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Education

1994-1998	Masters and B.A. Physics Oxford University, UK - Prof. Keith Burnett
1999-2003	Ph.D. Cognitive Science, Boston University, USA - Prof. Stephen Grossberg

Academic Positions

1998	Visiting Scientist	Mathematical modeling. Prof. Stephen Grossberg, Boston University
2003-2006	Postdoctoral Fellow	fMRI, behavioral investigations, neurophysiology Prof. Margaret Livingstone and Prof. David Hubel, Harvard Medical School, Boston, USA.
2005	Lecturer	Designed and taught undergraduate course: Psych 475: Experimental Methods: Learning & Perception University of Massachusetts (Boston)
2006-2007	Affiliated Fellow	fMRI. Sponsor: Prof. Livingstone Harvard NeuroDiscovery Center
2006-2007	Research Associate	Promotion from Research Fellow Prof. Margaret Livingstone and Prof. David Hubel Harvard Medical School, Boston
2008	Lecturer	Designed and taught graduate course. CN520: Principles & Methods of Cognitive & Neural Modeling 2 Boston University
2007-Present	Postdoctoral Fellow	fMRI & behavioral investigations Prof. Jeremy Wolfe and Prof. Todd Horowitz. Brigham & Women's, Hospital & Harvard Medical School

Grants and Fellowships

1997	-----------	Exhibitioner Magdalen College, Oxford University
1997	-----------	Commendation for Excellence for Practical Work, Oxford University
1999-2003	$66,000	Presidential University Graduate Fellowship, Boston University
2004-2006	$129,000	Helen Hay Whitney Postdoctoral Research Fellowship
2005-2008	$300,000	Co-Pi ARO 46961-LS. Principle PI: Prof. Margaret Livingstone

Teaching Assistanships

2001	Teaching Fellow	CN530 – Neural and Computational Models of Vision, Boston University, post-graduate course
2003	Guest Lecturer	CN810 –Topics in CNS: Vision in Man, Monkey, and Machine, Boston University, post-graduate course
2004	Tutor	Human Nervous System and Behavior, Harvard Medical School, post-graduate course
2004-2006	Teaching Fellow	Neurophysiology of Visual Perception, Harvard Medical School, undergraduate course
2005	Guest Lecturer	CN730 – Models of Visual Perception, Boston University, post-graduate course
2006	Guest Lecturer	PS222 – Perception and Behavior, Boston University, undergraduate course
2006	Substitute Tutor	Human Nervous System and Behavior, Harvard Medical School, post-graduate course

Membership

Association for Psychological Science, Cognitive Science Society, International Neural Networks Society, Vision Sciences Society.

Invited Talks

2002-2005	Harvard Vision Group (3 times)
2005	Boston University, Department of Cognitive and Neural Systems
2006	The College of the Holy Cross, Department of Psychology
2007	Harvard Medical School Friday Seminar Series
2007	Boston University, Tuesday Evening Lecture Series, College of Fine Arts
2007	Visual Attention Lab Seminar Series, Brigham and Women’s Hospital
2008	University of Massachusetts, Boston, Department of Psychology
2008	University of New South Wales, Sydney, Australia
2008	Plymouth University, Plymouth, UK

Service

2007-2009	Organization of the Visual Attention Lab Continuing Education Seminar Series
2007, 2009	Organization of high school visits
2007-	Maintenance of the Visual Attention Lab computer systems

2009- Online editor for ViperLib http://viperlibnew.york.ac.uk/ (A free web resource for lecturers of visual perception)

Ad hoc reviewer for: Cambridge University Press, Brain Research, Cognitive Science Society, Encyclopedia for Consciousness (Elsevier), Journal of Neurophysiology, Journal of Neuroscience, Journal of the Optical Society of America, Information Fusion, Neural Networks, Neuron, Perception, Perception and Psychophysics, Spatial Vision, Vision Research, Wellcome Trust (UK).

Students Mentored

Ian Cinnamon (2009, high school student), Michael Cohen (2008-2009, postgraduate research assistant), Dwight Curtis (2006, high school student), Ayman Jarbaren (2009, high school student), Hersh Sagreiya (2006-2007, undergraduate honors student), Cheng-Cheng Zheng (2006, postgraduate student).

