New light on the mind's eye

Using the pupil light response to study visual cognition

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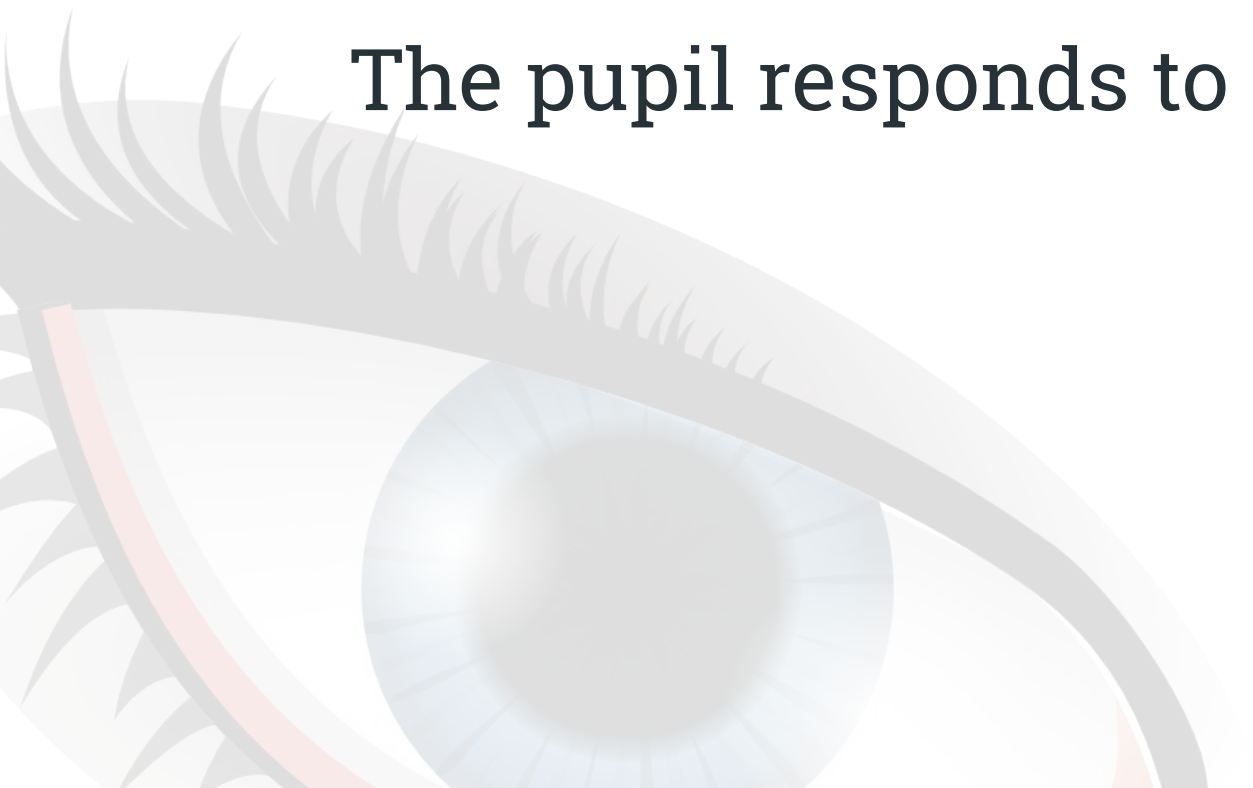
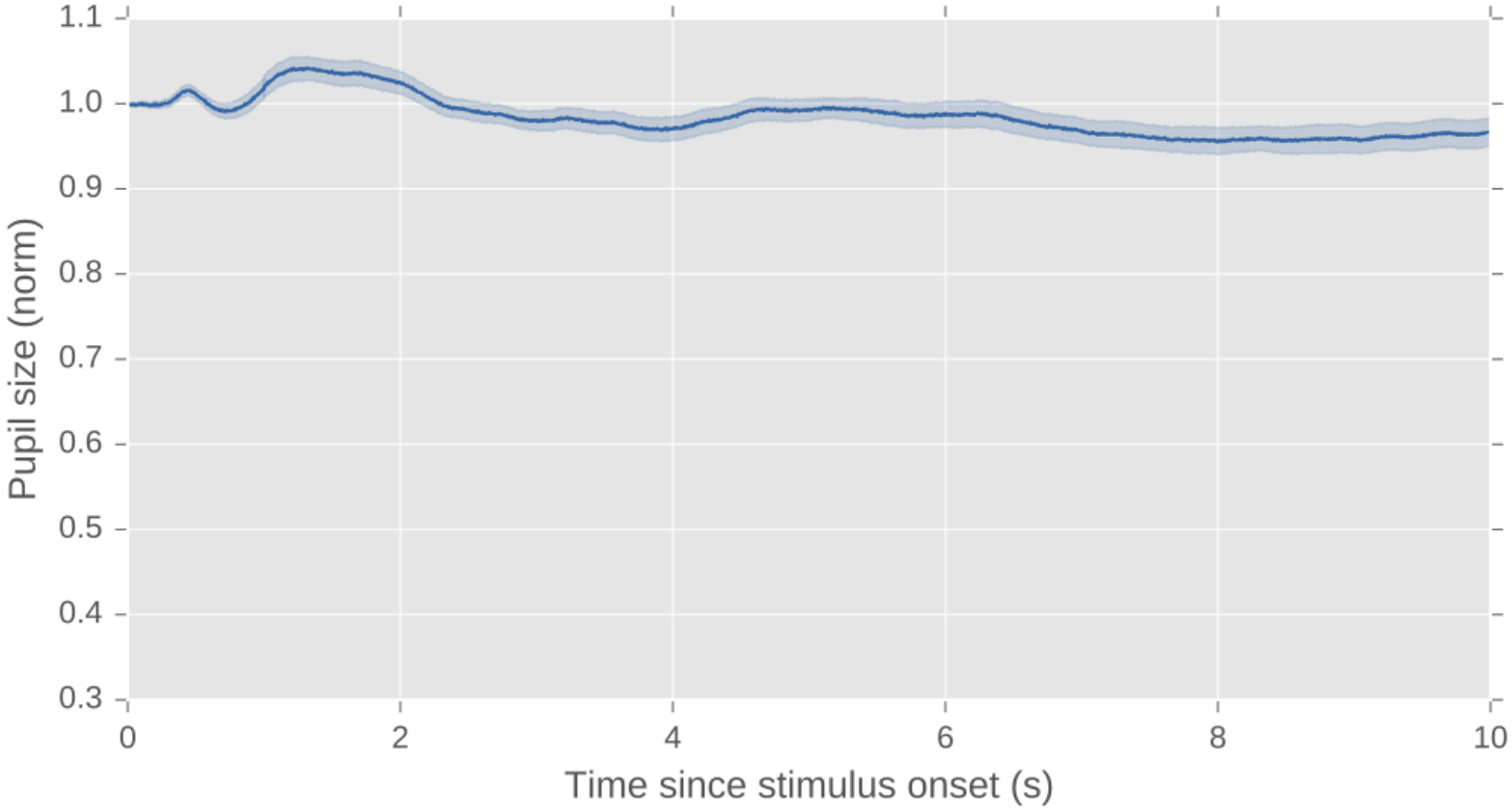
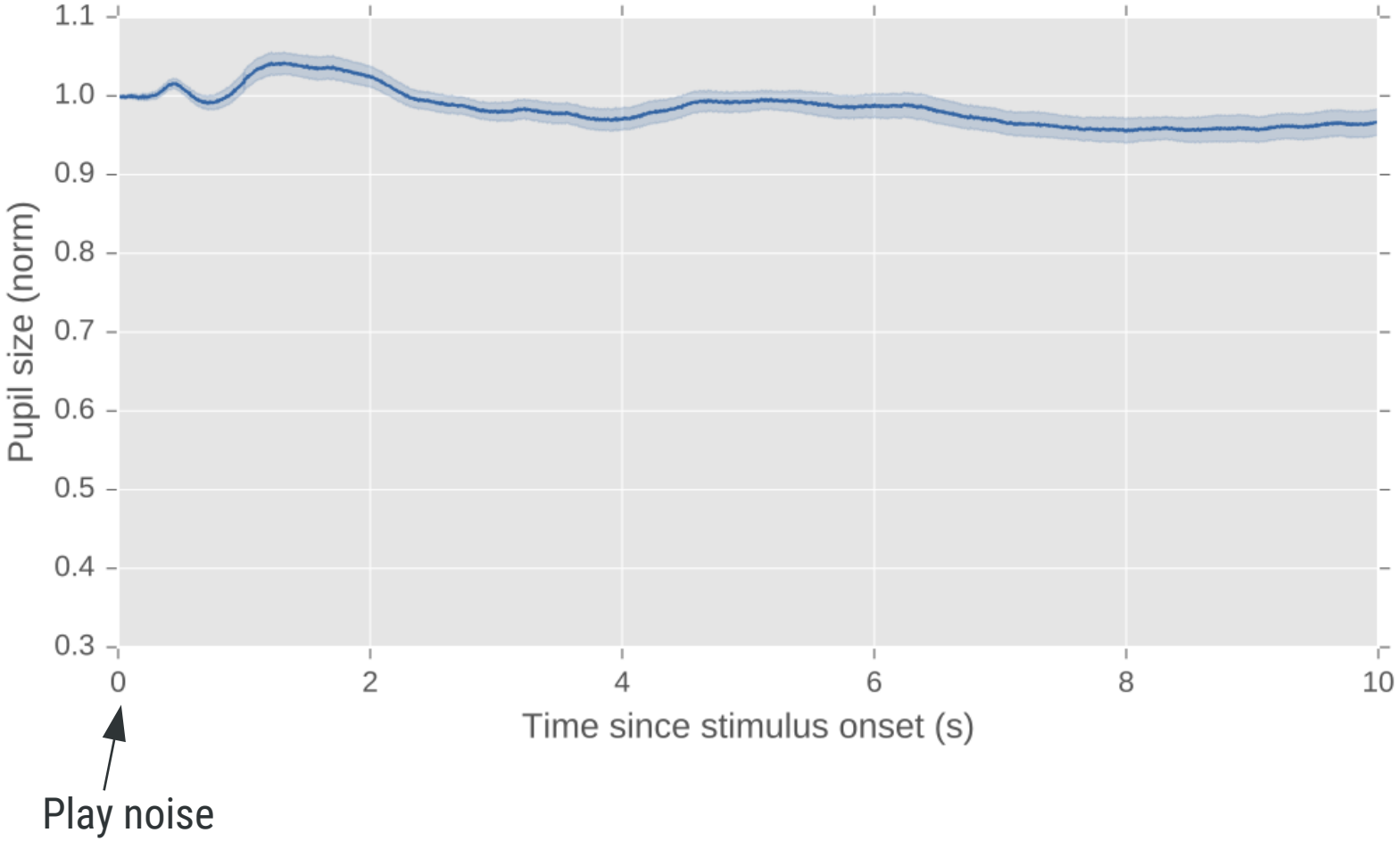
sebastiaanmathot

