The Role of Cognitive Strategy in Human-Computer Interaction

Anthony Hornof

Associate Professor
Computer and Information Science
University of Oregon

Collaborators: David Kieras, David Meyer, Tim Halverson, Yunfeng Zhang

Sponsorship: NSF, ONR

January, 2016

The Premise of This Talk

- The field of human-computer interaction needs better predictive engineering techniques.
- These engineering models should be based on a specification of the user, the task, and the device.
- The specification of the user should be based on how humans process information.
- People use *cognitive strategies*—plans that coordinate the perceptual, motor and memory processes needed to do tasks.

Efficiency inspires delight.

- Aesthetics and usability (as measured by speed and accuracy) both influence a user's feelings about an interface. Usability influences it more. (Thüring & Mahlke, 2007; Tuch et al., 2012)
- User interfaces that reduce the processing required to accomplish tasks are perceived as more aesthetic and appealing. (McDougall & Reppa, 2013)

Core Research Question: What are the cognitive strategies that people use (and do not use) when interacting with computers?

Cognitive psychologists have asserted such strategies for decades:

- Shiffrin & Atkinson (1969) - control processes to modulate information flows between processors.
- Baddeley (1974) - executive processes.
- Lachman et al. (1979) - the programs in the information processor.
- Rosenbaum (1991) - motor programs.

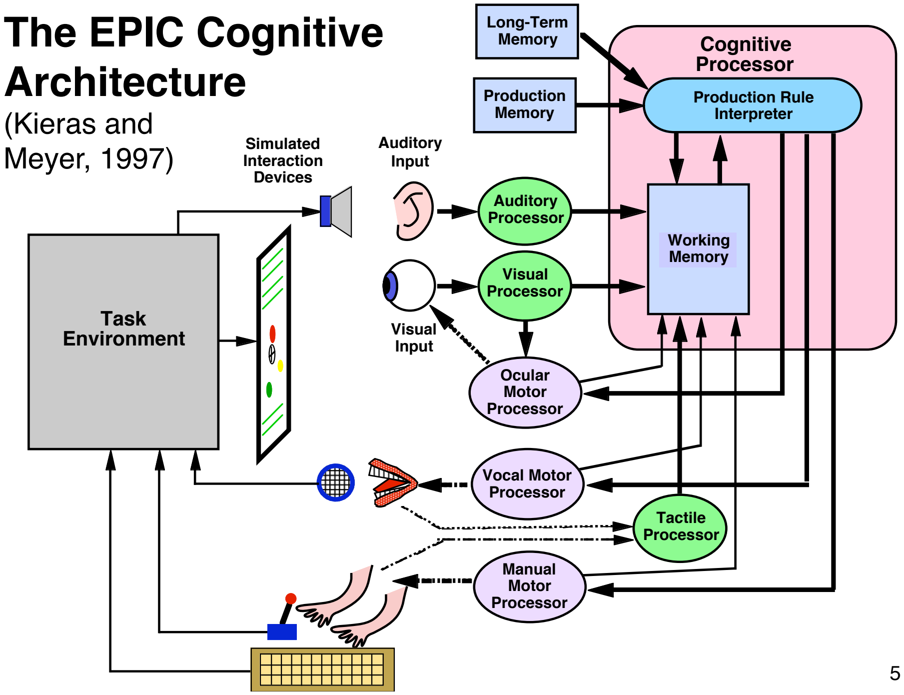
But few researchers have studied them. They are elusive.

Data and techniques that I use to expose the cognitive strategies:

- Cognitive modeling.
- Eye Tracking.

The EPIC Cognitive Architecture

(Kieras and Meyer, 1997)



The EPIC Cognitive Architecture

- EPIC: Executive Process-Interactive Control
  Kieras and Meyer (1997)
- Inspired in part by the Model Human Processor (Card, Moran, and Newell, 1983)
- Captures human perceptual, cognitive, and motor processing into a simulation framework
- Constrains the models that can be built
- Inputs into the architecture:
  - Task environment
  - Visual-perceptual features
  - **Cognitive strategies**
- Outputs from the running model:
  - Execution times
  - Trace of the processing
  - Eye movements

Cognitive strategies are simulated with production rules.
An EPIC production rule to move the eyes. (from Halverson & Hornof, 2011)

```
(Prepare_eyes_to_nearest_object
IF ((Step Prepare Eye)
   (Motor Ocular Modality Free)

   (Tag ?Word Object_Not_Fixated)
   (NOT (Tag ?Word Current Destination))

   (Visual ?Word In_Group ?Group)
   (Tag ?Group Unvisited)

   (Visual ?Word Eccentricity ?ecc)
   (Greater_than ?Ecc 1.0)
   (Least ?ecc))

THEN (
   (Send_to_motor Ocular Prepare Move ?Word)
   (Delete (Step Prepare Eye))
   (Add (Step Move Eye))
   (Add (Tag ?Word Next Destination))))
```

If the ocular modality is free

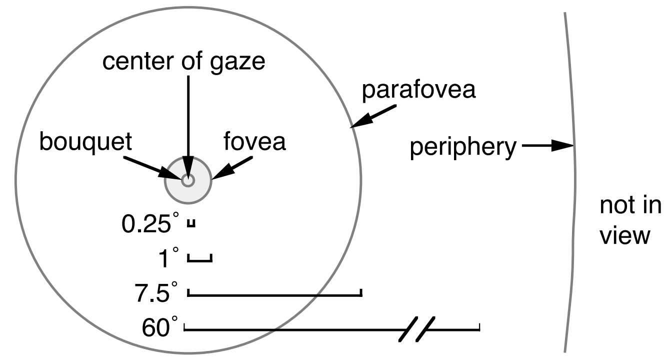
and a word has not been fixated and is not the destination of the current saccade

in a group that had not been visited

that has the least eccentricity and is not too close to the current fixation location

then prepare to move the eyes to that word.

The visual retinal zones in EPIC '97



Visual features (such as text, shape, color) are available as a function of the angular distance between an object and the point of gaze.

EPIC is well-suited to explore cognitive strategies

- EPIC makes an architectural commitment to only enforce serial processing for motor activities.
- Any number of production rules can fire in each 50 ms cycle. Strategies can be *written* to permit one rule to fire at a time (as in our initial model) and also to explore the potential for overlapped strategies (as in our second and third models).

Four Projects Exploring Cognitive Strategies for...

1. Visual search of pull-down menus.
2. Visual search of hierarchical displays.
3. Multimodal multitasking.
4. Individualized strategies for multitasking.

1. Cognitive strategies for visual search of pull-down menus.

Menu search and selection remains a dominant HCI interaction technique and yet the field still lacks a comprehensive predictive model of how people do it. It is not a solved problem.

Visual Search of Pull-Down Menus

Data from Nilsen (1991)

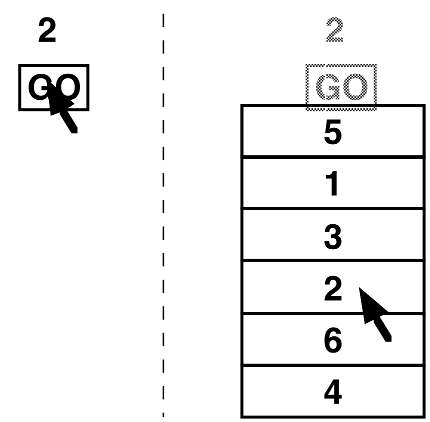
Models from Hornof & Kieras (97 & 99)

Menus:

- 3, 6, or 9 numerical digits.
- Randomly or Numerically ordered menus.
- Blocked by size and ordering.

Procedure:

- Study target digit.
- Click on "GO".
- Menu appears.
- Point to and click on target.



Randomly ordered 6-item menu

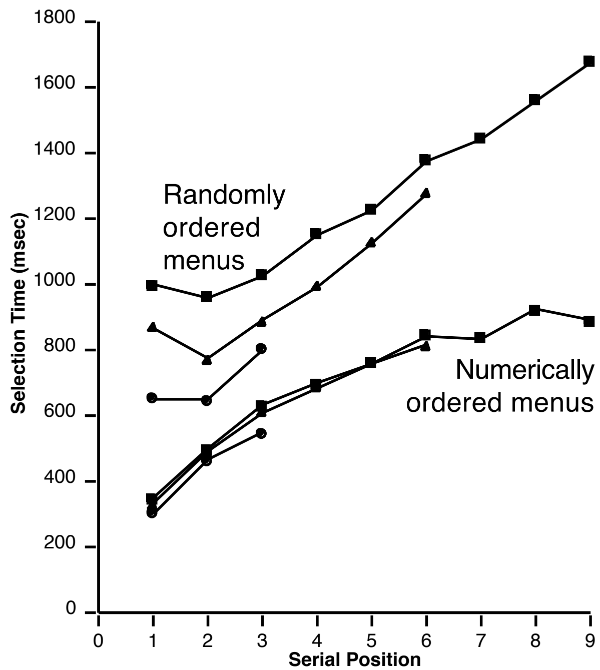
Human data

Main effects:

- Numerically-ordered menus are faster.
- Different slopes.

