

threatening actions may represent an important condition under which emotional processes impact perceptual analyses.

REFERENCES

- Adolphs, R. (1999). The human amygdala and emotion. *Neuroscientist*, 5, 125–137.
- Anderson, A. K., Christoff, K., Panitz, D., de Rosa, E., & Gabrieli, J. D. (2003). Neural correlates of the automatic processing of threat facial signals. *Journal of Neuroscience*, 23(13), 5627–5633.
- Baron-Cohen, S. (1995). *Mindblindness: An essay on autism and theory of mind*. Cambridge, MA: MIT Press.
- Brothers, L. (1997). *Friday's footprint: How society shapes the human mind*. London: Oxford University Press.
- Heberlein, A. S., Adolphs, R., Tranel, D., & Damasio, H. (2004). Cortical regions for judgments of emotions and personality traits from point-light walkers. *Journal of Cognitive Neuroscience*, 16(7), 1143–1158.
- Puce, A., & Perrett, D. (2003). Electrophysiology and brain imaging of biological motion. *Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences*, 358(1431), 435–445.

Recognizing novel deforming objects

Lewis L. Chuang

*Max Planck Institute for Biological Cybernetics, and Graduate School of
Neural and Behavioral Sciences, Tübingen, Germany*

Quoc C. Vuong

Max Planck Institute for Biological Cybernetics, Tübingen, Germany

Ian M. Thornton

Department of Psychology, University of Wales Swansea, Swansea, UK

Heinrich H. Bülthoff

Max Planck Institute for Biological Cybernetics, Tübingen, Germany

Visual object perception is dynamic as the result of an active observer or movement in the environment. Nonetheless, contemporary theories of object

Address correspondence to: Lewis Chuang, Max Planck Institute for Biological Cybernetics, Spemannstr. 38, 72076, Tübingen, Germany. E-mail: lewis.chuang@tuebingen.mpg.de

recognition commonly focus on how objects are represented in terms of their static properties, e.g., shape. When the contribution of motion has been considered, it has typically been with regards to how rigid rotation in depth could facilitate the reconstruction of an object's static 3-D shape (e.g., Ullman, 1979). Here, we propose that human observers represent an object's dynamic properties as a cue to its identity, independent of its contribution to shape perception. This information may facilitate recognition when shape information is less reliable, e.g., viewpoint variations.

Stone (1998) introduced a method that allowed the role of object motion to be studied, independent of static recognition cues. In this study, participants learned to discriminate between rigid amoeboid objects that were rotating in depth. After training, recognition performance was impaired when the rotation of the learned objects was reversed (i.e., by playing the frame sequence in reverse order). From this, Stone suggested that humans represented object motion during learning, as the *motion reversal* manipulation selectively distorted an object's learned motion but not its shape. That is, object representations that are solely defined by shape properties should not be affected by *motion reversal*. Several studies have replicated Stone's finding across a variety of novel rigid objects and learning paradigms (Liu & Cooper, 2003; Stone, 1999; Vuong & Tarr, 2004).

The work reported here extends these previous findings by investigating the visual learning of non-rigidly deforming shapes and how this learning generalizes to novel viewpoints of dynamic objects. We used amoeboid objects similar to those used by Stone (1998, 1999). However, our objects moved with characteristic patterns of *nonrigid* deformations instead of rigid rotations in depth. Samples of these stimuli can be viewed at <http://www.kyb.mpg.de/~chuang>. Unlike rigid rotations, nonrigid deformations are less likely to provide useful cues to 3-D shape. Experiments 1 and 2 investigated whether object learning is generally sensitive to nonrigid motion sequences, as it is to rigid motion. Experiment 3 examined whether learned motion can compensate for changes in viewpoint that distorts shape properties.

These three experiments observed the same design. Participants first learned to discriminate between two novel deforming objects and subsequently tested on their ability to recognize these learned targets from two distracters under testing conditions that differed across the three experiments. During testing, targets and distracter objects were presented in either forwards or reverse frame order. The reversed frame order introduced a motion reversal of the learned deformation pattern for the targets and was not expected to influence perception of the distracters. This manipulation defined the main independent variable of motion-type. The influence of motion-type on object recognition was indexed by performance decrements induced by this manipulation.

In Experiment 1, 12 participants were tested with an old–new recognition task after training. Motion reversal impaired accuracy performance of the targets, indicated by a comparison of sensitivity (d') for forwards ($M_{d'}=2.62$, $SE_{d'}=0.23$) against reversed motion ($M_{d'}=1.70$, $SE_{d'}=0.31$). This difference was significant, $F(1, 11)=6.44$, $\eta^2=0.37$, $p<.05$. In Experiment 2, we used a two-interval forced-choice (2IFC) task. Twelve participants selected the learned object from a pair of target and distractor. Here, motion reversal of the targets impaired performance for both accuracy, $F(1, 11)=12.7$, $\eta^2=0.54$, $p \leq .01$ and reaction time, $F(1, 11)=12.3$, $\eta^2=0.53$, $p<.01$. Overall, participants were faster and more accurate in identifying the learned objects deforming in the learned sequence ($M_{RT}=478$ ms, $SE_{RT}=71$; $M_{acc}=89.8\%$, $SE_{acc}=2.9$) than in the reverse sequence ($M_{RT}=551$ ms, $SE_{RT}=77$; $M_{acc}=83.1\%$, $SE_{acc}=3.9$). In conjunction with past experiments that used rigid objects, Experiments 1 and 2 demonstrate that observers encode the manner in which an object changes over time, irrespective of motion type (i.e., rigid vs. nonrigid motion).

