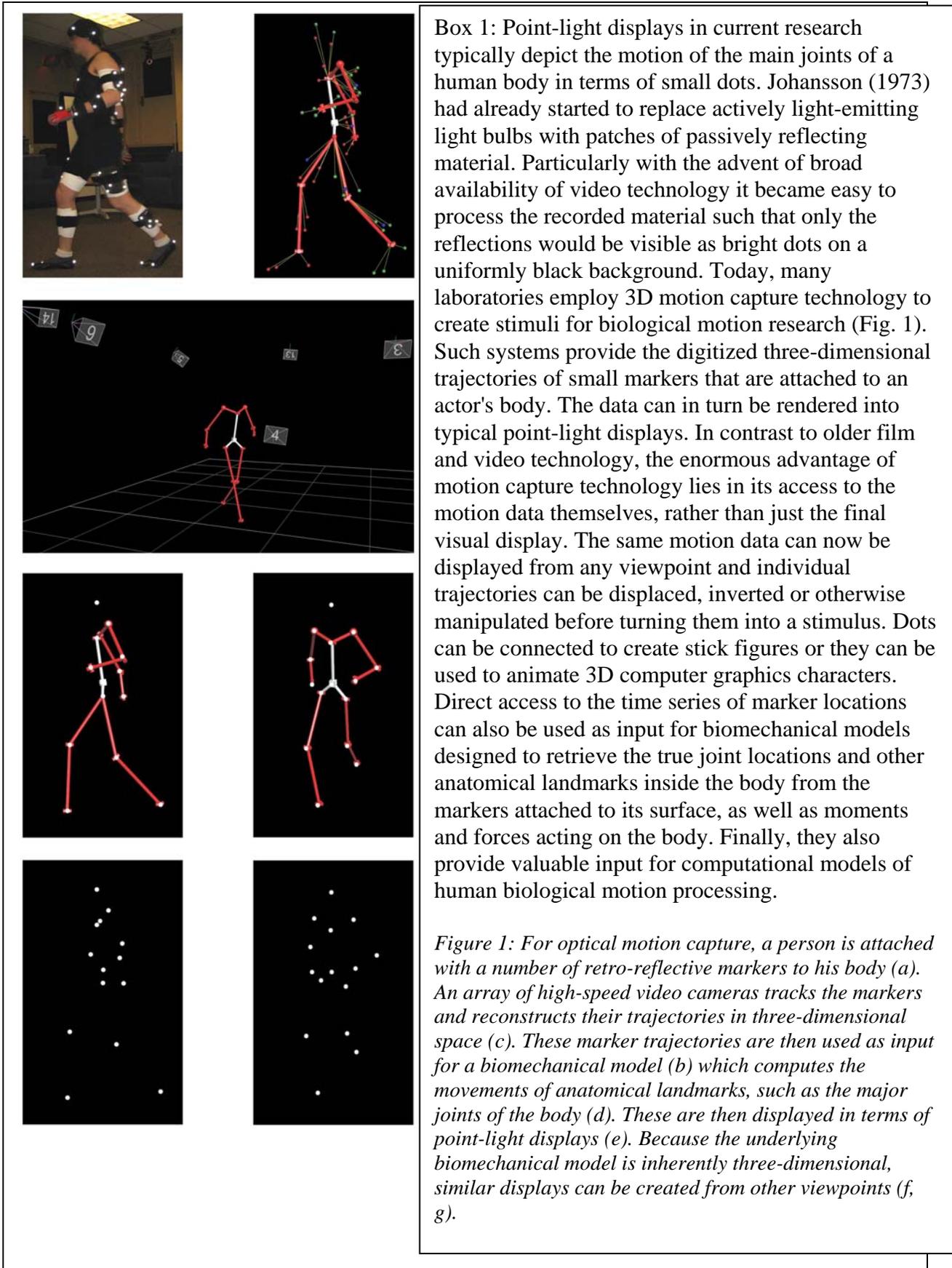# Biological motion perception

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A little more than 30 years ago, the Swedish psychologist Gunnar Johansson (1973; 1976) fascinated the vision science community with an arresting demonstration of the organizational efficiency of the human visual system: He attached small light bulbs to the major joints of a human figure dressed entirely in black. Filming the movement of that figure created a highly reduced display that consisted only of a small number of white dots moving against a black background. Yet, it created the vivid and immediate percept of a human figure in action. Less than 10 dots and 150 ms of display time were sufficient for a human observer to perceptually organize the dots into a fully coherent, articulated shape of a human figure, implicating the involvement of a highly specialized perceptual process. Today, we call Johansson's phenomenon **biological motion perception** and the **point-light displays** he first used to demonstrate it have become recognized as a very effective research tool for studying the mechanisms upon which it is based. A demonstration of point-light displays and their potential to convey information about a walking person can be found at http://www.biomotionlab.ca/Demos/BMLwalker.html.

