New light on the mind’s eye
Using the pupil light response to study visual cognition

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The pupil responds to three things.
Arousal.
Play noise
Brief, weak dilation that peaks 0.5 – 1 s after the stimulus
Brief, weak dilation that peaks 0.5 – 1 s after the stimulus.
Brief, weak dilation that peaks 0.5 – 1 s after the stimulus

Sometimes followed by a second phase of dilation

Play noise
Silence
Distance.
Cue to focus nearby
Rapid constriction

Cue to focus nearby
Rapid constriction

Cue to focus nearby

Cue to focus far away
Rapid constriction

Gradual dilation

Cue to focus nearby

Cue to focus far away
Light.
Light on

Red light
Blue light

Pupil size (norm)

Time since stimulus onset (s)
Light on

Very rapid constriction after ± 0.2 s

Red light
Blue light
Very rapid constriction after ± 0.2 s

Sometimes: pupil escape

Light on

Red light

Blue light
Very rapid constriction after ± 0.2 s

Sometimes: pupil escape

Light on

Light off

Red light

Blue light
Light on

Light off

Very rapid constriction after ± 0.2 s

Gradual dilation After ± 0.4 s

Sometimes: pupil escape

Red light
Blue light
Very rapid constriction after ± 0.2 s

Gradual dilation After ± 0.4 s

Sometimes: post-illumination pupil light response

Sometimes: pupil escape

Light on

Light off

Red light

Blue light
Captures lots of light
Captures lots of light

Has lots of optical distortions
Captures lots of light

Has lots of optical distortions
Captures lots of light
Has lots of optical distortions

Captures less light
Captures lots of light
Has lots of optical distortions

Captures less light
Has less optical distortions
The pupil light response

- The pupil light response is traditionally considered a reflex

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- Recent studies show cognitive influences[1]

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  - Visual attention

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  - Visual working memory

The pupil light response

- The pupil light response is traditionally considered a reflex
- Recent studies show cognitive influences[1]
- Today: The pupillary light response in
  - Visual attention
  - Visual working memory
  - Word comprehension

The pupillary light response and visual attention

Mathôt, Dalmaijer, Grainger, & Van der Stigchel (2014)
Visual attention
Visual attention

- If you attend to something, you see it more clearly
Visual attention

- If you attend to something, you see it more clearly
- Sudden visual events capture attention[1]
  - A light that is switched on
  - A sudden movement

Visual attention

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  - A light that is switched on
  - A sudden movement
- ... regardless of goals
  - It's reflexive

Visual attention

• If you attend to something, you see it more clearly
• Sudden visual events capture attention[1]
  – A light that is switched on
  – A sudden movement
• ... regardless of goals
  – It's reflexive
• ... and this can occur without eye movements
  – Covert visual attention

Visual attention
Visual attention

- Reflexive shifts of attention are brief
Visual attention

- Reflexive shifts of attention are brief
- ... and followed by inhibition (of return) [1]

Visual attention

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- This prevents us from attending to the same things over and over again [2]

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  - A been-there-done-that mechanism

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- Does the light response reflect:

Visual attention

- Reflexive shifts of attention are brief
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- Does the light response reflect:
  - Reflexive attention?

Visual attention

• Reflexive shifts of attention are brief
• ... and followed by inhibition (of return) [1]
• This prevents us from attending to the same things over and over again [2]
  – A been-there-done-that mechanism
• Does the light response reflect:
  – Reflexive attention?
  – Inhibition of return?

Methods

Adaptation
±3000 ms
Methods

Adaptation
±3000 ms

Cue
50 ms
Methods

Adaptation
±3000 ms

Cue
50 ms
Methods

Adaptation
±3000 ms

Cue
50 ms

Target
50 ms
Methods

- Adaptation: ±3000 ms
- Cue: 50 ms
- Target: 50 ms
- Mask: Until response
Methods

Adaptation
±3000 ms

Cue
50 ms

Target
50 ms

Mask
Until response
Methods

Adaptation ±3000 ms

Cue 50 ms

Target 50 ms

Mask Until response

SOA 100, 1000, or 2500 ms
Methods

Adaptation ±3000 ms
Cue 50 ms
SOA 100, 1000, or 2500 ms
Target 50 ms
Mask Until response

Attention
Methods

Adaptation ±3000 ms
Cue 50 ms
Target 50 ms
Mask Until response

Attention
Inhibition

SOA 1000, 1000, or 2500 ms
Results

![Graph showing the accuracy of valid and invalid cues over cue-target interval (ms)].