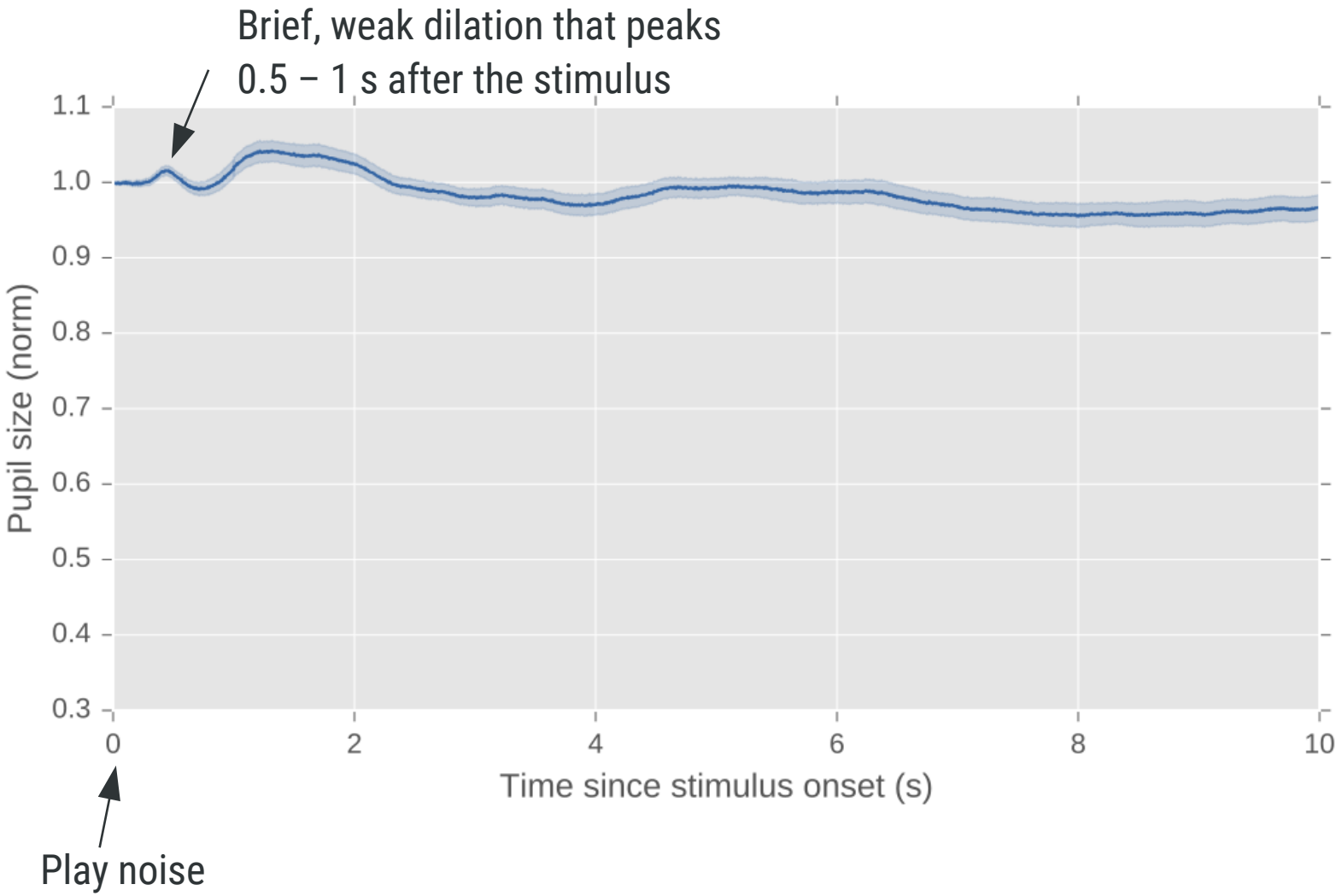
The pupil responds to three things.