Personal Details

I hold both Australian and British passports, was born in Hong Kong (1/31/1976) and am resident in the USA.

Journal Articles

These can be downloaded from: http://search.bwh.harvard.edu/new/staff_files/howe_pubs/howe.html

1) Howe PD (2001). A comment on the Anderson (1997), the Todorovic (1997), and the Ross and Pessoa (2000) explanations of White's effect. Perception, 30(8), 1023-1026. Commentary with original data.

2) Howe PD & Watanabe T (2003). Measuring the depth induced by an opposite-luminance (but not anti-correlated) stereogram. Perception, 32(4), 415-21.

3) Grossberg S & Howe PD (2003, authorship alphabetical, equal contributions). A laminar cortical model of stereopsis and three-dimensional surface perception. Vision Research, 43, 801-829.

4) Howe PD (2005). White's effect: removing the junctions but preserving the strength of the illusion. Perception, 34(5), 557-564.

5) Howe PD (2006). Testing the coplanar ratio hypothesis of lightness perception. Perception, 35(3), 291-301.

6) Howe PD & Livingstone MS (2006). End-stopping and the stereo aperture problem in macaque V1. Cerebral Cortex, 16(9), 1332-1337.

7) Howe PD, Thompson PG, Anstis SM, Sagreiya H, Livingstone MS. (2006). Explaining the Footsteps, Bellydancer, Wenceslas and Kickback Illusions. Journal of Vision, 6, 12(5), 1396-1405.

8) Howe PD & Livingstone MS. (2007) The Use of the Cancellation Technique to Quantify the Hermann Grid Illusion. PLoS ONE 2(2): e265

9) Howe PD, Sagreiya H, Curtis DL, Zheng CC, Livingstone MS. (2008) The double-anchoring theory of lightness perception: A comment on Bressan (2006). Psychological Review, 114(4), 1105-1110. Commentary with original data.

10) Howe PD, Horowitz TS, Wolfe JM (2008). Transient signals per se do not disrupt the flash-lag effect. Behavioral and Brain Sciences, 31(2), 206. Commentary with original data.

11) Hubel, DH, Howe PD, Duffy, AM, Hernandez, A (2009). Scotopic foveal afterimages. Perception, 38(2), 313-316.

12) Howe PD, Livingstone MS, Morocz I, Horowitz TS. (2009). An fMRI investigation into multiple object tracking. Journal of Vision, 9(4), 1-11.

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13) Howe PD, Cohen MA, Pinto Y, Horowitz TS. (submitted) Eight objects can be tracked in parallel.

14) Howe PD, Livingstone MS, Morocz I, Horowitz TS. (submitted) Undirected graphs for neuroimaging: A principled model-free method for determining the causal relationships between brain areas.

15) Howe PD, Cohen MA, Pinto Y, Horowitz TS. (submitted) Distinguishing between parallel and serial accounts of multiple object tracking.

16) Howe PD, Pinto Y, Horowitz TS. (submitted) The coordinate systems used in visual tracking.

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17) Howe PD & Horowitz TS. (in preparation) Is identity tracking a parallel process?

18) Cohen MA, Pinto Y, Howe PD, Horowitz TS. (in preparation) Tracking identities affects location tracking.

19) Pinto Y, Cohen MA, Howe PD, Horowitz TS. (in preparation) Complex familiar objects can be tracked better than unfamiliar objects.

Theses

PhD thesis: *Cortical mechanisms of depth and lightness perception: neural models and psychophysical experiments*.

Master's thesis: *An investigation into the range of validity of the recollision model of intense field upconversion*.

Review Chapters

1) Howe PD, Evans KK, Pedersini R, Horowitz TS, Wolfe JM., Cohen M (2009). Attention: Selective Attention and Consciousness. Encyclopedia for Consciousness. Elsevier, UK.

2) Howe PD (2009). Attention, Awareness and Neglect. Encyclopedia for Consciousness. Elsevier, UK.

