Challenges for Vision in Dynamic Environments

Mary Hayhoe
University of Texas at Austin

Jelena Jovancevic
University of Rochester

Brian Sullivan
University of Texas at Austin
Constraints on Vision:

*Acuity is limited.*
High acuity only in central retina.

*Attention is limited.*
Not all information in the image can be processed.

*Visual Working Memory is limited.*
Only a limited amount of information can be retained across gaze positions.

**Consequence:**
Information in scenes must be acquired sequentially via deployment of gaze
What controls the sequential acquisition of information from scenes?
One solution: Capture by pre-attentive stimulus features.

Image properties eg contrast, edges, chromatic saliency can account for some fixations when viewing images of scenes (eg Itti & Koch, 2001; Parkhurst & Neibur, 2003). (Also attentional capture by sudden onsets etc Theeuwes etal 2001.)
Limitations of stimulus-based mechanisms

Will this work in natural vision?

Natural environments are time-varying – need to account for sequences and timing of fixations.

No guarantee that salient stimuli will coincide with behaviorally relevant stimuli. Extensive bottom up analysis is computationally expensive.
Challenge for Gaze Deployment in Natural Environments

Real world is (1) dynamic and unpredictable (2) visual input changes with the observer’s actions - thus a salient stimulus in a 2D display may not be salient in the real world
Acquisition of visual information is goal driven

Viewing pictures of scenes is different from acting within real scenes.

Fixations tightly linked to actions: Land (2004); Hayhoe & Ballard (2005) etc
Eye movements are learned.

What objects are need for making tea?
What does a teapot look like?
How are steps sequenced?
What signals the end of an action?
Where to look when pouring?

etc
Neural Substrate for Learning Gaze Patterns

Dopaminergic neurons in basal ganglia signal expected reward. Neural basis for reinforcement learning models of behavior. (Schultz, 2000)

Neurons at all levels of saccadic eye movement circuitry are sensitive to reward. (eg Hikosaka et al, 2000; 2007; Platt & Glimcher, 1999; Sugrue et al, 2004; Stuphorn et al, 2000 etc)

This provides the neural substrate for learning gaze patterns in natural behavior, and for modelling these processes using Reinforcement Learning. (eg Sprague, Ballard, Robinson, 2007)

Note: assume information from a fixation provides secondary reward.
What evidence is there that gaze patterns can be understood in terms of reinforcement learning?
Is bottom up capture effective in natural environments?

Looming stimuli seem like good candidates for bottom-up attentional capture (Regan & Gray, 200; Franceroni & Simons, 2003).
Human Gaze Distribution when Walking

• **Experimental Question:**
  How sensitive are subjects to unexpected salient events?

Subjects walked along a footpath in a virtual environment while avoiding pedestrians.

Do subjects detect unexpected potential collisions?
Virtual Walking Environment

Virtual Research V8 Head Mounted Display with 3rd Tech HiBall Wide Area motion tracker

V8 optics with ASL501 Video Based Eye Tracker (Left) and ASL 210 Limbus Tracker (Right)
Virtual Environment

Bird’s Eye view of the virtual walking environment.
Experimental Protocol

• **1 - Normal Walking:** “Avoid the pedestrians while walking at a normal pace and staying on the sidewalk.”

• **2 - Added Task:** Identical to condition 1. Additional instruction:” Follow the yellow pedestrian.”
What Happens to Gaze in Response to an Unexpected Salient Event?

• **The Unexpected Event**: Pedestrians veered onto a collision course for 1 second (10% frequency). Change occurs during a saccade.

Does a potential collision evoke a fixation?
Fixation on Collider
No Fixation During Collider Period
More fixations on colliders in normal walking.
Why are colliders fixated?

Small increase in probability of fixating the collider could be caused

*either* by a weak effect of attentional capture

*or* by active, top-down search of the peripheral visual field.
Probability of Fixation During Collision Period

More fixations on colliders in normal walking.

No effect in Leader condition

Pedestrians’ paths

Colliding pedestrian path

Graph showing probability of fixation with different conditions:
- Normal Walking: Increasing probability of fixation
- Follow Leader: No change in probability of fixation
Why are colliders fixated?