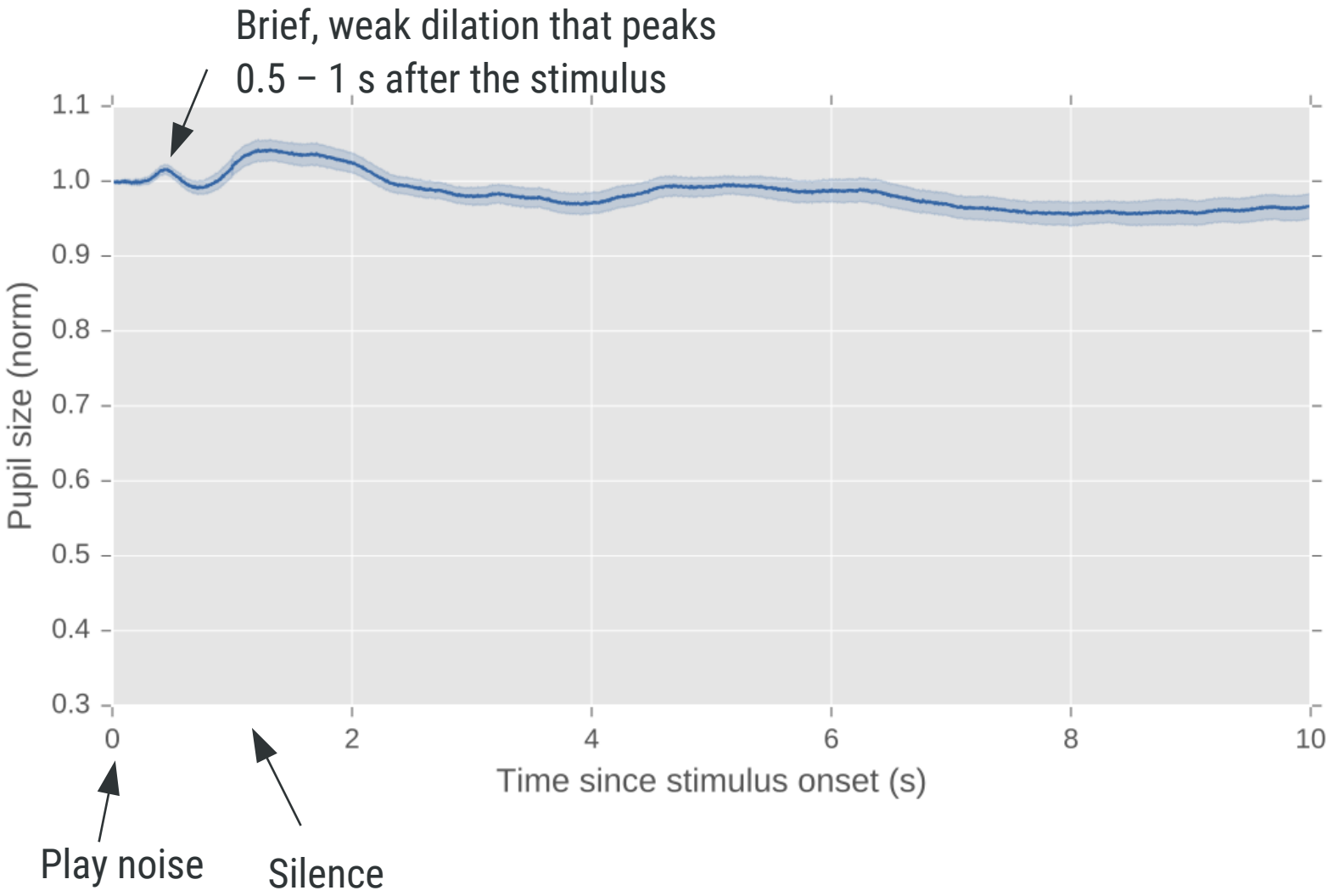


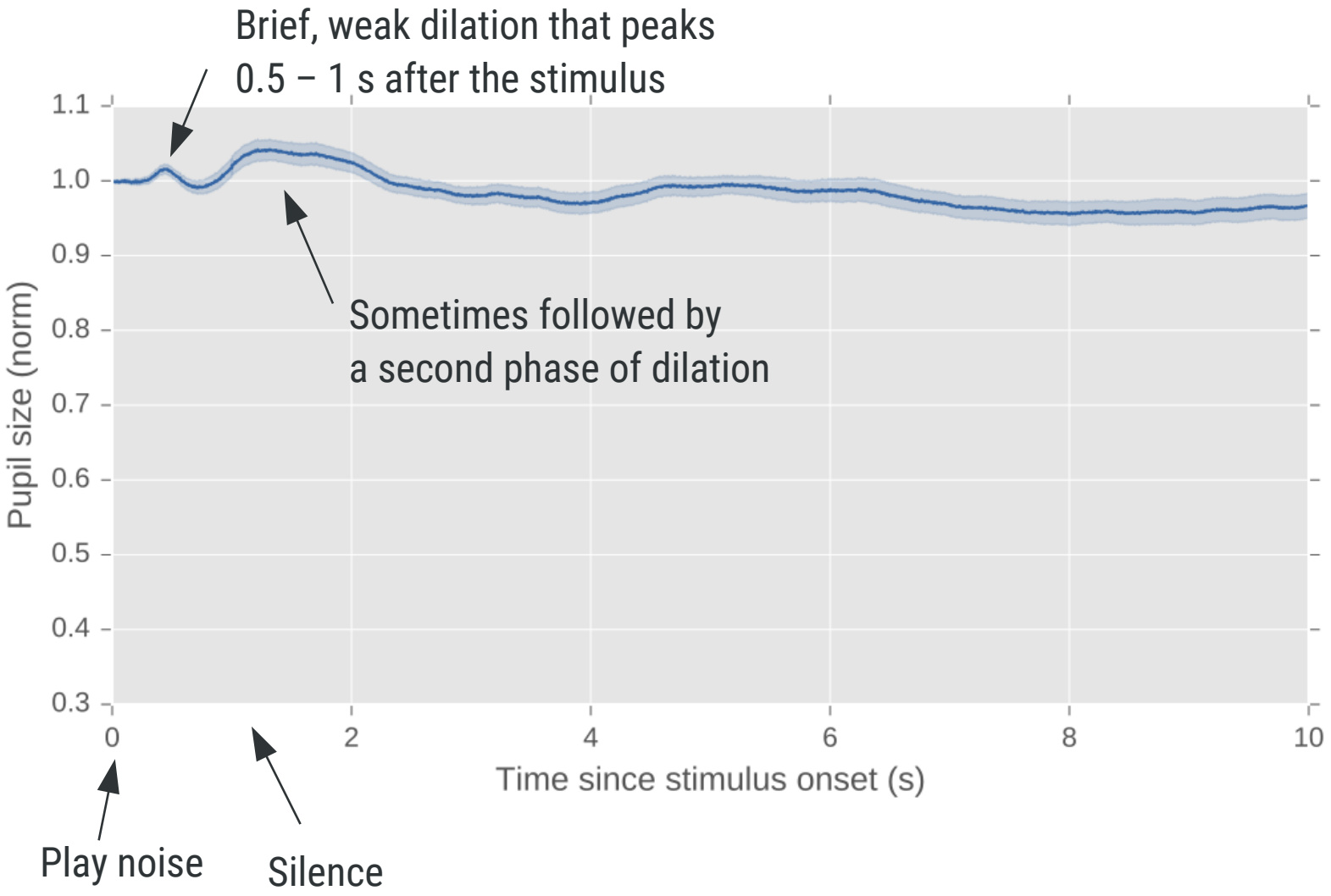

Arousal.


1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
Pupil size (norm)
0
2
4
6
8
10
Time since stimulus onset (s)