In Randomly ordered:

- Position 1 effect.
- Menu length effect.

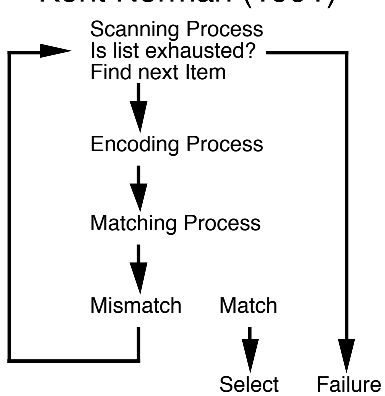


Explain the data by exploring strategies

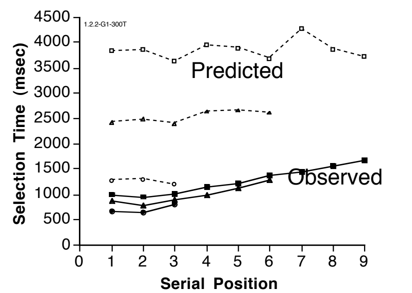
- The goal is to explore strategies while keeping the architecture constant.
- Exploring strategies presents two problems:
  1. Degrees of freedom.
  2. Falsification.
- These are addressed in part by:
  1. Proposing strategies that
     (a) are parsimonious (at least debatably), and
     (b) have been proposed and debated in the literature.
  2. Attempting to falsify some of the competing theories within the context of the model exploration.

Disconfirm strategies for searching randomly-ordered menus.

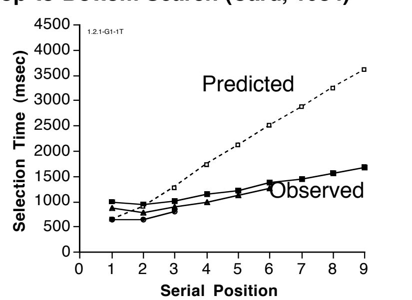
Serial processing strategy proposed by Kent Norman (1991)



Random Search (Lee & MacGregor, 1985)



Top-to-Bottom Search (Card, 1984)



Parallel processing strategies

Look at the precue.

Click the mouse on the GO box to show the menu and move eyes to where one of the top items will appear.

These steps take place in parallel.

Determine the item one foveal diameter below gaze.

Move eyes to that item.

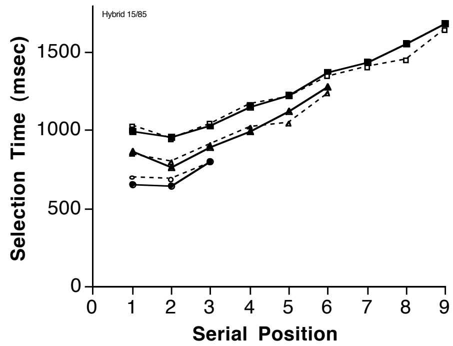
Quit searching when target item appears in working memory.

Move mouse and gaze to item.

Click mouse.

A mixture model of random and systematic, and different numbers of items perceived in parallel, explained the data

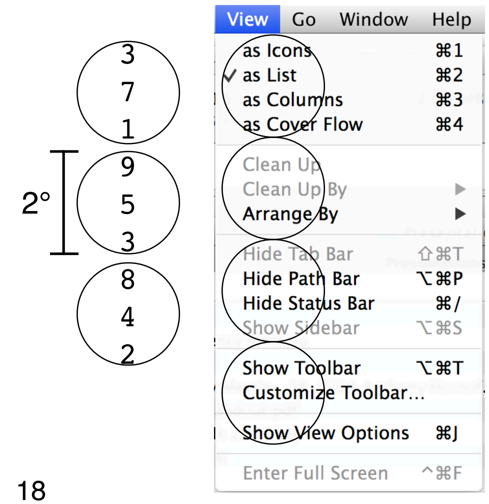
Dual Strategy / Varying Distance
Hybrid Model



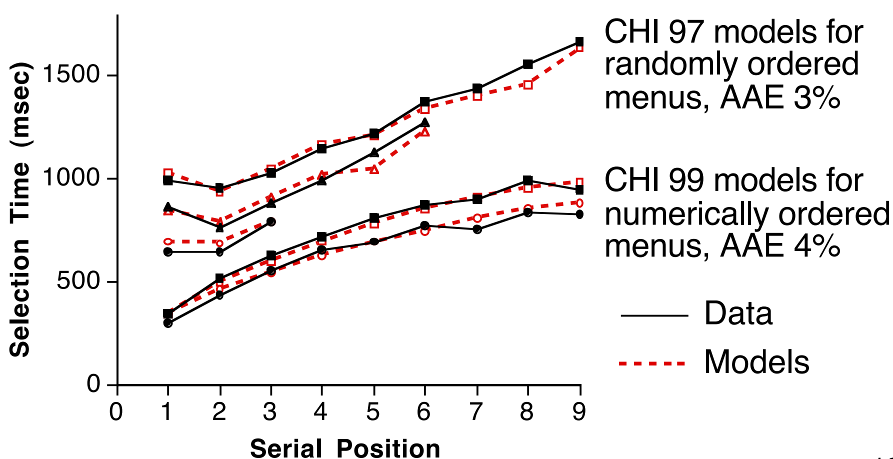
When you generate strategies that use the architecture as effectively as possible, you can predict some interesting behaviors

Maximally-efficient foveal sweeps

Parallelism built into the architecture permits multiple items to be considered in parallel.



Cognitive strategies are identified using reaction time data and the architecture



Eye movement data subsequently validated many aspects of the strategies

- People process multiple items in parallel.
- Scan paths are sometimes top-to-bottom, sometimes random, and sometimes a combination of the two.

  (Aaltonen et al., 1998; Byrne et al., 1999)

Eye tracking and cognitive modeling have a special synergy: The models provide specific theories that the data can confirm or disconfirm.

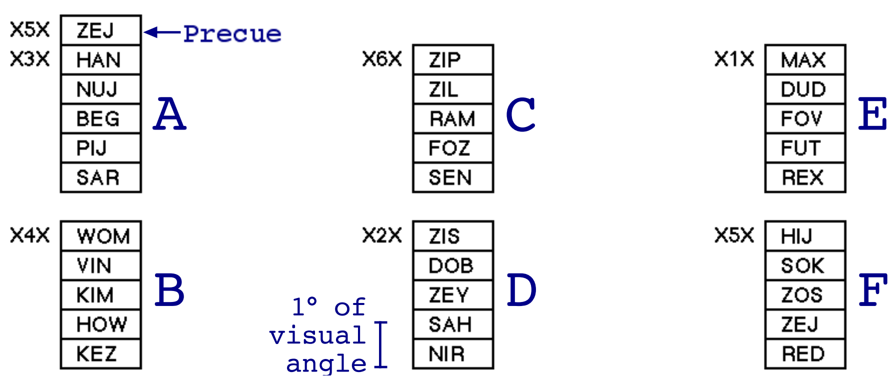
Four Projects Exploring Cognitive Strategies for...

1. Visual search of pull-down menus.
2. Visual search of hierarchical displays.
3. Multimodal multitasking.
4. Individualized strategies for multitasking.

2. Cognitive strategies for the visual search of hierarchical displays

This project demonstrates how people clearly use different strategies for different tasks.