Small increase in probability of fixating the collider could be caused

either by a weak effect of attentional capture
or by active, top-down search of the peripheral visual field.

Failure of collider to attract attention with an added task (following) suggests that detections result from active search.
Detecting a Collider Changes Fixation Strategy

Longer fixation on pedestrians following a detection of a collider
Subjects rely on active search to detect potentially hazardous events like collisions, rather than reacting to bottom-up, looming signals (attentional capture).

To make a top-down system work, Subjects need to learn statistics of environmental events and distribute gaze/attention based on these expectations.
Walking - Real World

- Experimental question:

  Do subjects learn to deploy gaze in response to the statistics of environmental events? I.e. are subjects sensitive to reward probability?
Experimental Setup

A subject wearing the ASL Mobile Eye

System components: Head mounted optics (76g), Color scene camera, Modified DVCR recorder, Eye Vision Software, PC Pentium 4, 2.8GHz processor
Experimental Design

- Occasionally some pedestrians veered on a collision course with the subject (for approx. 1 sec)

- 3 types of pedestrians:

  Trial 1: Rogue pedestrian – always veers
  Safe pedestrian – never veers
  Unpredictable pedestrian - veers 50% of time

  Trial 2: Rogue → Safe
  Safe → Rogue
  Unpredictable - remains same
Fixation on Veering Pedestrian
Effect of Veering Probability

Probability of fixating increased with higher veering probability.

(Probability is computed during period in the field of view, not just collision interval.)
Detecting Veering: proactive or reactive?

- Probability of fixating risky pedestrian similar, whether or not he/she actually veers on that trial.
Almost all of the fixations on the Rogue were made before the collision path onset (92%).

Thus gaze, and attention are anticipatory.
Learning to Adjust Gaze

- Changes in fixation behavior fairly fast, happen over 4-5 encounters (Fixations on Rogue get longer, on Safe shorter)

N=5
Shorter Latencies for Rogue Fixations

- Rogues are fixated earlier after they appear in the field of view. This change is also rapid.
Effect of Behavioral Relevance (Reward)

Fixations on all pedestrians go down when pedestrians STOP instead of COLLIDING. STOPPING and COLLIDING should have comparable salience. Note the Safe pedestrians behave identically in both conditions - only the Rogue changes behavior.
Summary

• Fixation probability increases with probability of veering onto a collision path.
• Fixation probability similar whether or not the pedestrian veers on that encounter.
• Fixations are anticipatory.
• Changes in fixation behavior fairly rapid (fixations on Rogue get longer, and earlier, and on Safe shorter, and later)
Virtual Humanoid has a small library of simple visual behaviors:

- Sidewalk Following
- Picking Up Blocks
- Avoiding Obstacles

Each behavior uses a *limited, task-relevant* selection of visual information from scene.
Controlling the Sequence of fixations

Choose the task that reduces uncertainty of reward the most
Agent must learn a policy for each sub-task, given the state information from gaze.

1. Visual Routine

Policy

Value of Policy

\[ V(s) = \max_{a} Q(s, a) \]
Learning of sidewalk navigation

- Three component tasks:
  - Obstacle avoidance, Litter pickup, Walkway following
Effect of reward weights

- Very different behaviors can be expressed by differentially rewarding individual tasks

<table>
<thead>
<tr>
<th></th>
<th>Target</th>
<th>Obstacle</th>
<th>Walkway</th>
</tr>
</thead>
<tbody>
<tr>
<td>0m</td>
<td>0</td>
<td>0.9</td>
<td>0</td>
</tr>
<tr>
<td>40m</td>
<td>1.6</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td>0.5</td>
<td>3.2</td>
</tr>
</tbody>
</table>

Reward weights estimated from human behavior using Inverse Reinforcement Learning - Rothkopf 2008.
Conclusions

Need reinforcement learning models to account for control of attention and gaze in natural world.

Fixations modulated by behavioral significance (reward, and probability of reward).

Control of gaze, and attention, is proactive, not reactive, and thus depends on prior knowledge.

Anticipatory use of gaze is probably necessary for much visually guided behavior, because of visuo-motor delays.

Subjects behave very similarly despite unconstrained environment and absence of instructions.