The **functional significance** of this fascinating phenomenon lies in the vitally important ability to detect and to adequately interpret the movements of another animal. The other animal might be a predator, potential prey, or of one's own kind. If the latter is the case, it might be a potential mate, a rival, or maybe a particular individual that we depend on, for instance, a parent or an offspring. Visual motion plays a major role in identifying another living creature and can inform the observer about its actions and intentions. Humans are highly **social animals**. Not surprisingly, this is reflected in many specializations of our sensory systems, such as the ability to comprehend speech, to recognize faces and – the topic of this chapter – to retrieve information from the way a person moves.

Signatures contained in biological motion patterns identify the agent as an animal or human figure (Mather & West, 1993) and reveal its actions (Dittrich, 1993). They are sufficient to recognize a familiar person (Cutting & Kozlowski, 1977; Troje, Westhoff, & Lavrov, 2005; Westhoff & Troje, in press) and to attribute socially relevant attributes such as sex, age, mental states, actions and intentions to unfamiliar individuals (Barclay, Cutting, & Kozlowski, 1978; Blakemore & Decety, 2001; Dittrich, Troscianko, Lea, & Morgan, 1996; Mather & Murdoch, 1994; Pollick, Paterson, Bruderlin, & Sanford, 2001; Runeson, 1994; Troje, 2002a, 2002b). Research into the cues that convey this information unveils a rich composition of configural, anthropometric features, on the one hand, and dynamic features such as speed, and spectral composition of the point-light trajectories, on the other hand (Pollick et al., 2001; Troje et al., 2005; Westhoff & Troje, in press). If pit against one another, the information provided by dynamic features clearly dominates the role of static features (Mather & Murdoch, 1994; Troje, 2002a).

Box 1: Point-light displays in current research typically depict the motion of the main joints of a human body in terms of small dots. Johansson (1973) had already started to replace actively light-emitting light bulbs with patches of passively reflecting material. Particularly with the advent of broad availability of video technology it became easy to process the recorded material such that only the reflections would be visible as bright dots on a uniformly black background. Today, many laboratories employ 3D motion capture technology to create stimuli for biological motion research (Fig. 1). Such systems provide the digitized three-dimensional trajectories of small markers that are attached to an actor's body. The data can in turn be rendered into typical point-light displays. In contrast to older film and video technology, the enormous advantage of motion capture technology lies in its access to the motion data themselves, rather than just the final visual display. The same motion data can now be displayed from any viewpoint and individual trajectories can be displaced, inverted or otherwise manipulated before turning them into a stimulus. Dots can be connected to create stick figures or they can be used to animate 3D computer graphics characters. Direct access to the time series of marker locations can also be used as input for biomechanical models designed to retrieve the true joint locations and other anatomical landmarks inside the body from the markers attached to its surface, as well as moments and forces acting on the body. Finally, they also provide valuable input for computational models of human biological motion processing.

Figure 1: For optical motion capture, a person is attached with a number of retro-reflective markers to his body (a). An array of high-speed video cameras tracks the markers and reconstructs their trajectories in three-dimensional space (c). These marker trajectories are then used as input for a biomechanical model (b) which computes the movements of anatomical landmarks, such as the major joints of the body (d). These are then displayed in terms of point-light displays (e). Because the underlying biomechanical model is inherently three-dimensional, similar displays can be created from other viewpoints (f, g).