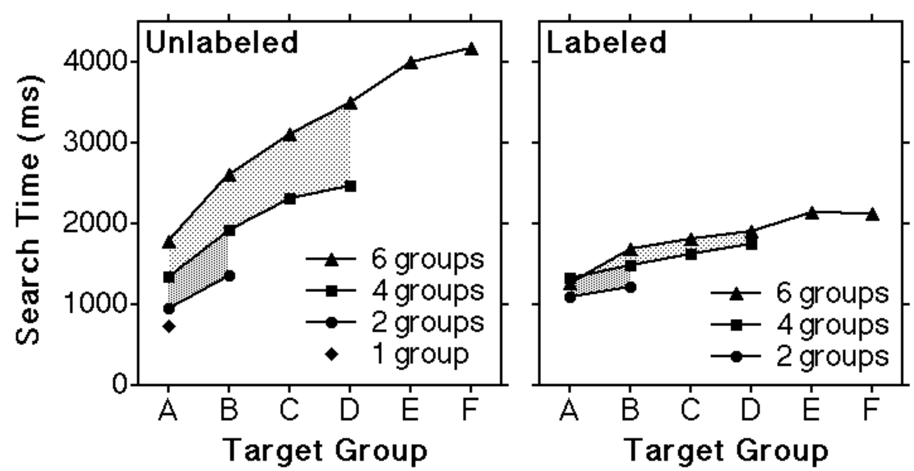
The Experimental Task



Experimental Design

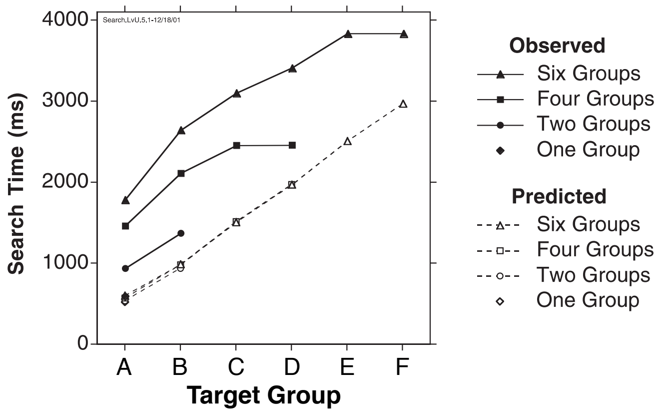
- 2 x 3 design. Layouts were labeled or unlabeled.
  Layouts had 2, 4, or 6 groups. Blocked by layout type.
- Procedure: Study precue, click on precue, find target, click on target.
- 16 participants, motivated to search quickly

Human Data



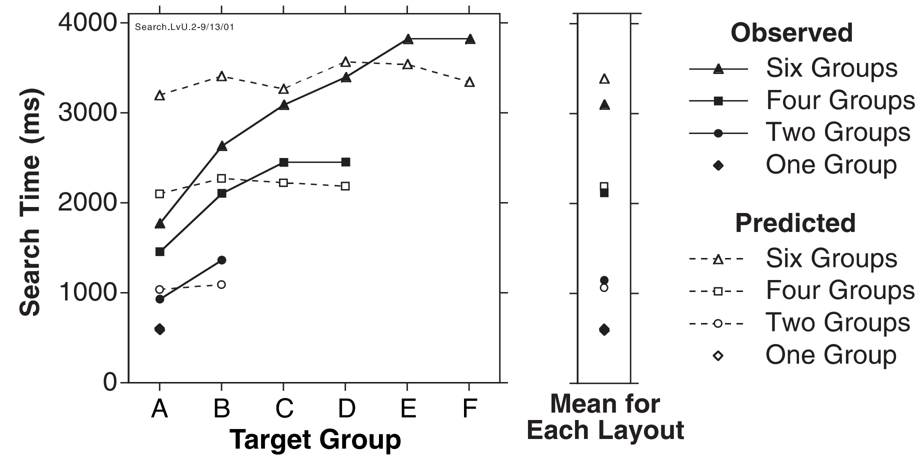
Trends: (a) Smaller layouts are faster. (b) Labeled layouts are faster. (c) Unlabeled layouts have a larger number-of-groups effect.

Unlabeled layouts: Systematic search strategy



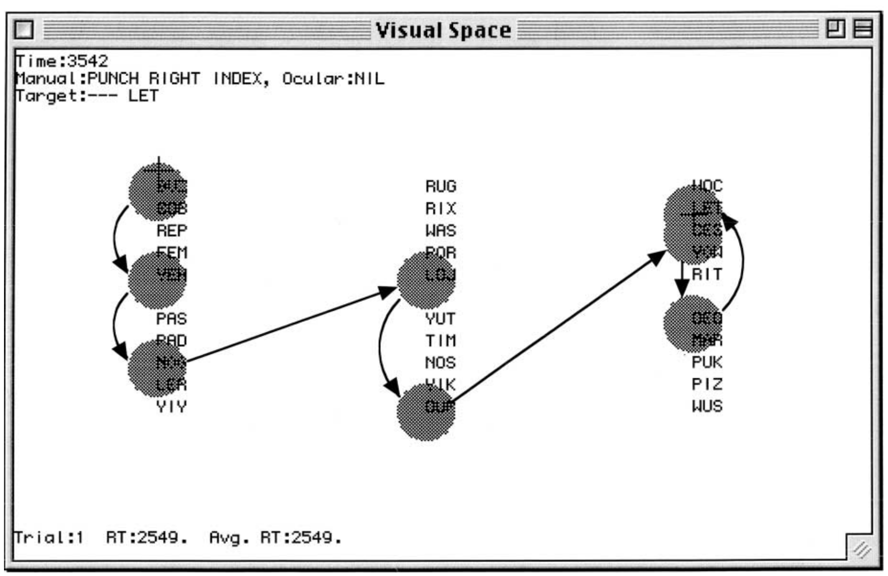
Again, neither a purely systematic nor a purely random search explain the data.

Unlabeled layouts: Random search strategy

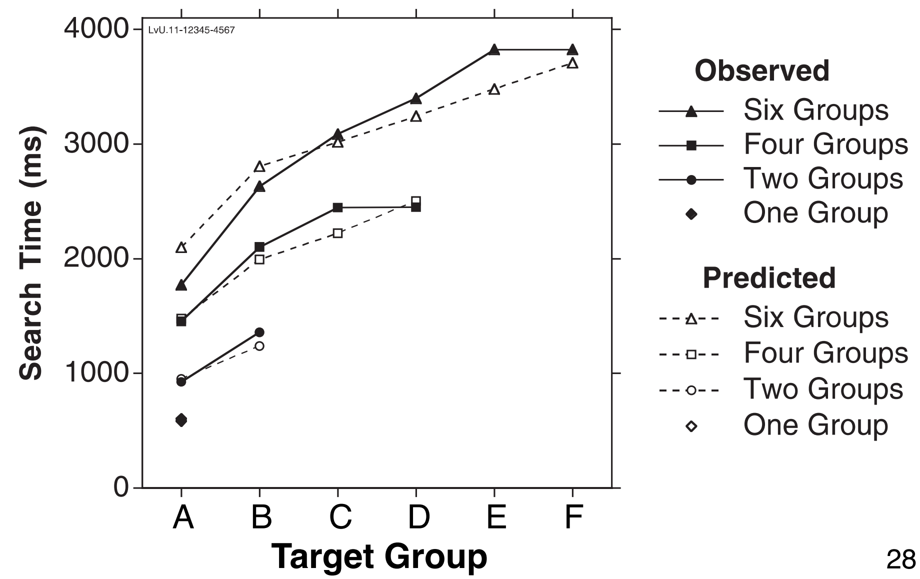


Unlabeled layouts: A "noisy-systematic" search strategy

Effectively combines random and systematic within a single strategy. Attempt to make a maximally-efficient foveal sweep, but it sometimes overestimates how far the eyes can move still foveate everything, sometimes missing.



The "noisy-systematic" search strategy explains the reaction time data for unlabeled layouts

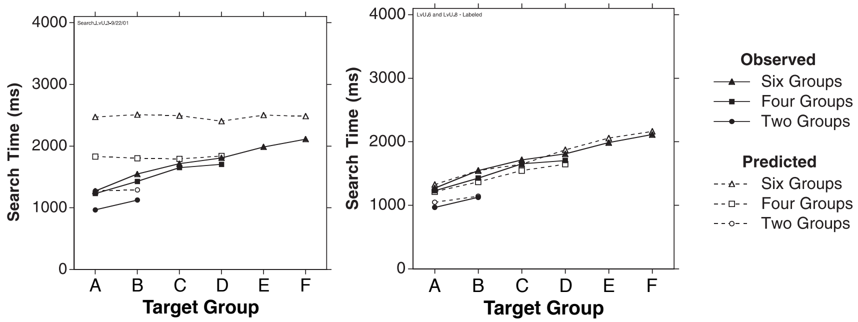


Labeled layouts

Assume that people search the group headings until they find the target group, and then search within the target group.

