of London*, 200, 269–294.
- Michalak, J., Troje, N. F., Fischer, J., Vollmar, P., Heidenreich, T., & Schulte, D. (2009). Embodiment of sadness and depression: Gait patterns associated with dysphoric mood. *Psychosomatic Medicine*, 71, 580–587.
- Pollick, F. E., Kay, J. W., Heim, K., & Stringer, R. (2005). Gender recognition from point-light walkers. *Journal of Experimental Psychology: Human Perception and Performance*, 31, 1247–1265.
- Reichel, F. R., & Todd, J. T. (1990). Perceived depth inversion of smoothly curved surfaces due to image orientation. *Journal of Experimental Psychology: Human Perception and Performance*, 16, 653–664.
- Rubin. (1958). Figure and ground. In D. Beardslee (Ed.), *Readings in perception*. (M. Wertheimer, Trans., pp. 35–101). Princeton: Van Nostrand. (Original work published in 1915.)
- Runeson, S., & Frykholm, G. (1981). Visual perception of lifted weight. *Journal of Experimental Psychology: Human Perception and Performance*, 7, 733–740.
- Schouten, B., Davila, A., & Verfaillie, K. (2013). Further explorations of the facing bias in biological motion perception: Perspective cues, observer sex, and response times. *PloS One*, 8, e56978.
- Schouten, B., Troje, N. F., Brooks, A., van der Zwan, R., & Verfaillie, K. (2010). The facing bias in biological motion perception: Effects of stimulus gender and observer sex. *Attention, Perception and Psychophysics*, 72, 1256–1260.
- Schouten, B., Troje, N. F., & Verfaillie, K. (2011). The facing bias in biological motion perception: Structure, kinematics, and body parts. *Attention, Perception and Psychophysics*, 73, 130–143.
- Schouten, B., Troje, N. F., Vroomen, J., & Verfaillie, K. (2011). The effect of looming and receding sounds on the perceived in-depth orientation of depth-ambiguous biological motion figures. *PloS One*, 6, e14725.
- Schouten, B., & Verfaillie, K. (2010). Determining the point of subjective ambiguity of ambiguous biological-motion figures with perspective cues. *Behavior Research Methods*, 42, 161–167.
- Sumi, S. (1984). Upside-down presentation of the Johansson moving light-spot pattern. *Perception*, 13, 283–286.
- Sweeny, T. D., Haroz, S., & Whitney, D. (2012).

- Reference repulsion in the categorical perception of biological motion. *Vision Research*, *64*, 26–34.
- Troje, N. F. (2002). Decomposing biological motion: A framework for analysis and synthesis of human gait patterns. *Journal of Vision*, *2*(5):2, 371–387, <http://www.journalofvision.org/content/2/5/2>, doi:10.1167/2.5.2. [PubMed] [Article]
- Troje, N. F. (2008). Biological motion perception. In A. Basbaum et al. (Eds.), *The senses: A comprehensive reference*. Oxford: Elsevier.
- Troje, N. F. (2010). Perceptual biases in biological motion perception and other depth-ambiguous stimuli. *Journal of Vision*, *10*(7):792, <http://www.journalofvision.org/content/10/7/792>, doi:10.1167/10.7.792. [Abstract]
- Troje, N. F. (2013). Vision as hypothesis testing: The case of biological motion perception. In: S. Leyssen & P. Rathgeber (Eds.), *Bilder animierter Bewegung / Images of animate movement*. Wilhelm Fink Verlag: Paderborn.
- Troje, N. F., & McAdam, M. (2010a). The viewing-from-above bias and the silhouette illusion. *i-Perception*, *1*, 143–148.
- Troje, N. F., & McAdam, M. (2010b). What causes the facing-the-viewer bias in biological motion? *Perception*, *39*, 150.
- Vanrie, J., Dekeyser, M., & Verfaillie, K. (2004). Bistability and biasing effects in the perception of ambiguous point-light walkers. *Perception*, *33*, 547–560.
- Vanrie, J., & Verfaillie, K. (2006). Perceiving depth in point-light actions. *Attention, Perception and Psychophysics*, *68*, 601–612.
- Vanrie, J., & Verfaillie, K. (2011). On the depth reversibility of point-light actions. *Visual Cognition*, *19*, 1158–1190.
- Woo, M., & Shreiner, D. (2003). *OpenGL programming guide: The official guide to learning OpenGL, Version 1.4*. Boston: Addison-Wesley Longman Publishing Co., Inc.