The ability to perceive biological motion arises early in life. Four-month-old **infants** stare at human motion sequences for longer durations than they will at the same number of dots undergoing random motions (Bertenthal, 1993; Fox & McDaniel, 1982) and event-related potential (ERP) studies imply that the brain areas involved are similar to the ones found in adults (Jokisch, Daum, Suchan, & Troje, 2005; Reid, Hoehl, & Striano, 2006). On the other hand, however, children show a number of fundamental differences in the way they perceive biological motion and keep improving their ability to retrieve the shape of a moving body until they reach adult levels of performance at about age five (Pavlova, Krageloh-Mann, Sokolov, & Birbaumer, 2001).

In the adult **brain**, multiple **areas** are involved in biological motion processing (for comprehensive reviews, see Allison, Puce, & McCarthy, 2000; Puce & Perrett, 2003). Recording from single cells in macaque cortex, Oram and Perrett (1994) first identified structures in the upper bank of the superior temporal sulcus (STS) as selectively responsive to human form and motion. A number of more recent brain imaging studies corroborate this finding and show that the posterior part of STS is particularly active when looking at point-light displays of an upright human walker (Bonda, Petrides, Ostry, & Evans, 1996; Grossman & Blake, 2002; Grossman, Blake, & Kim, 2004; Grossman et al., 2000; Peuskens, Vanrie, Verfaillie, & Orban, 2005). While STSp is clearly responsive to biological motion it is not clear how specific this area is. Stimuli such as faces (Grossman & Blake, 2002) speech (Beauchamp, 2005), the sound of footsteps (Bidet-Caulet, Voisin, Bertrand, & Fonlupt, 2005), and visual motion confined to specific limbs, the eyes or mouth (Grezes, Costes, & Decety, 1998; Puce, Allison, Bentin, Gore, & McCarthy, 1998) also result in STSp activation. Besides STSp, other areas have been identified that are

responsive to biological motion. They involve the ventral surface of the temporal lobe (Vaina, Solomon, Chowdhury, Sinha, & Belliveau, 2001), the fusiform gyrus (Beauchamp, Lee, Haxby, & Martin, 2002), and the fusiform face area (Grossman & Blake, 2002; Peelen & Downing, 2005). For all these areas, it is rather unclear if they respond specifically to human motion or if they are triggered generally by biological motion. Only very few imaging studies have contrasted representations of humans versus non-humans and none of these has used standard biological motion point-light displays (Buccino et al., 2004; Downing, Jiang, Shuman, & Kanwisher, 2001). More research is required to characterize and understand the neuronal circuits involved in the perception of biological motion.

Given the complexity and sophistication of biological motion perception it is not surprising that it is susceptible to **failure**. Case studies with brain-lesioned patients demonstrate a double-dissociation between general motion perception and the ability to see and interpret biological motion (McLeod, Dittrich, Driver, Perrett, & et al., 1996; Vaina, Lemay, Bienfang, Choi, & Nakayama, 1990). Specific deficits in the ability to perceive and adequately interpret biological motion patterns have also been described in the context of a number of different disorders. Autistic children have been demonstrated to show deficits in biological motion perception (Blake, Turner, Smoski, Pozdol, & Stone, 2003; Dakin & Frith, 2005) which is consistent with the finding that they also show STS abnormalities (Waiter et al., 2004). Patients suffering from periventricular leukomalacia (PVL) which is often present in children born prematurely have been described to be compromised in their ability to perceive biological motion (Pavlova, Marconato et al., 2006; Pavlova, Sokolov, Birbaumer, & Krageloh-Mann, 2006; Pavlova et al., 2005; Pavlova, Staudt, Sokolov, Birbaumer, & Krageloh-Mann, 2003). Impairments in

biological motion perception have also been described in schizophrenic patients (Kim, Doop, Blake, & Park, 2005) and in children with Down syndrome (Virji-Babul, Kerns, Zhou, Kapur, & Shiffrar, 2006).

In many respects, the information contained in biological motion and our ability to exploit it resembles the phenomenology of **face recognition**. For instance, both visual domains are highly susceptible to a pronounced **inversion effect**: If a point-light stimulus (or a face) is turned upside down, perception is strongly impaired (Pavlova & Sokolov, 2000; Sumi, 1984). For faces, there is convincing evidence that the inversion effect is caused by an impairment of mechanisms responsible for assessing the details of the spatial configuration of facial features (Farah, Tanaka, & Drain, 1995; Maurer, Grand, & Mondloch, 2002) and the same has been implied to be the case for biological motion (e.g. Dittrich, 1993; Proffitt & Bertenthal, 1990; Reed, Stone, Bozova, & Tanaka, 2003; Troje, 2003).