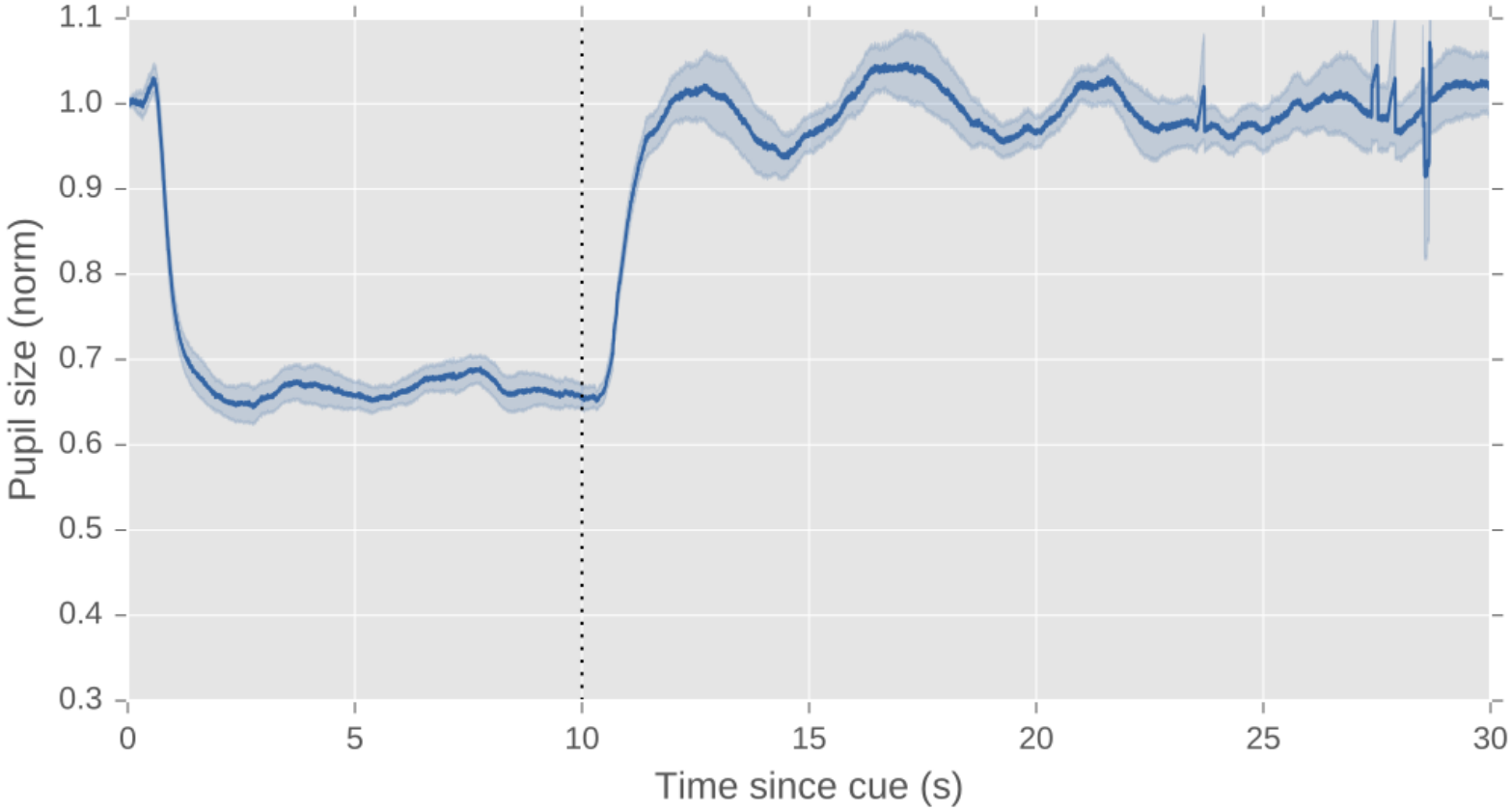

1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
Pupil size (norm)
0
2
4
6
8
10
Time since stimulus onset (s)
Play noise

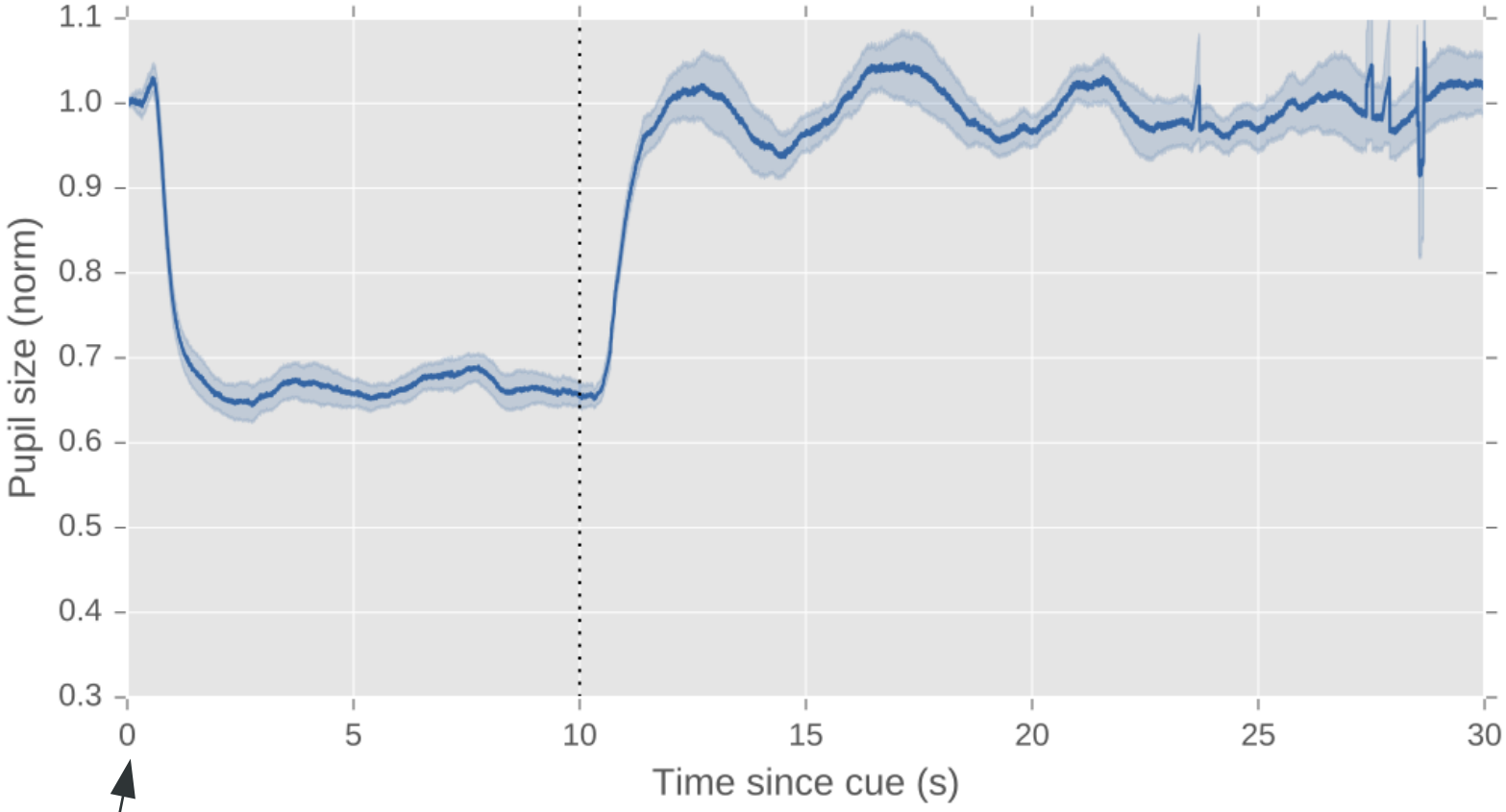

Brief, weak dilation that peaks
0.5 – 1 s after the stimulus
Pupil size (norm)
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0
2
4
6
8
10
Time since stimulus onset (s)
Play noise


Brief, weak dilation that peaks
0.5 – 1 s after the stimulus
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
Pupil size (norm)
0
2
4
6
8
10
Time since stimulus onset (s)
Play noise
Silence

