Low-Level Visual Processing Allows Humans to React to Animate Objects: Binding Memory as a Key Subsystem of Biological Motion Detection

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Abstract

We review the literature to date on biological motion detection and its important prerequisite, human binding memory. Binding memory is the system for combining features like shape, color and size into coherent visual objects, and tracking these objects through time in short-term memory. This in turn makes possible biological motion detection, which is crucial to a wide range of human social activity. Recent experiments have shown that binding memory is available from birth, declines with old age, and is improved by emotional arousal. Furthermore, binding memory has been shown to be disturbed in neurological disorders such as autism and schizophrenia. These results promise to contribute to a greater understanding of biological motion detection in the future.

Biological motion detection

Humans have a specialized system called biological motion detection that responds specially to the movements of living creatures. More specifically, biological motion detection is the cognitive process whereby the perception of motion patterns characteristic of living organisms evoke a compelling impression that a living thing is being observed (Johansson 1973). This distinct neurological process is important for developing an understanding of the minds of others, and for functioning socially in general; human understanding of what is and is not a living thing is based on cues including motion – such as walking, speaking, or yawning – and social skills are predicated on the ability to readily discriminate between living and non-living things (Blake et al., 2007).

Biological motion detection – which exists in a wide variety of animals including chickens (Simion et al., 2008) and macaques (Oram et al.,1994) – is functional in humans almost from birth (Simion et al., 2008). When two-day-old infants were shown various rudimentary animations consisting of black dots moving around on a white background, they spent more time looking at the patterns that resembled an upright, walking animal than any of the others. Because the animations used were so simple – comprised of just 13 dots and 23 looping frames of video – they are unintelligible jumbles when motionless. The fact that the infants could discriminate different moving patterns of objects from each other at birth indicates that they must already have some sort of functioning binding memory. This result seems to fit with the fact that binding memory does not require the hippocampus, a brain area widely implicated in memory but not functional at birth. In trials with a patient with severe hippocampal damage, binding memory (as measured by color- and shape-recognition tasks described below) for the patient was no different than that of control subjects (Baddeley et al., 2010).

The fact that newborns can detect biological motion from the simplest patterns (Simion et al., 2008) with an ability that does not depend, like so many other memory processes, on the hippocampus suggests that this is an important component of human cognition with highly-specialized neural correlates. In typical humans, biological motion detection has been localized to a small area in the superior-temporal sulcus (STS) (Grossman et al., 2000). This brain region was found to be sensitive to motion typical of animate creatures, and showed greater activation even when the body plan was reduced to abstract, simplified points of light moving in a pattern reminiscent of animal motion.

Despite the unitary, integrated nature of the perceptual experience of biological motion detection – and the ease with which the brain typically performs this task – this ability only arises through the coordinated effort of several complex systems in different parts of the brain. As the points-of-light experiment demonstrated, the low-level components of biological motion are simply visual stimuli with certain shapes, orientations, motions and colors associated with them. To detect biological motion, the brain must appropriately process these components in concert.

A closer look at how this processing works indicates that the brain perceives visual features (e.g. color, shape, and orientation) individually, and then uses short-term working memory to "bind" them together into a unitary experience, (Treisman 2003) allowing us to experience a world of coherent, integrated objects instead of disembodied or wrongly-combined shapes, colors, motions, and sizes (Treisman 1998). The combined system of visual object binding and short-term memory is called "visual binding working memory", or simply "binding memory." It is what allows people to experience, for example, a ball flying through the air as a single moving object, instead of as snapshots of identical balls tracing a path through space. Binding memory is an indispensable part of biological motion detection.

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Basic evidence for the existence of binding memory

Recent developments in binding memory research, elucidating its properties and limitations, promise to expand scientific understanding of biological motion detection. Several experiments have confirmed the premise of binding memory: that features of objects are first perceived separately before being bound together into a unified object. For example, in one experiment, subjects were shown collections of squares with varying orientations that were laid out in a grid, and they were asked to recall features of the squares at particular grid locations after a short delay (Bays et al., 2011). Interestingly, subjects often failed to recall which features went with which object, rather than forgetting the object altogether. This suggests that people perceive the separate features of an object individually, rather than as a single unified object, and have separate categories for different features (e.g. color, shape, and orientation).

In a similar experiment, researchers started from a baseline of three objects with six different features (Wheeler et al., 2002). When they doubled the number of objects, there was no appreciable change in recall performance, but halving the number of features resulted in a significant increase in performance recall. This suggests that perception can be limited by the number of features, but not by the number of objects. These results were further supported by a similar study, where subjects were briefly shown objects on a screen, followed by a blank interval, and were then asked to choose the object they had seen from an array of similar types of objects (Alvarez et al., 2004). Their capacity for remembering these objects varied widely, with a greater number of features to be recalled correlating with a decrease in performance. Since the increase in the number of features but not the number of objects led to a decrease in memory performance, it is likely that that features of objects are held separately in short term memory and then subsequently integrated. This is a limit of human binding memory: subjects' performance in object-recall tasks depend on the number features the objects have.