Random search of the group labels

Mostly systematic search of group labels

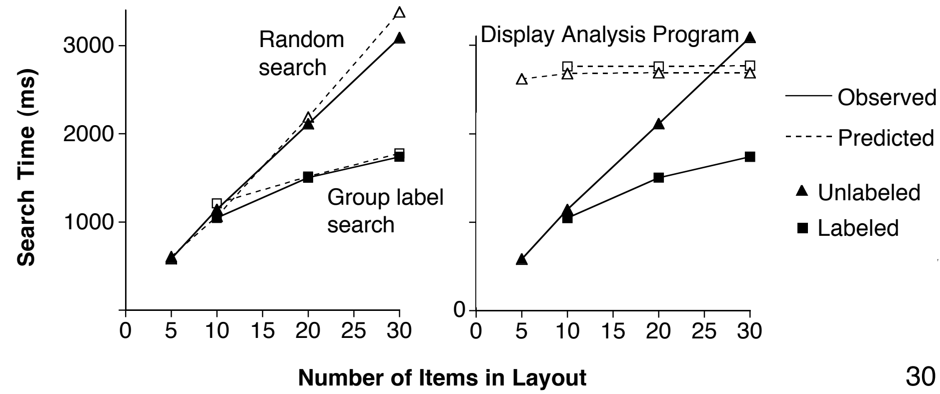


Better predictive tools are needed, and the tools need to use cognitive strategies.

The Display Analysis Program (DAP, Tullis 1988) did not incorporate cognitive strategies and could not explain the data.

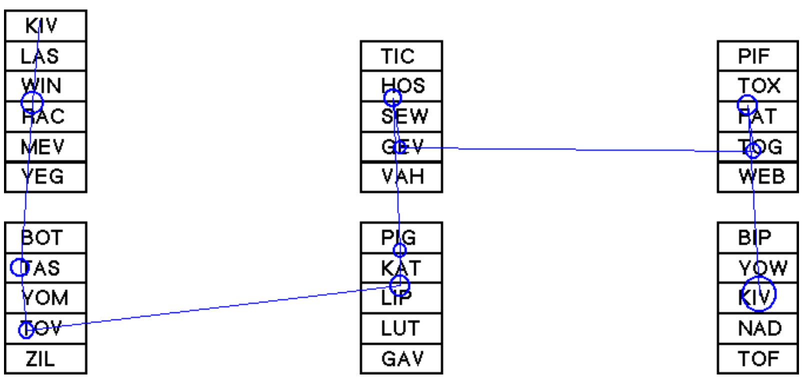
EPIC with the strategies shown.

Display Analysis Program (1988)



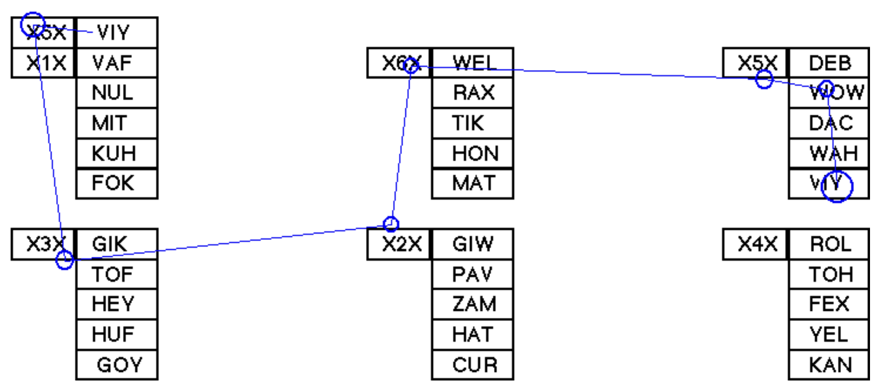
The models were built based on reaction time data and subsequently confirmed with eye tracking data.

Unlabeled Layout



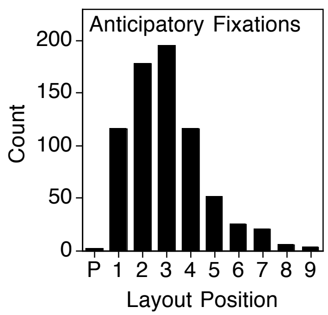
The models were built based on reaction time data and subsequently confirmed with eye tracking data.

Labeled Layout

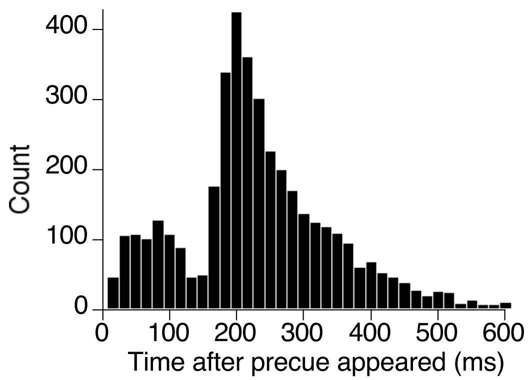


The cognitive strategies predicted the characteristics of the eye movements at the start of a trial.

Anticipatory Fixations



Second Fixations Respond to layout onset



Cognitive strategies for visual search should:

- Optimize architectural constraints.
- Make an initial anticipatory fixation.
- Respond to the onset of the layout.
- Examine more than one item with each fixation.
- Stop when the target appears in visual WM.

Four Projects Exploring Cognitive Strategies for...

1. Visual search of pull-down menus.
2. Visual search of hierarchical displays.
3. Multimodal multitasking.
4. Individualized strategies for multitasking.

3. Multimodal multitasking

Scientific goal: Develop a rigorous, accurate, reusable theory of the cognitive strategies and information processing involved in multitasking.

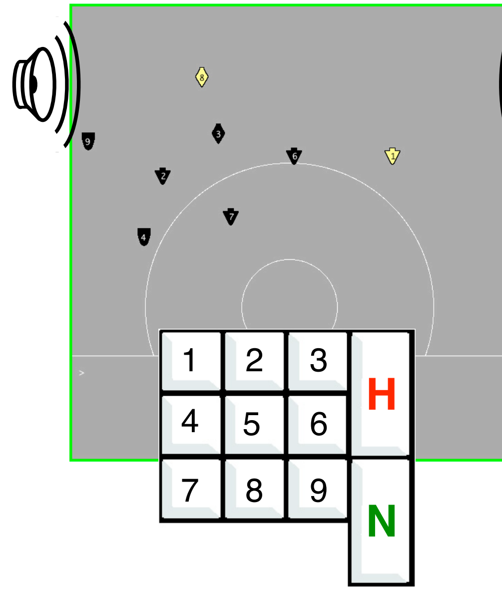
Practical Goal: Predict Human Performance

Present emergency workers with multimodal devices that support secondary tasks while personnel are engaged in other life-critical primary tasks.

Multimodal Dual Task

A version of the task developed by Ballas et al. (1992) at the Naval Research Laboratory (NRL).

Tactical Classification Task



Tracking Task

Two experimental conditions:

1. Peripheral visible or not

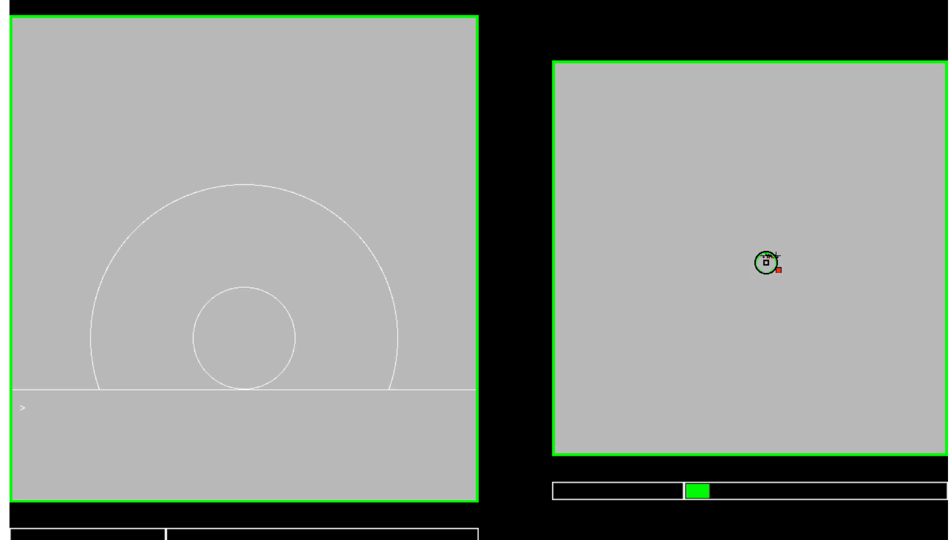
With peripheral *visible*, the contents of both displays are visible all the time.