A number of **debates** have arisen concerning the mechanisms that serve the complex visual abilities involved with biological motion perception. One of them concerns the question to what extent biological motion perception is driven by global, conceptual information processing and to what extent it is determined by local, low-level motion processing. While some authors think that local motion is sufficient (e.g. Mather, Radford, & West, 1992) others clearly demonstrate global effects (e.g.Neri, Morrone, & Burr, 1998). Another dispute which is connected to the question about the role of local vs. global information (Thornton, Pinto, & Shiffrar, 1998) concerns the contributions of attentional mechanisms (Cavanagh, Labianca, & Thornton, 2001; Thornton, Rensink, & Shiffrar, 2002) and the role of learning (Grossman et al., 2004; Hiris, Krebeck,

Edmonds, & Stout, 2005; Jastorff, Kourtzi, & Giese, 2006). Finally, there are seemingly contradictory findings about how well biological motion can be processed in the visual periphery (Gibson, Troje, Sadr, & Nakayama, in preparation; Ikeda, Blake, & Watanabe, 2005). Here, we want to argue that these controversies can be resolved only if we acknowledge that biological motion is not a single phenomenon, but consists of a number of different aspects which have to be distinguished carefully – both conceptually and experimentally. Typical paradigms used in biological motion research such as detecting a point-light walker in a mask, or deriving the direction into which the walker is facing might address very different processing stages and are not interchangeable, but may address very different processing stages.

The majority of biological motion research focuses on the impressive ability to organize the individual dots of a point-light display into the coherent structure of a human body. Here, we will refer to this as the structure-from-motion aspect of biological motion perception. In general, such a focus is not explicitly intended but results from a standard task widely used in biological motion research: the detection of a point-light walker which is masked by superimposing it with multiple **scrambled walkers**. Scrambled walkers are derived from veridical, coherent point-light walkers by adding a random but constant offset to the location of the single trajectories. This manipulation disrupts the structure of the display but leaves the local motion of the individual dots intact. The only difference between a display that consists only of a mask of scrambled walkers and one that embeds a coherent walker in this mask is the presence of the coherent structure of the single walker. A similar focus also characterizes large parts of the brain imaging literature. Here, brain activity in response to intact biological motion is often contrasted with responses to scrambled motion – a contrast that once again reduces biological motion perception

to its structure-from-motion aspect.

In a recent study by Troje and Westhoff (2006) it was shown that scrambled biological motion of humans and animals, even though devoid of any structural information, still carries information about the direction in which a walker was facing (Fig. 2). Interestingly, observers can exploit this information only if the stimulus is presented upright. Since the locations of the individual dot trajectories are random in a scrambled biological motion display, the information about the direction as well as the corresponding inversion effect must be contained in local dot trajectories. In fact, it could be shown that the critical information is carried by the motion of a human's or animal's feet. The dependence on orientation is hypothesized to be due to inherent expectations about the direction of gravitational acceleration, an assumption corroborated by earlier findings on the role of heuristics about gravity in the perception of biological motion (Jokisch & Troje, 2003; Runeson, 1994; Shipley, 2003) and non-animate motion (Pittenger, 1985; Watson, Banks, von Hofsten, & Royden, 1992). Troje and Westhoff (2006) suggest that the sensitivity to the dynamics of the feet reflects its potential role as a visual invariant for the non-specific detection of an animal in the visual environment.

I want to conclude this chapter by pointing out that biological motion perception is not just a single phenomenon. In order to fully understand and appreciate its rich and fascinating phenomenology we have to distinguish between a number of different processing levels:

1. **Life-detection**: Troje and Westhoff (2006) identified the ballistic movements of the limps of a terrestrial animal to provide an invariant that our visual system uses to spot an animal in the visual environment independent of its particular shape. The cue seems to work well not only for

foveal vision but also in the visual periphery and probably directs attention to an event of potentially vital significance. The underlying visual filter mechanism is expected to be evolutionary old and shared by other animals as well. Behavioural experiments on visually naïve, newly hatched chicks suggests that they use the same cue to identify the object of filial imprinting and they even show the same inversion effect (Vallortigara & Regolin, 2006; Vallortigara, Regolin, & Marconato, 2005).