3) Evans KK, Horowitz TS, Howe PD, Pedersini R, Kuzmova Y, Reijnen E, Pinto Y, Wolfe JM. (submitted). Visual Attention. In Nadel L (Ed) Wiley Interdisciplinary Reviews: Cognitive Science John Wiley & Sons Ltd.

Conference Presentations

1) Howe PD & Grossberg S (2002). A laminar cortical model of monocular and binocular interactions in depth perception. Journal of Vision, 2(7), 324.

2) Howe PD & Grossberg S (2002). Laminar cortical architecture in depth perception. 6th International Conference on Cognitive and Neural Systems, 6.

3) Howe PD & Livingstone MS (2005). Binocular vision and the correspondence problem. Journal of Vision, 5(8), 800.

4) Livingstone MS & Howe PD (2005). White's effect: removing the junctions but preserving the strength of the illusion. Journal of Vision, 5(8), 563.

5) Howe PD & Livingstone, M.S. (2005). Binocular vision and the stereo correspondence problem. Ninth International Conference on Cognitive and Neural Systems.

6) Howe, PD (2005). Stereoscopic depth discrimination in the visual cortex: V1 partially solves the single object correspondence problem. 48th Annual Meeting of Helen Hay Whitney Fellowship Society.

7) Howe, PD & Livingstone, M.S. (2006). A simple context-dependent and luminance driven model of lightness perception. Journal of Vision, 6(6), 704.

8) Howe, PD & Livingstone, M.S. (2006). A simple luminance- and contrast- driven model of lightness perception. Tenth International Conference on Cognitive and Neural Systems.

9) Sagreiya, H, Howe, PD & Livingstone, M.S. (2006). The footsteps illusion is caused by motion capture. Tenth International Conference on Cognitive and Neural Systems.

10) Howe PD, Thompson PG, Anstis SM, Sagreiya H, Livingstone MS. (2007). Explaining the Footsteps, Bellydancer, Wenceslas and Kickback Illusions. Journal of Vision, 7(9), 982.

11) Cohen M, Howe PD, Horowitz TS, Wolfe JM(2008). Support for a postdictive account of the flash-lag effect. Journal of Vision, 8(6), 600.

12) Howe PD, Livingstone MS, Istvan M, Horowitz TS, Wolfe JM(2008). A neurophysiological model of multiple object tracking derived from fMRI. Journal of Vision, 18(6), 220.

13) Howe PD, Cohen M, Yair Pinto, Horowitz TS, (2009). Distinguishing between parallel and serial accounts of multiple object tracking. Journal of Vision, 9(8), 239.

14) Horowitz TS, Cohen M, Howe PD (2009). Do multiple object tracking and letter identification use the same visual attention resource? Journal of Vision, 9(8), 247.

References

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Teaching Statement

I love to teach and have always sought opportunities to teach beyond what was expected of me. For example, during the second year of my first postdoc, I volunteered to teach a course at the University of Massachusetts, Boston, even though, due to visa regulations, I could not accept any payment.

Lecturing Philosophy

The most important part of teaching is being enthusiastic. In addition, I have found three techniques to be especially effective. First, I always make available copies of my PowerPoint slides before the start of each lecture. This ensures that the students' lecture notes will be accurate and gives the students time to pay attention to what I am saying, instead of merely making notes. Second, I repeatedly quiz the students during the lecture. Every 25 minutes or so, I have the students work through, in writing, a simple question directly related to the material just covered in the lecture. Having given them 3-4 minutes to write down their answer, I then write out the answer on the whiteboard and, by observing the reactions of the students, I can see if they have understood the material. This gives me the chance to clear up any confusions before they create further problems. Although questioning the students does take up valuable lecture time, in the long run it makes for faster progress. Third, I ensure that the students are quizzed on each major concept at least three times: once during the lecture in which the concept is first presented (as described above), once in a homework assignment and once in an in-class examination.

Lab Philosophy

I also enjoy teaching labs and have taught a statistics lab (SPSS) as part of my Research Methods course at the University of Massachusetts (Boston). Typically, I design my labs to have three sections. First, I give my students a set of instructions (usually containing screen shots) of how to do a particular task (e.g. how to perform an ANOVA on a particular data set). Second, I perform the task in front of them, precisely as laid out in the instructions, so that they can see how they should do it. Third, using the instructions they then perform the same task on their own. In this way my students make rapid progress and I ensure that they have accurate notes so that they can perform the task on their own as needed.