With peripheral is *not visible*, only the blips on the display that you are currently looking at. Simulates two displays far apart.

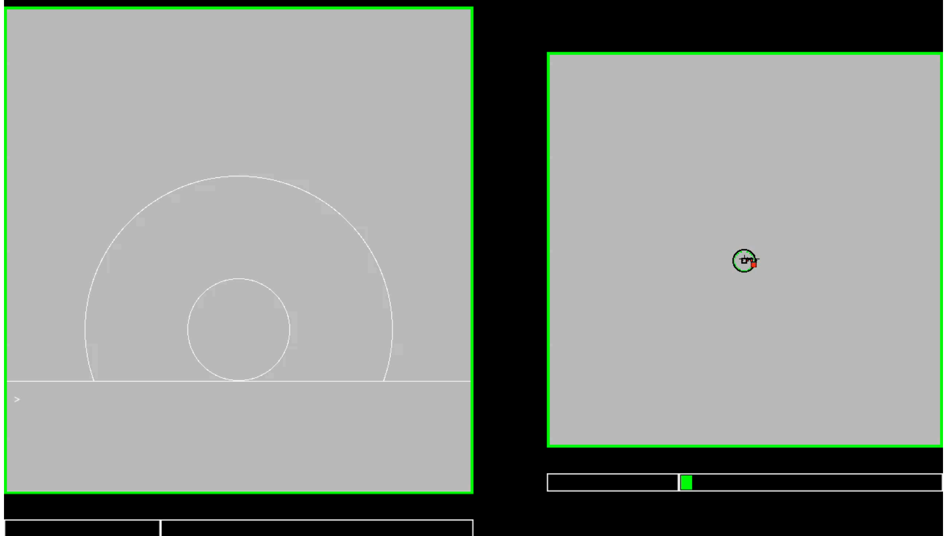
2. Sound on or off

When sound is on, an alarm indicates the color change that signals that a blip is ready to classify.

Peripherally visible, Sound off



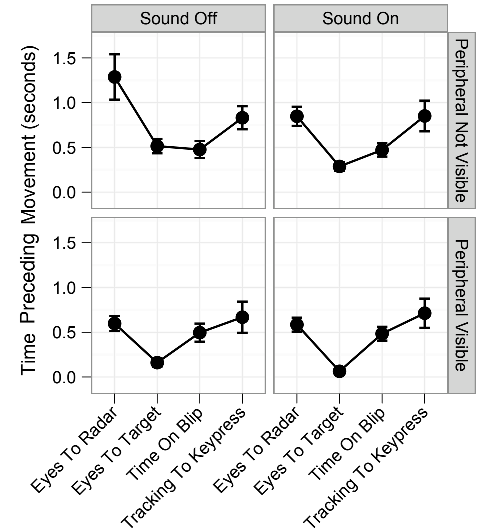
Peripheral not visible, Sound on



The eye movement data reveal many aspects of multitasking

The time preceding eye movements across the lifetime of a blip after it becomes ready to classify.

“Tracking to Keypress” is the how long the eyes are back on the tracking display before a blip is keyed in.



Two strategies will be presented

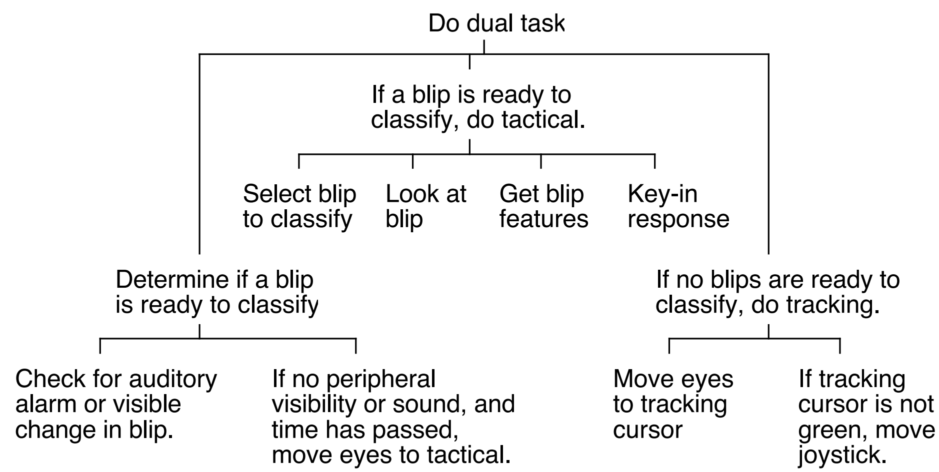
1. Independent Subtask Strategy

2. Independent Eye and Hand Strategy

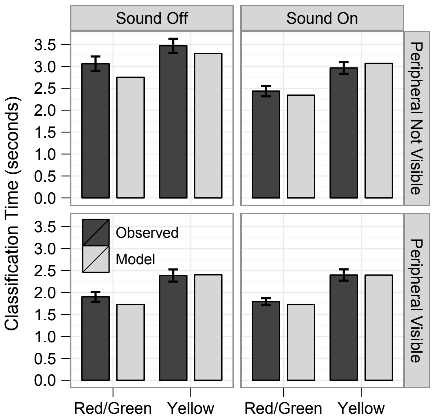
Independent Subtask Strategy

Enforces mutual exclusion between the two subtasks.

Strict serial processing of each subtask.

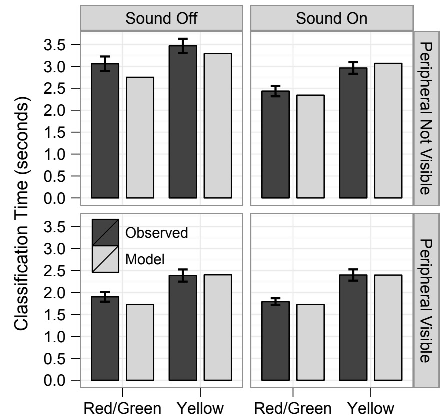


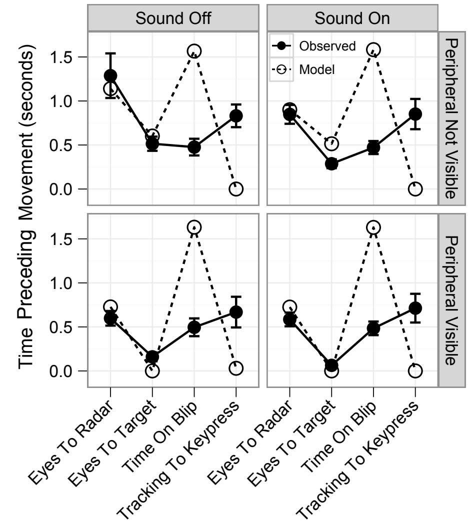
Independent Subtask Strategy



Predicts reaction times (AAE 5%)

Independent Subtask Strategy

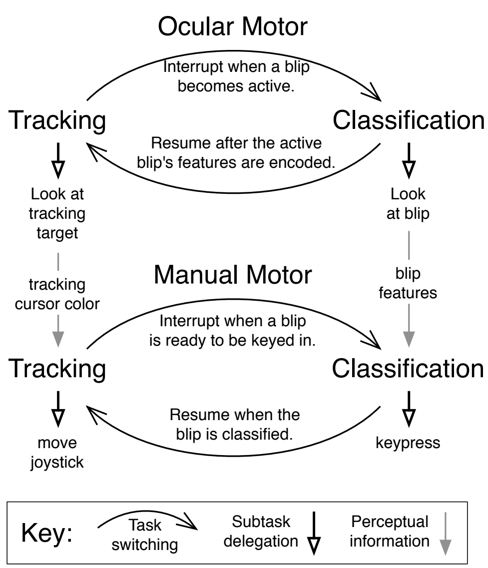




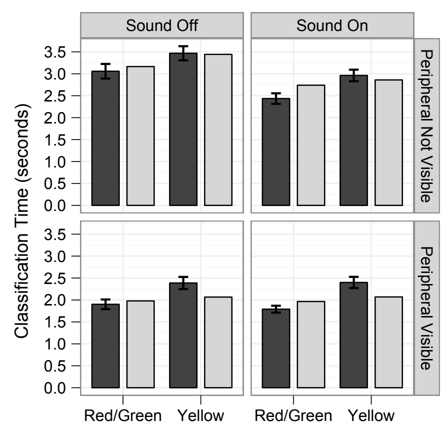
Predicts reaction times (AAE 5%)
but not eye movements (AAE 91%)
or tracking error (AAE 44%)

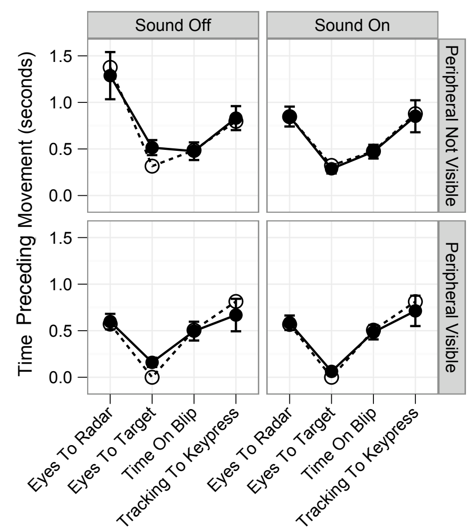
Independent Eye and Hand Strategy

- Maximizes human parallel processing that is built into the EPIC cognitive architecture.
- Ocular motor and manual motor processing run independently.
- State transition diagram summarizes the strategy.