Effects of old age and disease on binding memory

Recent studies have also explored the effects of old age and diseases such as autism spectrum disorders (ASD) and schizophrenia on binding memory. For example, functional magnetic resonance imaging (fMRI) measurements of brain activity were taken in ASD patients as they performed a biological motion detection task (Herrington et al., 2007). The ASD subjects showed less activity in the fusiform gyrus as compared to control subjects, an area previously implicated in the processing of visual feature binding. These results fit with those of another study in which autistic and normal children were asked to perform two tasks: one involving the detection of abstract shapes in a still image, and one involving the detection of biological motion (Blake et al., 2003). Performance for both groups was similar on the first task, but the autistic children performed far worse on the task with the simulated biological motion. This supports the claim that autistic individuals generally have more trouble binding orientation and position information together through time, and thus have a harder time detecting biological motion.

Studies with another disease, schizophrenia, have also highlighted the critical importance of binding memory and biological motion detection by showing what happens when there is a binding memory deficit. In a study with schizophrenic patients, visual working memory was tested for two features of drawings of familiar items: their location in a grid, and the identity of the item (Burglena et al., 2003). The test was done under two sets of circumstances: in the first, subjects were asked to simply recall the features independently. Specifically, they had to say where on the grid an object had been displayed (regardless of which object), or what object had appeared (regardless of where). In the second set of circumstances, subjects were asked to recall an object and its location (a test of binding memory). Although schizophrenic patients generally have impaired working memory, this experiment's results showed that they had disproportionately poor performance in binding memory.

Yet another study explored the effects of age on binding (Kessels et al., 2007). Young adults (mean age of 25) and older adults (mean age of 66) were asked to view a series of familiar objects displayed on a grid. They were then asked to recall either just the objects, just the grid locations that were occupied, or both the object and the grid location in which it was displayed. Even after taking into account the fact that memory generally declines with age, the older adults had disproportionately poor performance on the final task. This suggests that binding memory performance declines markedly with age, and to an even greater degree than other kinds of memory.

The fact that autism and schizophrenia – broad and severe cognitive disturbances – correlate with binding memory problems underscores the relevance of this ability to normal human cognition (Herrington et al., 2007, Blake et al., 2003, Burglen et al., 2003).

Effects of attention and emotional arousal in binding memory

The effects of attention and emotional arousal in the function of binding memory have been explored experimentally as well. In one study, subjects were shown shapes with distinctive colors and orientations on a computer screen (Johnson et al., 2008). They were then asked to state either which features had been simply present (to test memory but not binding), or which features had gone with which shape (to test binding). Performance was evaluated both in the presence and absence of distracting stimuli. Interestingly, the presence of a distraction impaired performance equally for individual feature recall as well as bound object recall. In other words, the fact that the subjects' being distracted did not specifically impede their feature binding any more than it did the processing of the features alone indicates that one need not pay attention to an object to properly process it together with all of its features.

In another study, subjects were shown words of varying colors and levels of emotional significance (e.g. "slaughter" or "emergency" for highly-emotional words, and "taxi" or "dormitory" for neutral words) (Doerksen et al., 2001). They were then asked to recall either one separate feature of the object (e.g. the word), another feature (e.g. the color), or the bound object (e.g. the word and the color it was displayed in). Unsurprisingly, subjects exhibited an enhanced recall for highly emotional words. However, a high emotional valence also enhanced recall for the associated color, suggesting a binding effect. In other words, emotional arousal enhances not only memory, but binding efficiency as well. These are surprising strengths: binding memory can function even when people are not paying attention and can actually be improved by emotional arousal.

Future directions

Biological motion detection is so important that it becomes functional almost immediately out of the womb and underpins people's basic ability to interact with each other (Simion et al., 2008). More research into binding memory is needed to gain a greater understanding of biological motion detection and the corresponding elements of high-level social cognition. Not enough is known about what other lower-level systems aside from feature binding are indispensible to biological motion detection.

Further research is also needed to determine the extent to which feature binding deficits in pathological cases contribute to problems with biological motion detection, in order to learn more precisely just how much it depends on binding. This might be accomplished by combining some of the experimental paradigms above to explore the effects of conditions like emotional arousal on binding and motion detection in subjects with neurological disorders.

Furthermore, more work is required to understand the neural correlates of binding memory in cases of these neurological diseases, particularly those with salient social implications, such as Alzheimer's, ASD, and schizophrenia. Advances in this area promise to not only enrich the understanding of how biological motion detection works in humans, but of the pathologies themselves.

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