- **Valid cue** $(N=4148)$
- **Invalid cue** $(N=4130)$
Results

![Graph showing accuracy vs. cue-target interval]

- **Valid cue** ($N=4148$)
- **Invalid cue** ($N=4130$)
Results

![Graph showing the accuracy of valid and invalid cues over cue-target interval (ms). The graph compares the accuracy (%) between valid cue (N=4148) and invalid cue (N=4130).](graph.png)
Results

- **Accuracy (%)**
  - Valid cue ($N=4148$)
  - Invalid cue ($N=4130$)

- **Response time (ms)**

![Graphs showing the relationship between cue-target interval and accuracy/response time for valid and invalid cues.](chart.png)
Prediction

Shortly After cue

Attend bright

Small pupil
Prediction

Shortly After cue

Attend bright → Small pupil → Attend dark → Large pupil
Prediction

Shortly After cue

Attend bright  Small pupil  Attend dark  Large pupil

Longer after cue
Prediction

Shortly After cue

Attend bright

Small pupil

Longer after cue

Inhibit bright

Large pupil

Attend dark

Large pupil
Prediction

Shortly After cue:
- Attend bright → Small pupil
- Inhibit bright → Large pupil

Longer after cue:
- Attend dark → Large pupil
- Inhibit dark → Small pupil
Results
Results

![Graph showing pupil size over time with different colored lines for different conditions. The graph includes labels for 'Cue on bright (N=2055)' and 'Cue on dark (N=2044)' and shows the time since cue onset in milliseconds (ms).]
Results

Cue on bright ($N=2055$)
Cue on dark ($N=2044$)
Pupillary cuing effect
Pupillary inhibition
Interim discussion
Interim discussion

• Pupil size reflects reflexive attention
Interim discussion

- Pupil size reflects reflexive attention
  ... and subsequent inhibition of return
Interim discussion

- Pupil size reflects reflexive attention...
  and subsequent inhibition of return
- Can we link this to behavior?
  - Strong behavioral effect $\rightarrow$ Strong pupillary effect
Results
Results
Results

Sample: 1852 ms
$r = .790, p < .001$
Results

Sample: 1852 ms
\[ r = .790, \, p < .001 \]
Results

SOA: 2500 ms (behavior), 2500 ms (pupil)

Behavior - pupil correlation ($r$)

Accuracy

Response times

Time since cue onset (ms)
Discussion
Discussion

- Pupil inhibition is related to behavioral inhibition of return
Discussion

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... suggesting that both reflect the same mechanism
Discussion

- Pupil inhibition is related to behavioral inhibition of return
  ... suggesting that both reflect the same mechanism
- The pupillary light response is a sensitive measure of visual attention and inhibition
The pupillary light response and visual working memory

Blom, Mathôt, Olivers, & Van der Stigchel (2016)
http://dx.doi.org/10.1037/xhp0000252
Attention and working memory
Attention and working memory

- Attention and working memory are linked
Attention and working memory

- Attention and working memory are linked
  - Things in working memory capture attention[1]

Attention and working memory

- Attention and working memory are linked
  - Things in working memory capture attention[1]
  - Attention disrupts working memory[2]

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- General idea:

Attention and working memory

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  - The same brain areas are used for:

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    - Visual perception

Attention and working memory

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• General idea:
  – The same brain areas are used for:
    • Visual perception
    • Attention

Attention and working memory

- Attention and working memory are linked
  - Things in working memory capture attention[1]
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- General idea:
  - The same brain areas are used for:
    - Visual perception
    - Attention
    - Working memory

Attention and working memory

- Attention and working memory are linked
  - Things in working memory capture attention[1]
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- General idea:
  - The same brain areas are used for:
    - Visual perception
    - Attention
    - Working memory
  - “Emergent properties”[3]

Attention and working memory
Attention and working memory

- Can we use the pupillary light response to track attention during a working memory task?
Attention and working memory

● Can we use the pupillary light response to track attention during a working memory task?
● Is there a difference between encoding (≈attention) and maintenance of working memory?
Paradigm

Exp. 1

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Cue</td>
<td>Memory array</td>
<td>Retention</td>
<td>Same or different?</td>
</tr>
<tr>
<td>1 s</td>
<td>3 s</td>
<td>4 s</td>
<td>Until response</td>
</tr>
</tbody>
</table>
Paradigm

**Exp. 1**

- **Cue**: 1 s
- **Memory array**: 3 s
- **Retention**: 4 s
- **Same or different?** *Until response*
Paradigm

Exp. 1

Cue
1 s

Memory array
3 s

Retention
4 s

Same or different?
Until response
Paradigm

Exp. 1

Cue
1 s

Memory array
3 s

Retention
4 s

Same or different?
Until response
Paradigm

Exp. 1

Cue
1 s

Memory array
3 s

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4 s

Same or different?
Until response
Paradigm

Exp. 1

Cue
1 s

Memory array
3 s

Retention
4 s

Same or different?
Until response

Encoding

Maintenance
Prediction

Memorize bright Small pupil
Prediction

Memorize bright → Small pupil

Memorize dark → Large pupil
Results
Results

The graph illustrates the changes in pupil size (normalized) over time since cue onset (s). The x-axis represents time in seconds, ranging from 0 to 8, while the y-axis shows pupil size normalized from 0.80 to 1.10. The graph is divided into three phases: Cue, Memory array, and Retention.