Courses That I Can Teach

I have designed and taught courses on Research Methods and Cognitive and Neural Modeling. I can teach courses on Mathematical Modeling, Statistics, Attention, Cognitive Science, and Neuroscience. Of course, I would also be happy to teach Introduction to Psychology or other courses as required.

Mentoring

I have mentored 6 students, 4 of whom obtained an authorship on at least one journal article. The other 2 were high school students that I supervised as part of the RSI program run by MIT. My research area is well suited for student collaborations. The students only have to acquire a very rudimentary knowledge of the MATLAB® programming language before they can fully participate in my research. Once they have assisted in running an experiment, I find that they can often devise interesting extensions. For example, the work in my first *Journal of Vision* articles was initiated by Hersh Sagreiya and formed the basis of his honors thesis at Harvard University.

Class Evaluation

I have taught two classes, one at the University of Massachusetts and the other at Boston University. Both were well received and in each case I was asked back to teach the class the following year. Here is the evaluation for the more recent one, CN520: Principles and Methods of Cognitive and Neural Modeling 2. 2008, Boston University.

The lecture notes, syllabus and additional information are available on the course website:
http://www.bucn520.com/

Email address / user name: CN520 (all in uppercase)
Password: student (all in lowercase)

Copies of the original student comments and evaluations are available from the departmental secretary Robin Amos, ramos@cns.bu.edu. All evaluations were anonymous and on a scale of 1 (poor) - 5 (excellent) unless otherwise stated.

Course Evaluation

1. Relevance of assigned readings	4.8
2. Difficulty of course [(1) easy to (5) difficult]	3.7
3. Workload in course [(1) light to (5) heavy]	3.5
4. Criterion 4 not applicable to this course	
5. Criterion 5 not applicable to this course	
6. Usefulness of assignments and papers	5.0
7. Overall course rating	4.8

Faculty Evaluation

8. Effectiveness in explaining concepts	4.8
9. Ability to stimulate interest in subject	4.2
10. Encouragement of class participation	4.7
11. Fairness in grading	4.7
12. Promptness in returning assignments	4.7
13. Quality of feedback to students	4.7
14. Availability outside of class	4.2
15. Overall rating of instructor	4.7

Research Statement

In my earlier research, I studied the early stages of human and macaque visual processing: lightness perception, depth perception, motion perception, and the perception of time (please see the attached research summary for more details). Recently, I have become interested in more cognitive issues, in particular attention.

Attention plays a central role in cognition. Because we have limited capacity, to avoid being overwhelmed, we use attentional processes to select some stimuli at the expense of others. Disorders of attention are characteristic of a wide variety of clinical disorders and diseases including attention deficit disorder (Mason et al., 2003), autism (Burack, 1994; O'Riordan et al., 2001), schizophrenia (Mathalon et al., 2004), Parkinson’s Disease (Berry et al., 1999; Briand et al., 2001; Horowitz et al., in press), borderline personality disorder (Posner et al., 2002) and obsessive-compulsive disorder (Clayton et al., 1999; Cohen et al., 2003). Changes in attention also characterize the normal aging process (Bherer et al., 2005; Greenwood & Parasuraman, 2004; Lee et al., 2003), response to a variety of drugs (Carter et al., 2005; Marrocco & Davidson, 1998) and the response to sleep deprivation in naïve subjects (Horowitz et al., 2003; McCarthy & Waters, 1997; Sanders, 1982) and medical personnel (Lockley et al., 2004). An effort to understand these changes in the normal workings of attention requires a comprehensive understanding of that normal state.