Independent Eye and Hand Strategy





Predicts reaction times (AAE 7%)
and eye movements (AAE 10%)
and tracking error (AAE 14%)

Cognitive strategies in multitasking

- Skilled multitasking may involve running the ocular-motor and manual-motor processes independently and in parallel.
- There may not be independent strategies or mechanisms that actively coordinate between two task strategies (as in Kieras, Ballas, & Meyer, 2001; Salvucci and Taatgen, 2008).
- Eye movement data can help reveal the strategic interleaving of perceptual and motor processes in a time-critical dual task.

Four Projects Exploring Cognitive Strategies for...

1. Visual search of pull-down menus.
2. Visual search of hierarchical displays.
3. Multimodal multitasking.
4. Individualized strategies for multitasking.

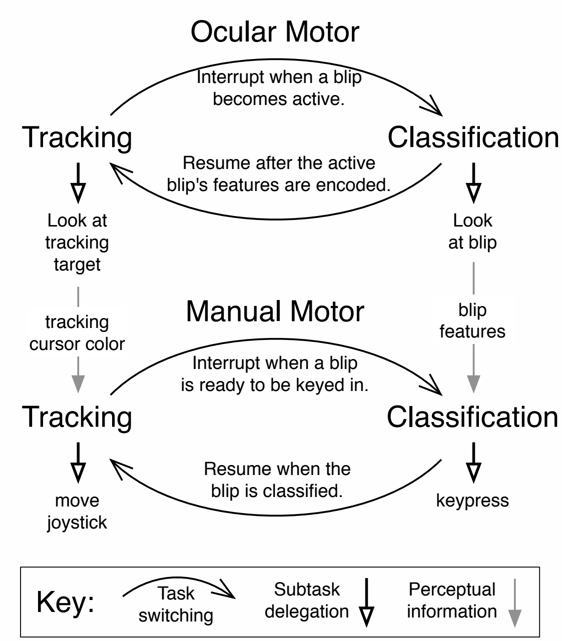
4. Individualized cognitive strategies for multitasking

Now we look for individual differences in the cognitive strategies that participants used in the multimodal dual task.

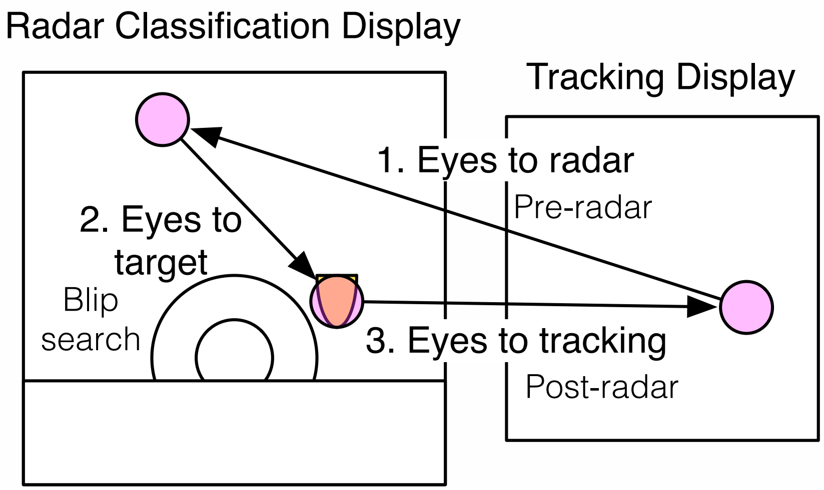
All participants use this overall strategy.

But what, for example, are the subtle differences in how individuals decide how and when to make these transitions.

Yunfeng Zhang's 2015 dissertation work. Now at IBM TJ Watson.



Most blips were classified with two to three eye movements



Four Strategy Dimensions

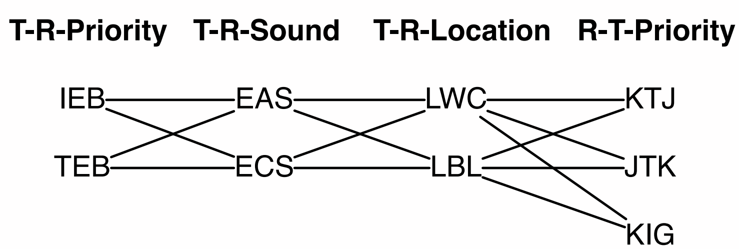
1. Tracking-to-Radar-Priority. When to move the eyes to the radar display after knowing a blip change color.
- **Immediate-Eyes-to-Blip (IEB).** Move immediately.
- **Track-then-Eyes-to-Blip (TEB).** Tracking until the cursor is green.

2. Tracking-to-Radar-Sound. When to move the eyes to the radar display after an auditory cue.
- **Eyes-to-All-Sounds (EAS).** Move for all sounds.
- **Eyes-to-Color-change-Sounds (ECS).** Move only for color-change sounds.

3. Tracking-to-Radar-Location. In the peripheral-not-visible conditions, where to put the eyes in the radar display when switching to the classification task.
- **Look-Window-Center (LWC).** Go to center.
- **Look-prior-Blip-Location (LBL).** Go to a black blip recalled from a previous visit.

4. Radar-to-Tracking-Priority. What to do with the hands after the model acquired the visual features of a yellow blip.
- **Keypad-Then-Joystick (KTJ).** Always key-in the classification response before doing any tracking.
- **Keypad-If-Green (KIG).** If the tracking cursor is not green, do some tracking until it is green, and then key in.
- **Joystick-Then-Keypad (JTK).** Always do some tracking before keying in the classification response.

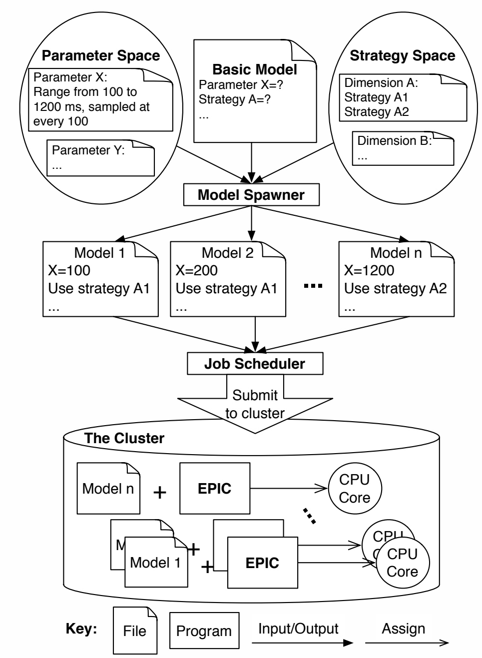
Explored all possible paths through the master strategy.



Ran the strategies through a Parallelized Cognitive Modeling System

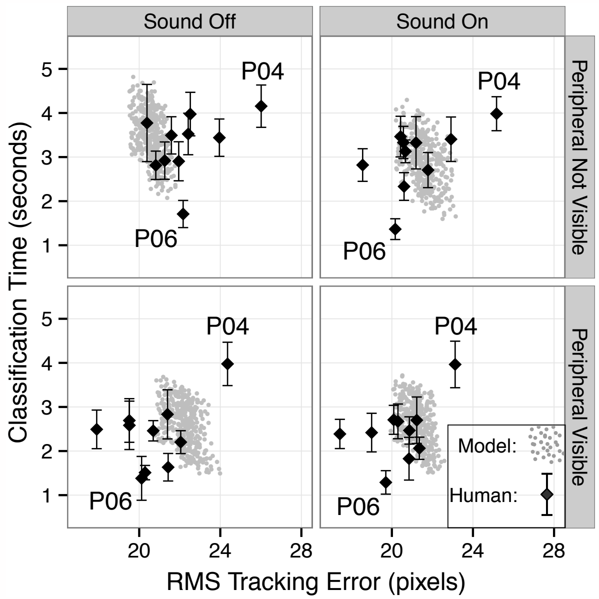
Two key components:

- Model Spawner: Automatic model generation.
- Job Scheduler: Parallel model execution.