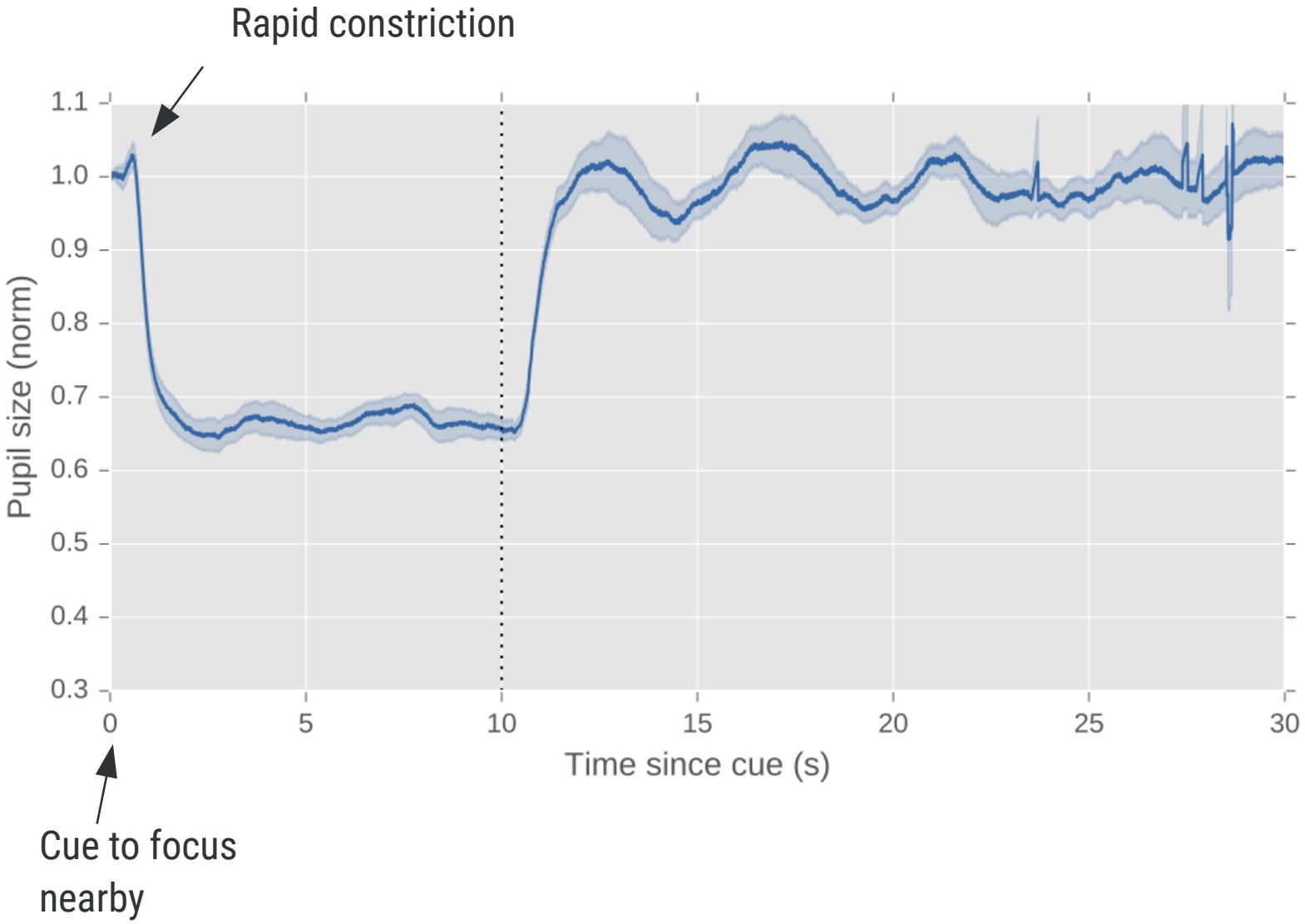

Brief, weak dilation that peaks
0.5 – 1 s after the stimulus
Sometimes followed by
a second phase of dilation
Pupil size (norm)
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0
2
4
6
8
10
Time since stimulus onset (s)
Play noise
Silence

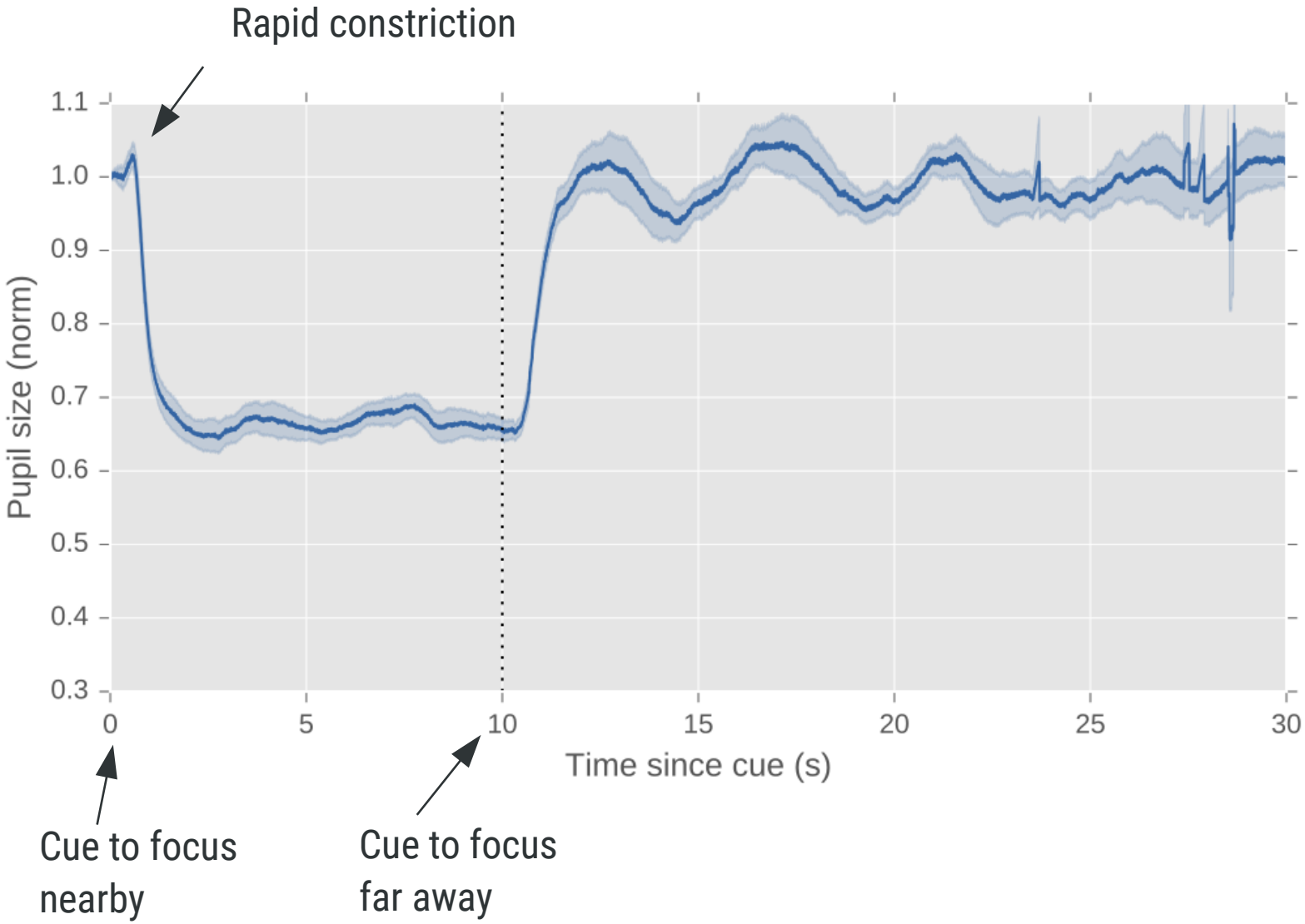

Distance.