2. **Structure-from-motion**: Once a living creature is detected, its movements can be used to perceptually organize it into a coherent, articulated body structure, resulting in "basic level" (Rosch, 1988) agent recognition (e.g., is this a human, a cat, a bird?). This mechanism does not work very well in the visual periphery (Ikeda et al., 2005), and probably requires attention (Cavanagh et al., 2001; Thornton et al., 2002). In contrast to the early "life detection" stage, it requires learning and individual experience (Jastorff et al., 2006). It is also subject to an inversion effect, which, however, is independent of the one operating on the "life detection" mechanism and rather related to the orientation dependency of configural processing observed in face recognition. The relation between the two mechanisms for life detection and for structure-from-motion retrieval might be similar to the relation between two processes in the development of face recognition suggested by Morton and Johnson (1991). These authors suggested that an innate system guides attention to face-like patterns, while a second mechanism is responsible for learning about the detailed characteristics of faces required for individual face recognition.

3. **Action recognition**: On this level, structural and kinematic information is integrated into a system that classifies and categorizes the action. Efficient classification on this level is expected

to be invariant to the particular agent, viewing conditions and the style of the action. As yet, we know rather little about this processing level. More research is required to understand which features define a particular action. Some interesting ideas may come from recent work on general event perception (e.g. Zacks, 2004). Given the ease with which the human visual system categorizes actions, the difficulty to experimentally and theoretically identify action-specific invariants is surprising – and probably related to the harsh contrast between human "basic" level (Rosch, 1988) object classification and the lack of good computational models for it.

4. **Style recognition**: Once both agent and action are identified, pattern recognition at a "subordinate" level (Rosch, 1988) helps to retrieve further information about the details of both. For instance, once we know we are confronted with a human walker (let's say, rather than a hunting tiger) we are able to use motion as a source of information about individual identity, gender, age, emotional state, personality traits and as a complex means for signaling and communications. Depending on the particular property, the results of initial data processing required to characterize and isolate diagnostic features might eventually feed into different neuronal circuits, and in that respect "style recognition" might not be due to a single mechanism but to several. Yet, at least from a computational point of view, it is very likely that all of them share certain processing principles (Troje, 2002a, 2002b).

Adopting this multi-level view has important implications for understanding biological motion perception. It resolves many of the above mentioned debates (local vs. global, role of attention and learning, foveal vs. peripheral vision) in a canonical way. Furthermore, it generates new hypotheses about the development of biological motion perception, both ontogenetically and

evolutionarily. It also has implications concerning the role of impaired biological motion perception in disorders that affect social competence and the complex sensory basis of communicative behaviour.