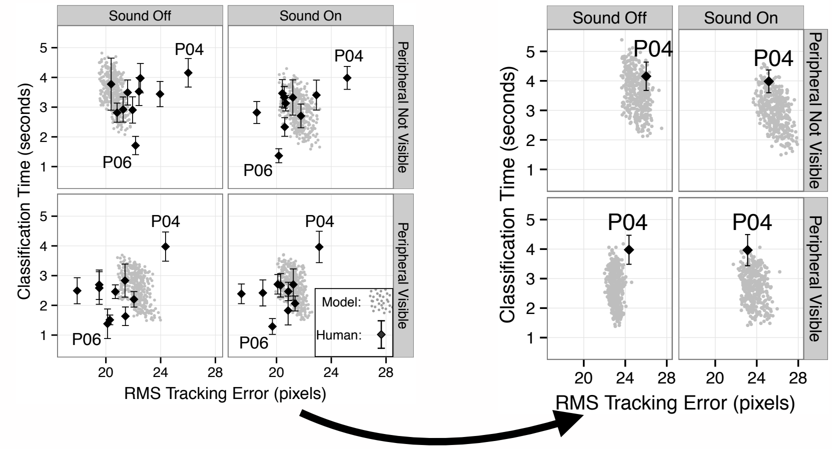


The system initially produces a cloud of predictions smaller than the cloud of individualized performance data.

Used EPIC's default encoding time parameters.

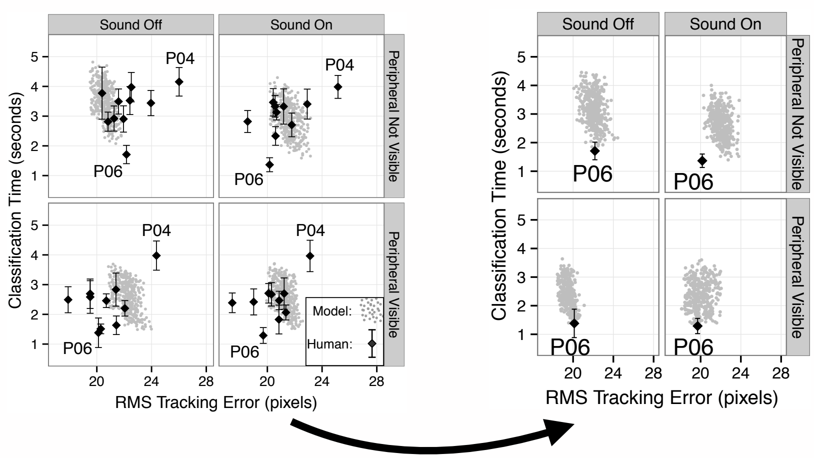


And so the model parameters are calibrated to individual data. P04, the worst performer.



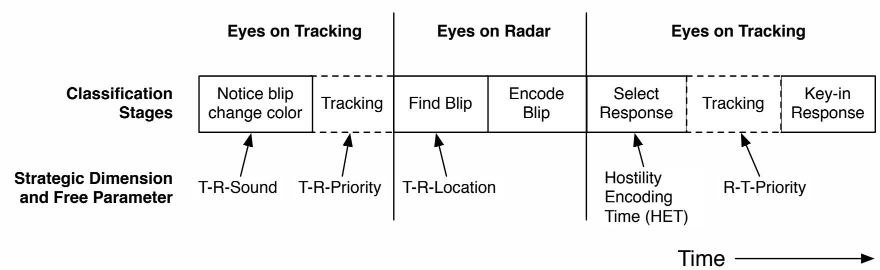
After the model's parameters are calibrated for P04's encoding time for *text* and *speed-and-direction*, and keystroke execution time.

And so the model parameters are calibrated to individual data. P06, the best performer.

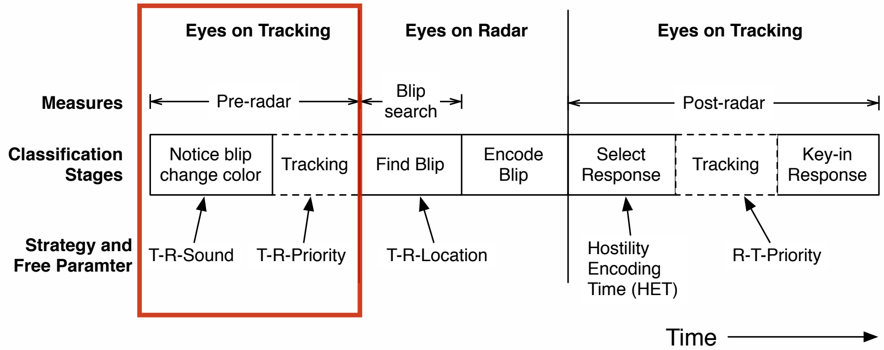


After the model's parameters are calibrated for P06's encoding time for *text* and *speed-and-direction*, and keystroke execution time.

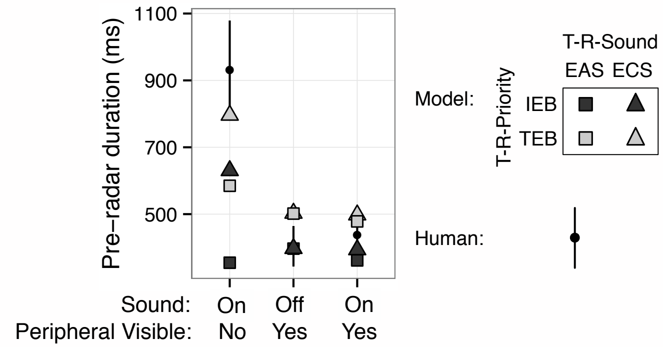
To figure out which substrategy each participant is using, it is determined which strategic dimension contributes to each time period in the eye movement data.



The tracking-to-radar-sound and tracking-to-radar-priority strategic dimension contribute to eyes-on-tracking time.



Compare the prediction to the observed within that one period in the eye movement data



For the Tracking-to-Radar-Sound dimension, Eyes-to-Color-change-Sounds (triangles) fits the sound-on peripheral-not-visible condition best.

Continue this process for each strategic dimension to determine the individualized strategy for each participant

Top performers make some strategic decisions that are different from the bottom performers.

Participants		Strategy Dimensions				interact HET (ms)	RMSD		
		T-R-Priority	T-R-Sound	T-R-Location	R-T-Priority		EM (ms)	CT (ms)	TE (pixels)
Top Performers	P06	IEB	EAS	LBL	KTJ	100	304	189	1.61
	P20	TEB	ECS	LBL	KIG	600	503	601	0.72
	P07	IEB	ECS	LBL	KIG	200	279	469	1.96
	P11	TEB	ECS	LBL	JTK	600	427	528	2.34
	P17	TEB	ECS	LBL	KIG	800	285	425	1.57
		IEB	ECS	LBL	KIG	800	349	441	1.76
Bottom Performers	P10	TEB	ECS	LBL	JTK	200	313	380	0.62
		TEB	ECS	LBL	KIG	900	415	422	0.77
	P09	TEB	ECS	LBL	JTK	1000	474	622	1.57
	P12	IEB	ECS	LBL	KIG	600	212	318	1.26
	P16	TEB	ECS	LBL	JTK	1600	437	679	0.89
	P04	TEB	ECS	LBL	JTK	1100	335	506	1.37

Individualized cognitive strategies for multitasking

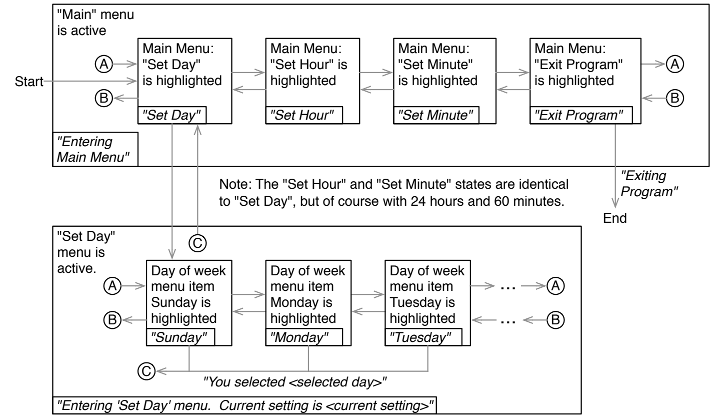
- Multitasking requires microstrategy selection, coordination, and execution.
- Individualized multitasking performance can be explained by individualized substrategy selection.
- Multitasking is a skill, but not a general skill. It is a skill that needs to be learned by each individual person, for each pair of tasks.