The blue line represents Black participants (N=487), and the orange line represents White participants (N=503). Throughout the sequence, the pupil size for Black participants generally remains higher than that for White participants, indicating potential differences in cognitive engagement across these groups.
But first ...

... Let's compare this to an attention-only condition
Paradigm

**Working-memory condition**

- **Experiment 1**

  - **Cue**
    - 1 s
  - **Memory array**
    - 3 s
  - **Retention**
    - 4 s
  - **Same or different?**
    - Until response

**Attention condition**

- **Experiment 1**

  - **Target**
    - 1 s
  - **Search array**
    - 3 s
  - **Pause**
    - 4 s
  - **Target present?**
    - Until response

What you just saw →

To see the effect of attention alone →
Paradigm

What you just saw →

Working-memory condition
- Exp. 1
- Cue 1 s
- Memory array 3 s
- Retention 4 s
- Same or different? Until response

To see the effect of attention alone →

Attention condition
- Exp. 1
- Target 1 s
- Search array 3 s
- Pause 4 s
- Target present? Until response
Paradigm

**Working-memory condition**

What you just saw →

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</table>
```

**Attention condition**

To see the effect of attention alone →

```
<table>
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<th>Pause</th>
<th>Target present?</th>
</tr>
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<tbody>
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```
Paradigm

Working-memory condition

Cue 1s  Memory array 3s  Retention 4s  Same or different? Until response

Attention condition

Target 1s  Search array 3s  Pause 4s  Target present? Until response

What you just saw →

To see the effect of attention alone →
Results

The results that you just saw
(working-memory task)
Results

The results that you just saw (working-memory task)

The effect of attention alone
Results

- The pupillary light response reflects
Results

- The pupillary light response reflects
  - Encoding of working memory (≈attention)
Results

- The pupillary light response reflects
  - Encoding of working memory ($\approx$ attention)
  - But not maintenance of working memory
Results

• The pupillary light response reflects
  - Encoding of working memory (≈attention)
  - But not maintenance of working memory

• Perhaps
Results

- The pupillary light response reflects
  - Encoding of working memory (≈attention)
  - But not maintenance of working memory
- Perhaps
  - Participants verbalized the stimuli?
Paradigm

Exp. 2

Cue 1 s

Memory array 3 s

Retention 4 s

Same or different? Until response
Results
Results

• The pupillary light response reflects
  – Encoding of working memory (≈attention)
  – But not maintenance of working memory
• Perhaps
  – Participants verbalized the stimuli?
  – Only task-relevant features were encoded?
Paradigm

Cue 1 s

Memory array 3 s

Retention 4 s

Same or different? Until response
Results

![Graph showing pupil size over time with different conditions and participant counts]
Discussion

- The pupillary light response reflects

Discussion

- The pupillary light response reflects
  - Encoding of working memory (≈attention)

Discussion

- The pupillary light response reflects
  - Encoding of working memory (≈attention)
  - But not maintenance of working memory

Discussion

• The pupillary light response reflects
  – Encoding of working memory (≈attention)
  – But not maintenance of working memory

• Perhaps

Discussion

• The pupillary light response reflects
  - Encoding of working memory (≈attention)
  - But not maintenance of working memory

• Perhaps
  - Participants verbalized the stimuli?

Discussion

- The pupillary light response reflects
  - Encoding of working memory (≈attention)
  - But not maintenance of working memory

- Perhaps
  - Participants verbalized the stimuli?
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Discussion

• The pupillary light response reflects
  − Encoding of working memory (≈attention)
  − But not maintenance of working memory

• Perhaps
  − Participants verbalized the stimuli?
  − Only task-relevant features were encoded?
  − Working-memory maintenance and attention are qualitatively different?

Discussion

- The pupillary light response reflects
  - Encoding of working memory (≈attention)
  - But not maintenance of working memory
- Perhaps
  - Participants verbalized the stimuli?
  - Only task-relevant features were encoded?
  - Working-memory maintenance and attention are qualitatively different?
    - An “accessory” memory state that does not interact with perception[1]

The pupillary light response and word comprehension

Mathôt, Grainger, & Strijkers (2017)
http://dx.doi.org/10.1177/0956797617702699
Embodied language

- When you read a word, you automatically[1]

Embodied language

- When you read a word, you automatically[1]
  - Activate associated actions

Embodied language

- When you read a word, you automatically[1]
  - Activate associated actions
  - Simulate associated sensory input

Embodied language

- When you read a word, you automatically\[1\]
  - Activate associated actions
  - Simulate associated sensory input
- Are these internally generated representations

Embodied language

- When you read a word, you automatically[1]
  - Activate associated actions
  - Simulate associated sensory input

- Are these internally generated representations
  - Abstract?