I am particularly interested in the selection mechanisms that allow an observer to chose which object(s) to attend to. Currently, I use the multiple object tracking paradigm because this proves to be a particularly productive way to study the *dynamic* aspects of attentional selection. In this paradigm, the observer is shown a number of identical objects, a subset of which are identified as the targets to be tracked. The objects then move around the display in a random fashion. Because all the objects are identical, the only way this task can be performed is by attending to the targets. The first interesting aspect of MOT is that observers can do it at all. You can use your attention to somehow “hold on” to several items as they wander about. The second striking feature is that you can only track 3-4 items at a time. The task is severely capacity limited. My particular interest is in understanding the mental processes underlying tracking. For example, some of my studies have investigated whether we track objects by attending to each one in turn or by attending to them all simultaneously. Another study investigates the coordinate system used to track objects. Ultimately, I wish to construct a computational model that explains behavioral data on tracking in terms of the underlying neural structure. For my PhD, I constructed a similar model for depth perception. Because objects need to be tracked before they can be attended, understanding tracking is a prerequisite to a complete understanding of attention.

Another reason to study this laboratory curiosity is because it is the distillation of a task we perform in the real world. For example, when driving we need to keep track of moving objects (cars, pedestrians etc) and some jobs require the tracking of moving objects (e.g. air traffic controllers). For more details, please see my research summary.

Research Summary

To download my papers: http://search.bwh.harvard.edu/new/staff_files/howe_pubs/howe.html

1. Depth Perception: Computational Investigations

Computational models play a crucial role in vision research. They summarize what we know and suggest which experiments need to be performed. I constructed a model of depth and lightness perception that simulated, and thereby explained, twenty visual phenomena in terms of known neuroanatomy and neurophysiology (Grossberg and Howe, 2003; Figure 1). This formed the basis of my supervisor's subsequent work in visual perception and was the inspiration behind several of my subsequent psychophysical and neurophysiological investigations.

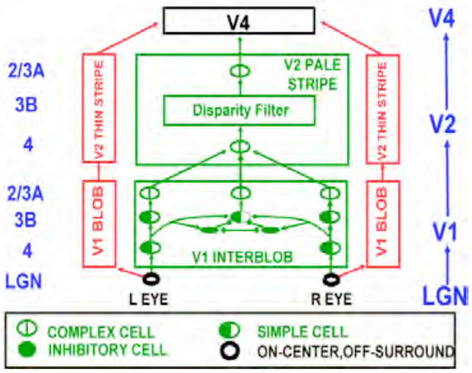


Figure 1. The model of Grossberg and Howe (2003). It was able to correctly simulate 20 visual phenomena based on known brain neurophysiology.

2. Depth Perception: Behavioral Investigations

Models need to be tested to reveal their flaws. I performed a psychophysical investigation to test a prediction of the above model. I showed that the model's prediction that under certain conditions opposite-luminance stereograms should produce stereo-depth was correct (Howe and Wanatabe, 2003; Figure 2). This finding proved to be important in my subsequent neurophysiological study into depth perception.

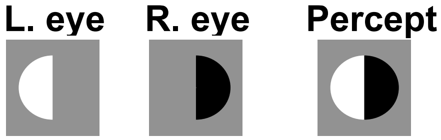


Figure 2. A stereogram used by Howe and Watanabe (2003) to test a prediction of the Grossberg and Howe (2003) model.

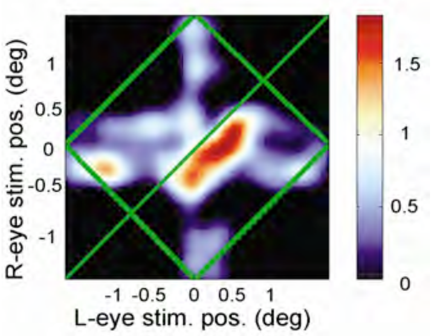


Figure 3. A figure from Howe and Livingtone (2006) that shows the response of a cell in the macaque primary visual cortex as a function of the position of the stimulus in the left -and right-eye receptive fields. The elongation of the area of high activity along the green diagonal indicates that this cell was sensitive to stereo disparity.

3. Depth Perception: Neurophysiology

I have recorded extracellularly from neurons in the primary visual cortex of macaque monkeys. Such cells have very small receptive fields, so sometimes generate spurious depth signals, an issue knows as the stereo aperture problem. I investigated how subsequent stages of the visual system could ignore these spurious depth signals and so create a valid depth percept (Howe and Livingstone, 2006; Figure 3). Our finding proved to be compatible with previous work on the motion aperture problem suggesting that similar principles might be generally applicable throughout the visual system, wherever an "aperture problem" occurs.