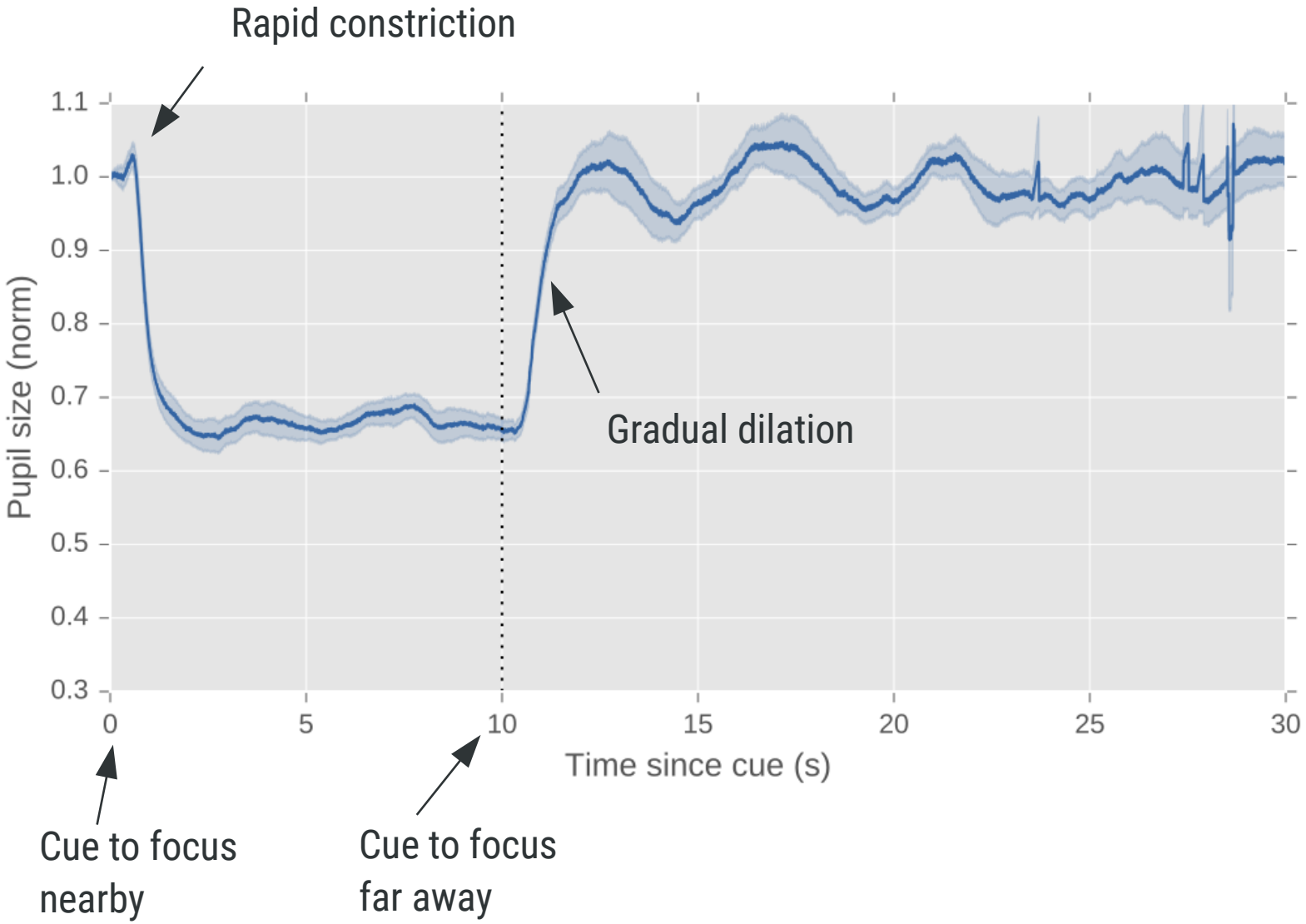

Pupil size (norm)
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0
5
10
15
20
25
30
Time since cue (s)