Embodied language

- When you read a word, you automatically[1]
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  - Simulate associated sensory input
- Are these internally generated representations
  - Abstract?
    - Not involving early sensory and motor cortex

Embodied language

- When you read a word, you automatically[1]
  - Activate associated actions
  - Simulate associated sensory input
- Are these internally generated representations
  - Abstract?
    - Not involving early sensory and motor cortex
  - Or concrete?

Embodyed language

- When you read a word, you automatically\[1\]
  - Activate associated actions
  - Simulate associated sensory input
- Are these internally generated representations
  - Abstract?
    - Not involving early sensory and motor cortex
  - Or concrete?
    - Involving early sensory and motor cortex

\[1\] Reviewed in Glenberg & Gallese (2012)
Embodied language

- When you read a word, you automatically[1]
  - Activate associated actions
  - Simulate associated sensory input
- Are these internally generated representations
  - Abstract?
    - Not involving early sensory and motor cortex
  - Or concrete?
    - Involving early sensory and motor cortex
- Can we test this using the pupillary light response?

Methods
Methods

- Single word shown for 3 s
Methods

• Single word shown for 3 s
  - Brightness-conveying, darkness-conveying, neutral, and animal names
Methods

- Single word shown for 3 s
  - Brightness-conveying, darkness-conveying, neutral, and animal names
  - Matched on visual and lexical properties
Methods

- Single word shown for 3 s
  - Brightness-conveying, darkness-conveying, neutral, and animal names
  - Matched on visual and lexical properties
- Press key for animal names
Methods

- Single word shown for 3 s
  - Brightness-conveying, darkness-conveying, neutral, and animal names
  - Matched on visual and lexical properties
- Press key for animal names
Predictions

Darkness-conveying words
Predictions

Darkness-conveying words

Brightness-conveying words
Predictions

Darkness-conveying words

Brightness-conveying words
Results
Results
Discussion

- Pupil size reflects semantic brightness
Discussion

- Pupil size reflects semantic brightness
  - Read “sun” → small pupil
Discussion

• Pupil size reflects semantic brightness
  – Read “sun” → small pupil
  – Read “night” → large pupil
Discussion

• Pupil size reflects semantic brightness
  – Read “sun” → small pupil
  – Read “night” → large pupil

• Does it also work with spoken words?
Results

- Brightness-conveying words ($N_{aur}=936$)
- Darkness-conveying words ($N_{aur}=971$)
- Neutral words ($N_{aur}=997$)

$p < .05$, $p < .01$
Discussion
Discussion

- Pupil size reflects semantic brightness
Discussion

- Pupil size reflects semantic brightness
  - Read or hear “sun” → small pupil
Discussion

- Pupil size reflects semantic brightness
  - Read or hear “sun” → small pupil
  - Read or hear “night” → large pupil
Discussion

• Pupil size reflects semantic brightness
  - Read or hear “sun” → small pupil
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• Word comprehension activates sensory representations (at least sometimes):
Discussion

- Pupil size reflects semantic brightness
  - Read or hear “sun” → small pupil
  - Read or hear “night” → large pupil
- Word comprehension activates sensory representations (at least sometimes):
  - And these affect pupil size
Discussion

• Pupil size reflects semantic brightness
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• Word comprehension activates sensory representations (at least sometimes):
  - And these affect pupil size
  - Embodiment?
Discussion

• Pupil size reflects semantic brightness
  - Read or hear “sun” → small pupil
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• Word comprehension activates sensory representations (at least sometimes):
  - And these affect pupil size
  - Embodiment?
  - Or preparation?
Conclusion
Conclusion

- Pupillary responses are not passive reflexes
Conclusion

- Pupillary responses are not passive reflexes
  ... but are types of eye movements that reflect high-level visual processing
Conclusion

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  ... but are types of eye movements that reflect high-level visual processing
- “External attention”
Conclusion

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  ... but are types of eye movements that reflect high-level visual processing
- “External attention”
  - Directing your attention to something out there
Conclusion

- Pupillary responses are not passive reflexes
  - but are types of eye movements that reflect high-level visual processing
- “External attention”
  - Directing your attention to something out there
- “Internal attention”
Conclusion

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  ... but are types of eye movements that reflect high-level visual processing
- “External attention”
  - Directing your attention to something out there
- “Internal attention”
  - Sensory representations without visual input
Conclusion

• Pupillary responses are not passive reflexes
  ... but are types of eye movements that reflect high-level visual processing

• “External attention”
  – Directing your attention to something out there

• “Internal attention”
  – Sensory representations without visual input
  – But where does working memory stand in this?
Thank you!

Sebastiaan Mathôt