4. Lightness Perception: Behavioral Investigations

Lightness perception is a fundamental aspect of vision. Previously, it was thought that either T-junctions or coplanarity were the major determinants of lightness. I showed that their importance had been exaggerated (Howe, 2001; Howe 2005; Howe, 2006; Figures 4 & 5). When subsequently investigating the double anchoring theory of lightness perception, I proved that, contrary to this theory, perceptual grouping does not always determine an object's lightness (Howe et al., 2007). It seems that lightness is determined by a number of different, and sometimes conflicting, principles, so it cannot be explained by a single, unified grand theory as has been the implicit assumption of many previous investigations. If true, this would require a paradigm shift in our thinking of how lightness research should be conducted.

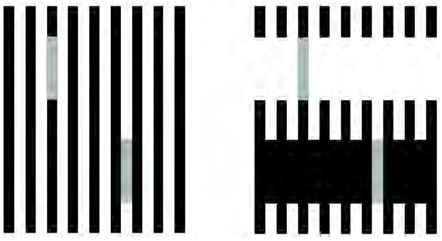


Figure 4. Stimuli used by Howe (2001) to demonstrate the inadequacy of various T-junction accounts of lightness perception.

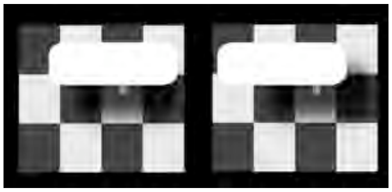


Figure 5. Stimuli used by Howe (2006) to test the coplanar ratio hypothesis of lightness perception.

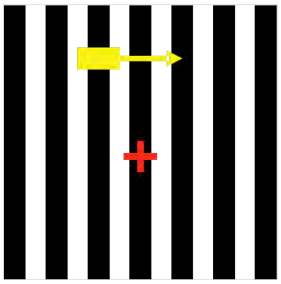


Figure 6. The Footsteps Illusion stimulus used by Howe et al. (2006). Although the yellow bar moves at a constant rate, observers may perceive it to repeatedly stop moving.

5. Motion Perception: Behavioral Investigations

The Footsteps Illusion (Figure 6) demonstrates the dramatic effect a background can have on the perceived speed of an object. This can be important in situations where a person needs to accurately estimate the speed on an object (e.g. when driving). In this illusion, a yellow bar moves over a black and white background. Although the yellow bar moves at a constant rate, most subjects perceive it to come to a complete standstill when it reaches a white stripe. In the past, this illusion has been explained in terms of the variations in contrast at the leading and trailing edges of the yellow bar. I demonstrated that this explanation was incomplete and the illusion is mainly caused by a competition between the vertical and horizontal edges of the moving bar (Howe et al., 2006).

6. The Herman Grid Illusion

In the Hermann grid illusion (Figure 7), illusory dark gray smudges are seen at the intersections of the grid (when viewed under the appropriate conditions). The illusion has been extensively studied because it thought to directly reflect the functioning of the early visual system. Often, its strength is measured by placing a disk at an intersection and measuring the luminance of the disk required to nullify the corresponding illusory dark gray smudge. I showed that this technique is invalid because this manipulation creates an entirely different illusion, which I called the blanking illusion. The latter can be explained by Weber's law and collinear facilitation (Howe and Livingstone, 2007).

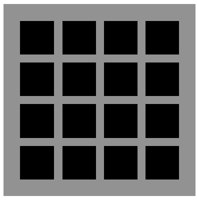
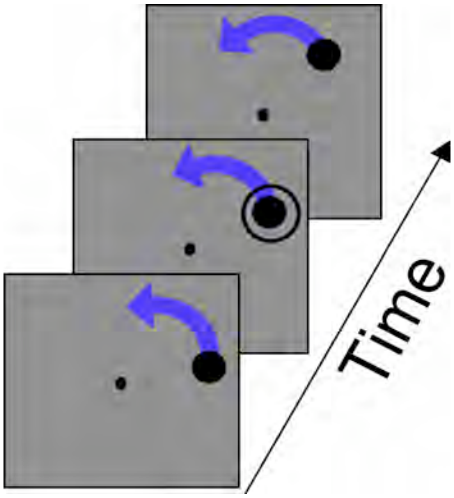