Before I finish this short review on biological motion perception I want to point out that it is by no means comprehensive. Much more work has been done in all the areas that I tried to cover here. In addition there are topics that I did not address at all. One of them refers to the large field of computational models for human motion recognition. Some of the models are explicitly biologically motivated, trying to incorporate information we have about the physiology of biological motion perception (e.g. Giese & Poggio, 2003). On the other hand, there is a large body of work conducted in the fields of computer vision and machine learning which approaches biological motion perception from the perspective of pattern recognition. Another area which I did not even try to address under the limited scope of this chapter is the interesting question of understanding biological motion in the context of human interaction. Concepts such as simulation theory, common-coding theory (Prinz, 1997), the direct-matching hypothesis (Rizzolatti, Fogassi, & Gallese, 2001) and particularly the discovery of mirror neurons in the monkey brain (Gallese, Fadiga, Fogassi, & Rizzolatti, 1996; Rizzolatti, Fadiga, Gallese, & Fogassi, 1996) provide an interesting basis for speculations about how the behaviour between two interacting people becomes coupled and coordinated (Blakemore & Decety, 2001; Decety & Grezes, 1999). The perception of social contingency and the mechanisms through which it determines our own actions in social situations probably has to be considered a fifth level in the above proposed taxonomy of levels of biological motion perception.
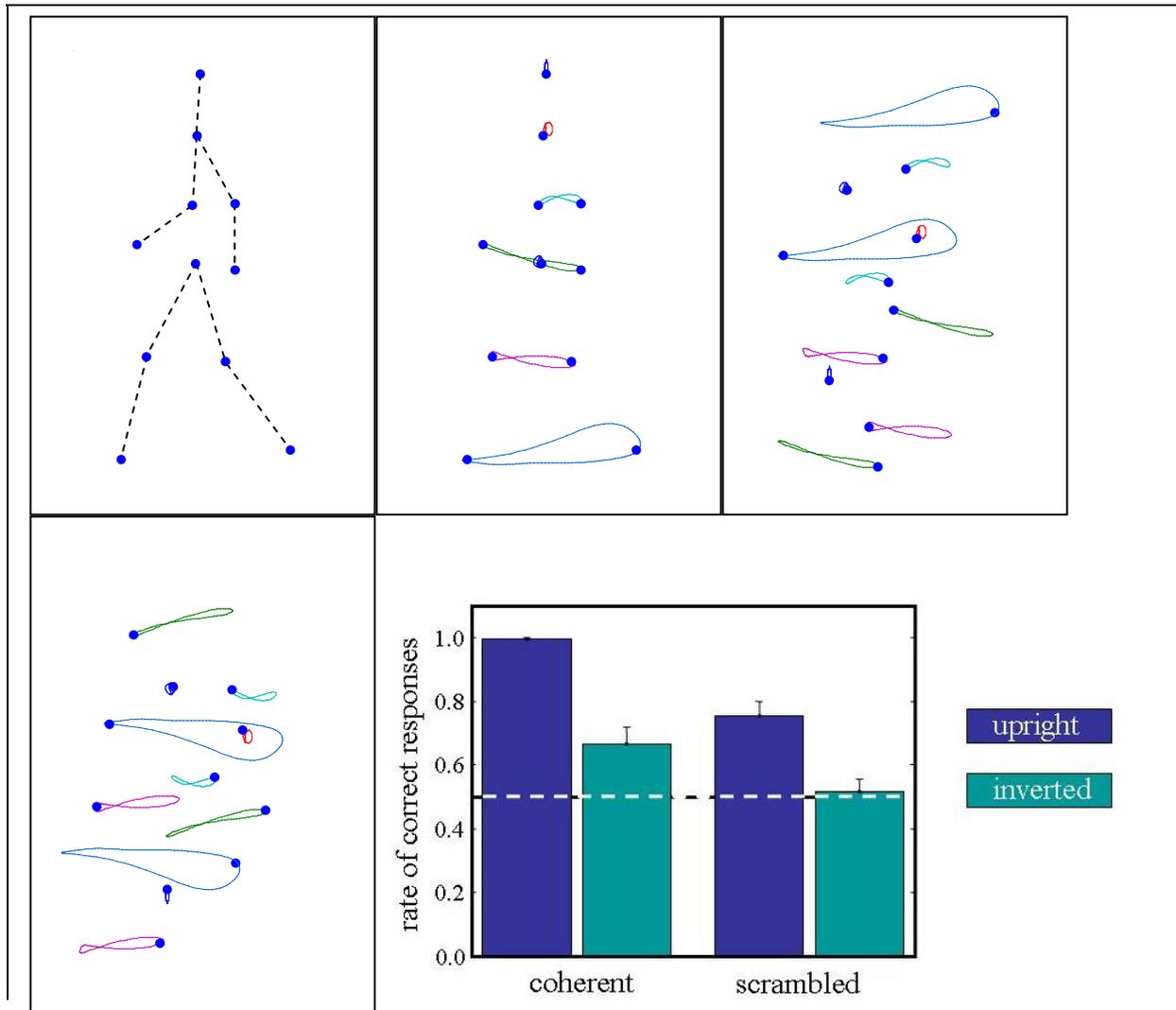
Figure 2: Scrambled biological motion is derived from normal, coherent biological motion (a, b) by randomly offsetting the trajectories of the individual dots (c). This disrupts the structure of the human figure. Yet, if asked in which direction "this odd creature" is facing, observers are still quite accurate. Only if the scrambled point-light display is turned upside down (d), performance drops to chance level (e). The dashed lines which show the articulation of the individual dots (a) and the solid lines which illustrate their trajectories (b, c, and d) are not shown in the experiment. Visit http://www.biomotionlab.ca/Demos/scrambled.html for an interactive animation that demonstrates the stimuli. For experimental details, see Troje and Westhoff (2006).

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