Finally in Experiment 3, 20 participants were tested in a 2IFC task similar to Experiment 2 except that targets and distractors were now presented from different viewpoints during testing (0° , $\pm 10^\circ$, $\pm 20^\circ$, $\pm 30^\circ$ about the azimuth, relative to the learned viewpoint). It is commonly found that changing the viewpoint affects visual object recognition, as this manipulation changes the appearance of an object. This viewpoint effect was replicated here: Accuracy decreased as a function of increasing viewpoint, $F(3, 57)=25.0$, $\eta^2=0.57$, $p<.001$. Importantly, there was also a main effect of motion type across the different viewpoints, $F(1, 19)=13.7$, $\eta^2=0.42$, $p<.01$. That is, observers were more accurate for forwards than reversed motion (see Figure 1c). Finally, there was an interaction between viewpoint and motion type, $F(3, 57)=2.83$, $\eta^2=0.13$, $p<.05$. This interaction is illustrated in Figure 1(c) and appears to be the result of a lack of difference between forward and reverse motion at 0° . Removing the data point eliminates the interaction, $F(2, 38)=0.993$, $\eta^2=0.50$, $p=.38$. These results indicate that the benefit from learned object motion is maintained despite changes in viewpoint. It is not clear why this is not the case at 0° when multiple viewpoints are presented. This remains an open question for future research.

The results presented here help extend previous findings on the role of motion in object recognition. First, visual object learning involves the representation of characteristic object motion and this includes nonrigid deformations. Second, this benefit of learned object motion is robust across viewpoints and, in this aspect, different from the role of shape cues in object recognition. It should also be noted that the role of nonrigid motion in learning is not confined to novel objects. Recent experiments in face learning found that the presence of facial motion, e.g., emotional expressions, can facilitate subsequent face recognition, particularly when static cues were

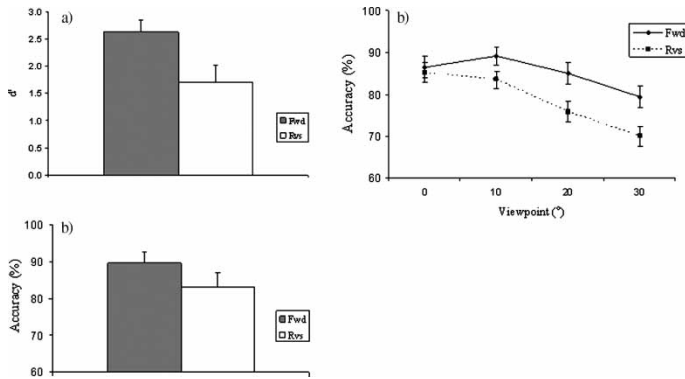


Figure 1. Summary of mean accuracy across different testing paradigms. (a) Experiment 1: Old–new recognition. (b) Experiment 2: 2IFC recognition. (c) Experiment 3: 2IFC across viewpoints. Error bars denote standard error.

rendered less informative or when task demands were increased (Knappmeyer, Thornton, & Bühlhoff, 2003; Pilz, Thornton, & Bühlhoff, in press). A question that remains to be answered is *how* dynamic information is represented. Some theorists may argue that object motion is a complex feature that requires a combination of both spatial and temporal inputs (Giese & Poggio, 2003). Alternatively, our present findings can also be explained by associative learning through the temporal contiguity of static features (Miyashita, 1988). A resolution of this debate presents potential for future research in object recognition.

REFERENCES

- Giese, M. A., & Poggio, T. (2003). Neural mechanisms for the recognition of biological movements and action. *Nature Reviews Neuroscience*, 4, 179–192.
- Knappmeyer, B., Thornton, I. M., & Bühlhoff, H. H. (2003). The use of facial motion and facial form during the processing of identity. *Vision Research*, 43, 1921–1936.
- Liu, T. S., & Cooper, L. A. (2003). Explicit and implicit memory for rotating objects. *Journal of Experimental Psychology-Learning Memory and Cognition*, 29, 554–562.
- Miyashita, Y. (1988). Neuronal correlate of visual associative long-term memory in the primate temporal cortex. *Nature*, 335, 817–820.
- Pilz, K., Thornton, I. M., & Bühlhoff, H. H. (in press). A search advantage for faces learned in motion. *Experimental Brain Research*.
- Stone, J. V. (1998). Object recognition using spatiotemporal signatures. *Vision Research*, 38, 947–951.
- Stone, J. V. (1999). Object recognition: View-specificity and motion-specificity. *Vision Research*, 39, 4032–4044.
- Ullman, S. (1979). *The interpretation of visual motion*. Cambridge, MA: MIT Press.
- Vuong, Q. C., & Tarr, M. J. (2004). Rotation direction affects object recognition. *Vision Research*, 44, 1717–1730.