Once you think in terms of cognitive strategies, you think differently about interface design

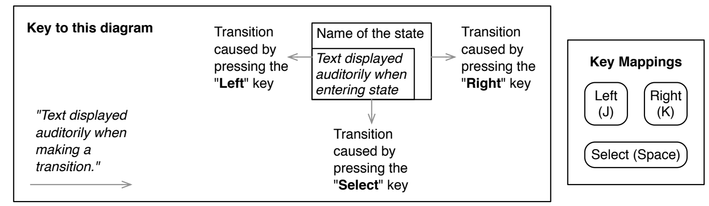
When you design an interface, you are designing a cognitive strategy.

I have the students in my user interface classes think about interfaces in terms of cognitive strategies.

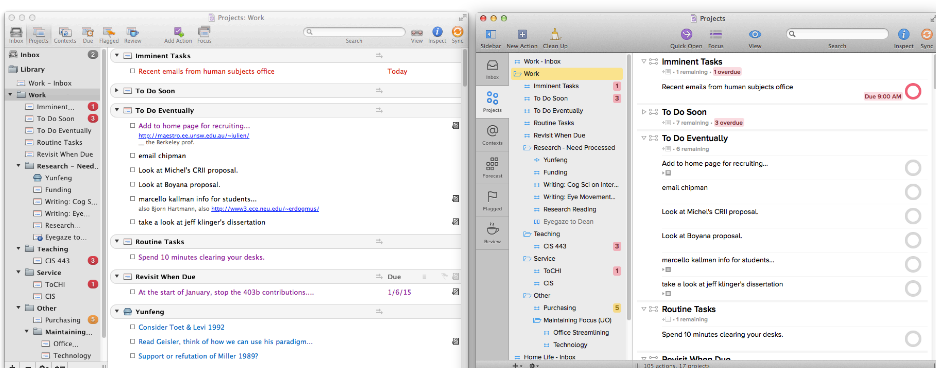
Students specify a user interface as a state transition diagram.



The compactness of the instructions relate to the compactness of the cognitive strategy, and ease of use.



Cognitive strategies could have helped to predict the customer complaints after a recent software update. The new version requires more eye and hand movements to do the same tasks.



OmniFocus Version 1

OmniFocus Version 2

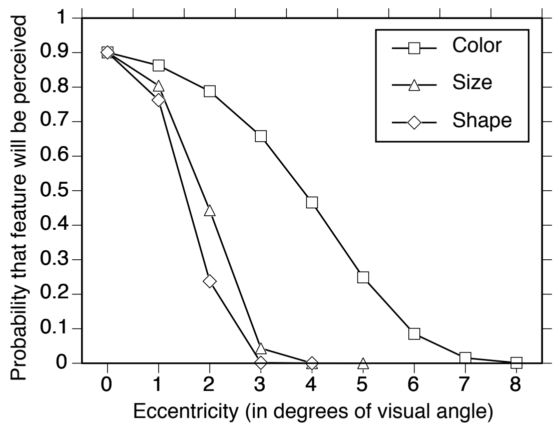
Visual search is best characterized as cognitive strategies moving the eyes to optimize the availability of the visual features that are needed to do a task.

“Because eye movements are always directed by the active cognitive process, an explanation of the eye movements must rely on an understanding of the controlling cognitive strategy.” Russo (1978)

An obsession with “covert shifts of attention” has held back the study of visual search for decades.

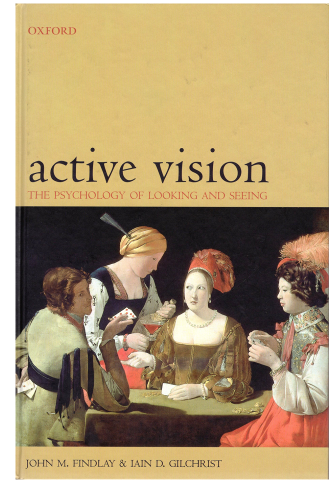
Visual search is best characterized as cognitive strategies moving the eyes to optimize the availability of the visual features that are needed to do a task.

EPIC's new availability functions will replace its fixed-diameter foveal regions.



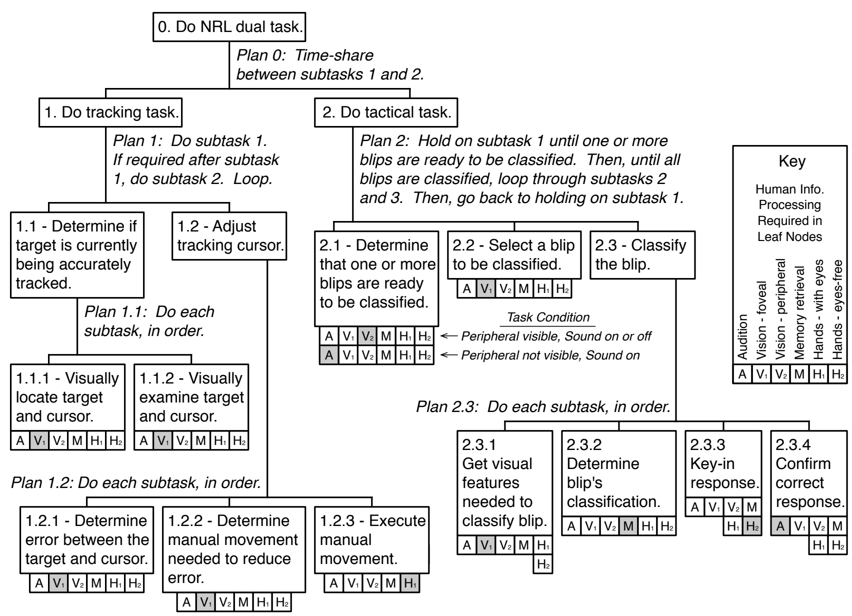
Visual search is best characterized as cognitive strategies moving the eyes to optimize the availability of the visual features that are needed to do a task.

There is little or no evidence that, when the eyes are permitted to move freely, covert visual attention moves independently of the eyes in a visual search task.
Findlay & Gilchrist (2003)

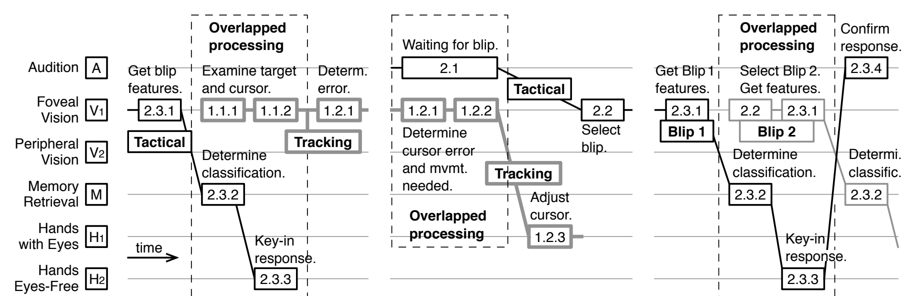


Findlay & Gilchrist (2003)

Future Work: Semi-automated cognitive strategy generation



Future Work: Semi-automated cognitive strategy generation



Overlap 1. The hands key-in a tactical task response after the eyes move to tracking.

Overlap 2. After an auditory signal is received, a little more tracking is completed, and then a switch to the tactical.

Overlap 3. Two blips are classified in an overlapped, "pipelined" manner.

Cognitive strategy are important for understanding and predicting aspects of human-computer interaction

- To deny the importance of cognitive strategies in such a model would seem to lead to a slippery slope back to behaviorism.
- And yet, cognitive strategies are not included in most HCI models of menu search. (Sears 1994; Findlater 2004; Cockburn 2009). Most models are regression fits of specific sets of data.
- To arrive at a useful engineering model, I believe we need to unpack the regression functions and identify the architectural and strategic components that generate the data.
- Cognitive strategies are a critical component of computational cognitive models of HCI tasks.