Figure 7. The Hermann grid illusion. Illusory dark smudges are seen at the gray intersections



7. The Flash-Lag Effect

A stationary ring flashed over a moving dot will appear behind the moving dot, an illusion known as the flash-lag effect. This illusion is of interest because it shows how the brain compensates for the delays inherent in neural processing. By investigating how the visual system handles transient signals, I demonstrated that the commonly accepted explanation for this illusion requires a substantial modification (Howe et al., 2008).

Figure 7. The flash-lag effect. If a stationary ring is flashed over a moving dot it will appear to lag the moving dot. This illusion is thought to demonstrate how humans compensate for the delays inherent in neural processing.

8. fMRI Investigation Into Sustained Attention

Multiple Object Tracking (MOT) is of interest because it allows us to study sustained attention. Previous fMRI studies identified the brain areas involved in MOT by comparing the brain activity when the subject tracked multiple objects to the brain activity when the subject passively viewed the same stimulus. However, when one tracks objects one must also attend to them, but when passively viewing a scene one neither attends nor tracks the objects. Consequently, these previous studies could not determine whether the reported brain areas were responsible for attending to the objects or for tracking the objects. By using a baseline condition that involved attention, I was able to avoid this confound and show that the areas responsible for tracking were fewer than previously thought (Howe et al., 2009). This finding allowed me to create a tentative neural model of MOT that I will use as the basis for future fMRI investigation into sustained attention.

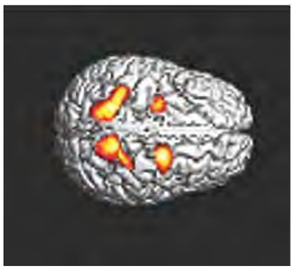
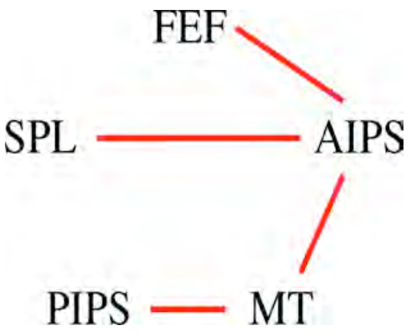


Figure 8. An fMRI scan revealing some of the brain areas active when an observer tracks multiple objects.



9. Development Of Novel fMRI Data Analysis Techniques

Once one has used fMRI to identify which brain areas are active when an observer performs a given task, the next step is determine how these brain areas interact when the observer performs the task. I have recently developed a new fMRI data analysis technique that does this and calculates the effective connectivity of a given set of brain areas (Howe et al. submitted). This technique can be used in a wide variety of fMRI investigations regardless of their exact subject matter. In the future I intend to make the underlying computer code publicly available.

Figure 9. The connectivity structure recovered from the fMRI data. The brain areas are frontal eye fields (FEF), anterior intraparietal sulcus (AIPS), superior parietal lobule (SPL), posterior intraparietal sulcus (PIPS) and medial temporal area (MT).

10. Scotopic Foveal Afterimages

If, after being in the dark for many minutes, one views an extended surface in a dimly lit room, one fails to see any hint of the dark spot at the center of gaze that might be expected from the absence of rods in the fovea. This suggests that some sort of "filling-in" mechanism must operate by which the brightness of the surround propagates into the center. We found that if after viewing the surface for some seconds it is suddenly completely darkened one sees a relatively bright spot, about two degrees in size, at the point of fixation (Hubel, Howe, Duffy and Hernandez, 2009). The spot gradually fades over many seconds. If the surface is now restored to its original luminance a dark spot of similar size appears where one fixates, that again lasts for several seconds. It is hoped that by studying this phenomena we will gain insight into "filling-in", a phenomenon that appears to be ubiquitous in visual perception.

Figure 10. Rods are photoreceptors used by the visual system to see in low illumination levels. In the fovea there are very few rods, so one would expect that, in low illumination levels, there would be a blind spot at the point of fixation. Surprisingly, this blind spot is often "filled-in".

11. Multiple Object Tracking: Serial or Parallel?

In a world without moving objects, attention could simply be directed to locations. However, because objects do move, they first have to be tracked before they can be attended. Tracking is thus a fundamental attentional operation and, to some extent, the limits of object-based attention are determined by the limits of tracking. Humans can track multiple moving objects. Is this accomplished by attending to each object in turn (the serial model) or do we attend to all the objects simultaneously (the parallel model). In our displays, the objects moved either sequentially or simultaneously. The serial model predicts that tracking performance should be greatest in the first condition. Conversely, a parallel model predicts equal performance in the two conditions. Our data was consistent only with a parallel model (Howe et al., submitted, 2 papers).

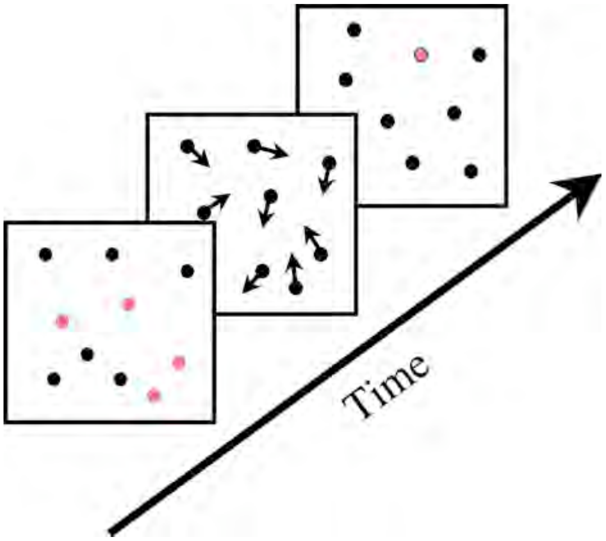


Figure 11. A typical multiple object tracking experiment. At the start of the trial 4 of the 10 disks turn red to indicate that they are targets to be tracked. The disks then all become the same color and move about the display for several seconds. At end of the trial the disks freeze and the observer indicates which were the targets.

11. The Coordinate Systems Used In Object Tracking

Here we ask which coordinate system is used to track objects, retinal (retinotopic), scene-centered (allocentric), or both. While maintaining gaze on a fixation cross, observers tracked three of six disks, which were confined to move within an imaginary square. Relative to the imaginary square, the disks all moved at the same speed. By moving either the imaginary square (and thus the disks contained within), the fixation cross, or both, we could increase the disk speed in one coordinate system while leaving it unchanged in the other. Increasing the disks' speeds in either coordinate system reduced tracking ability by an equal amount. These data support the hypothesis that humans track objects *simultaneously* in both retinotopic and allocentric coordinates (Howe et al., submitted). This finding imposes a strong constraint on models of multiple object tracking.

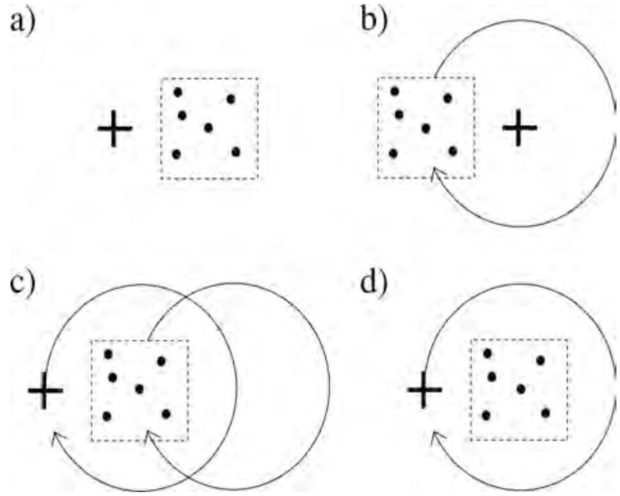


Figure 12. The four stimulus conditions used in the experiment. In all cases the disks were confined to move within an imaginary square. Either the fixation cross, the imaginary square or both would move, thereby causing each disk to have a different speed in the retinotopic and allocentric coordinate systems.

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