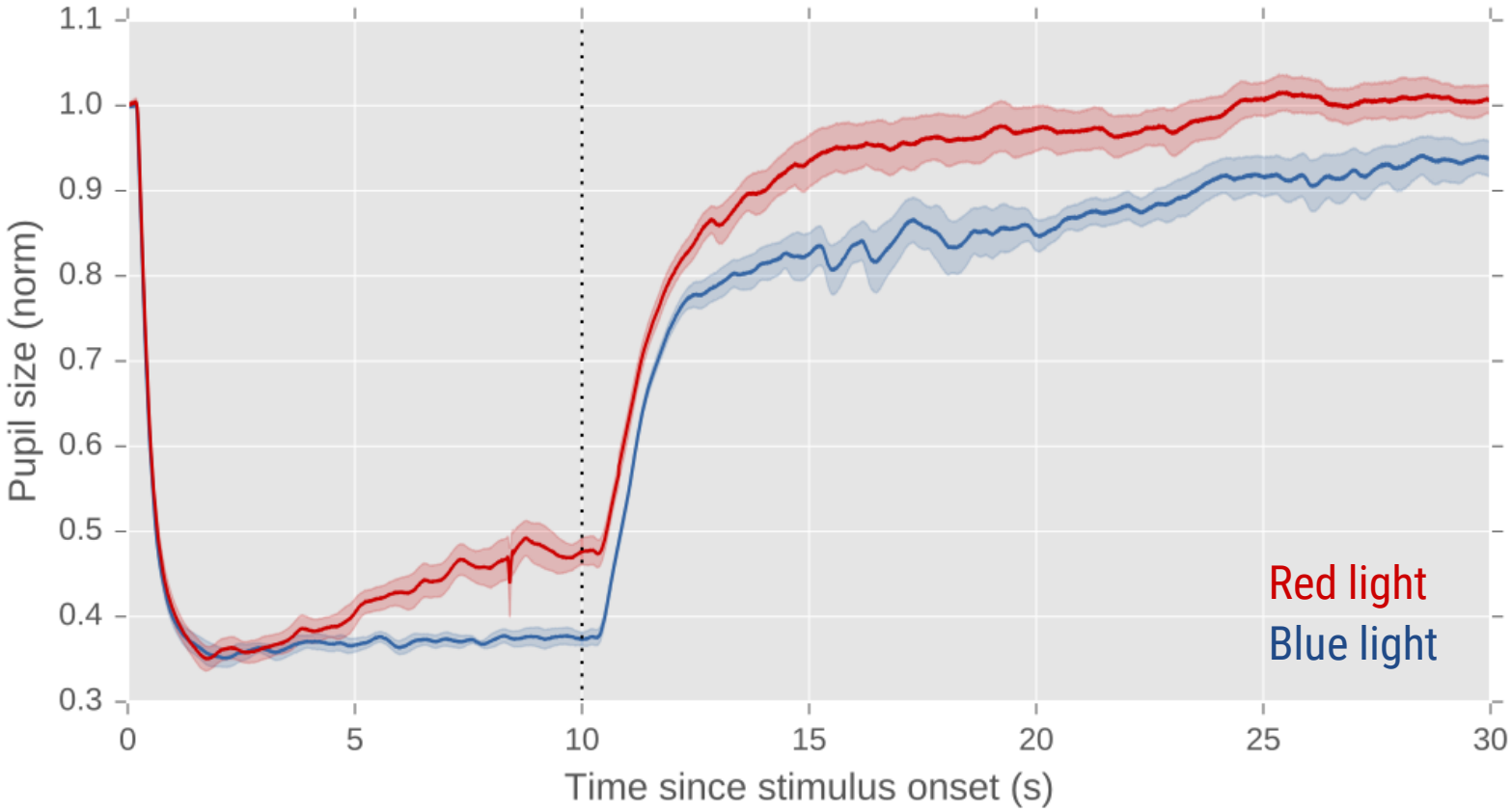
Cue to focus nearby

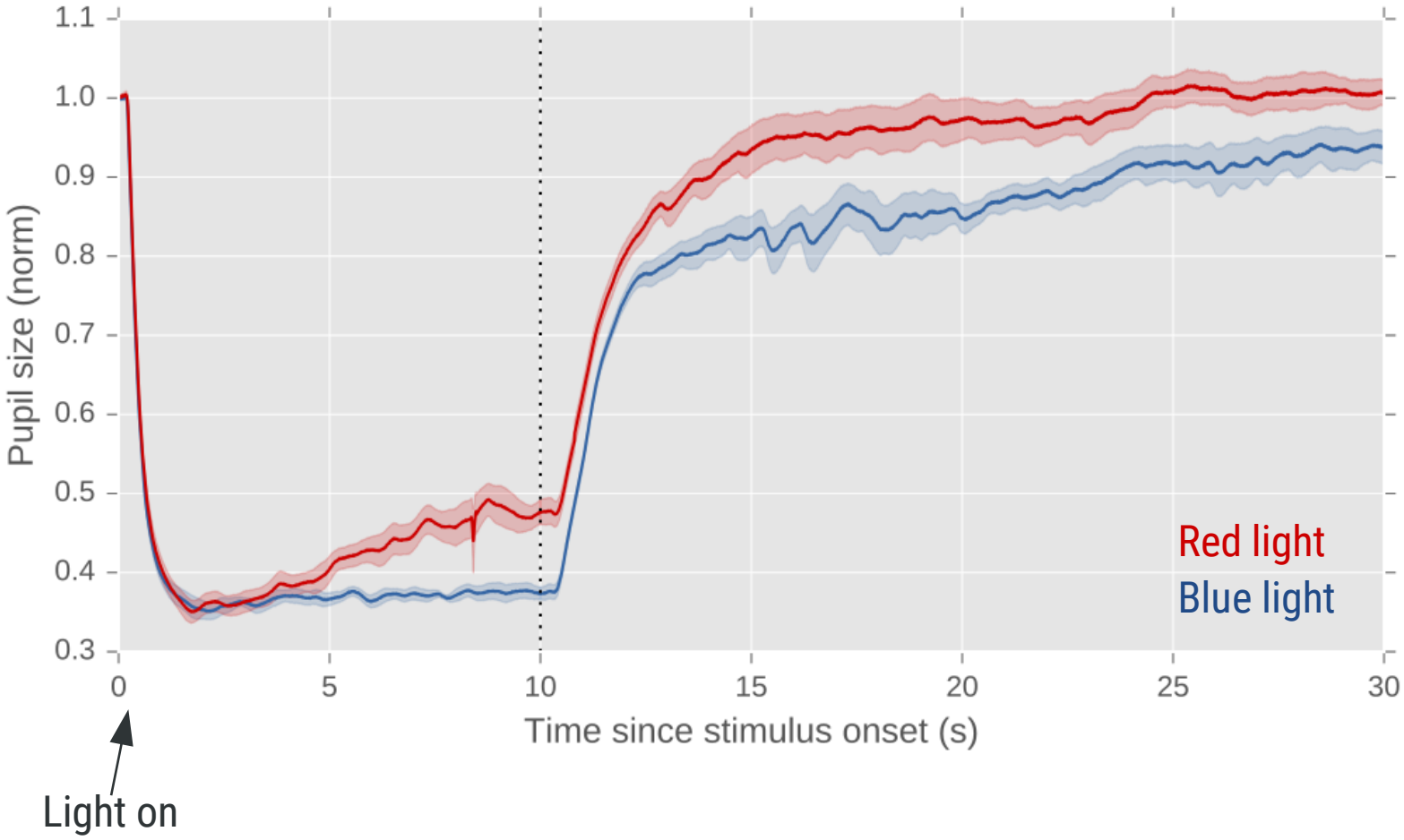

Rapid constriction
Pupil size (norm)
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0
5
10
15
20
25
30
Time since cue (s)
Cue to focus nearby

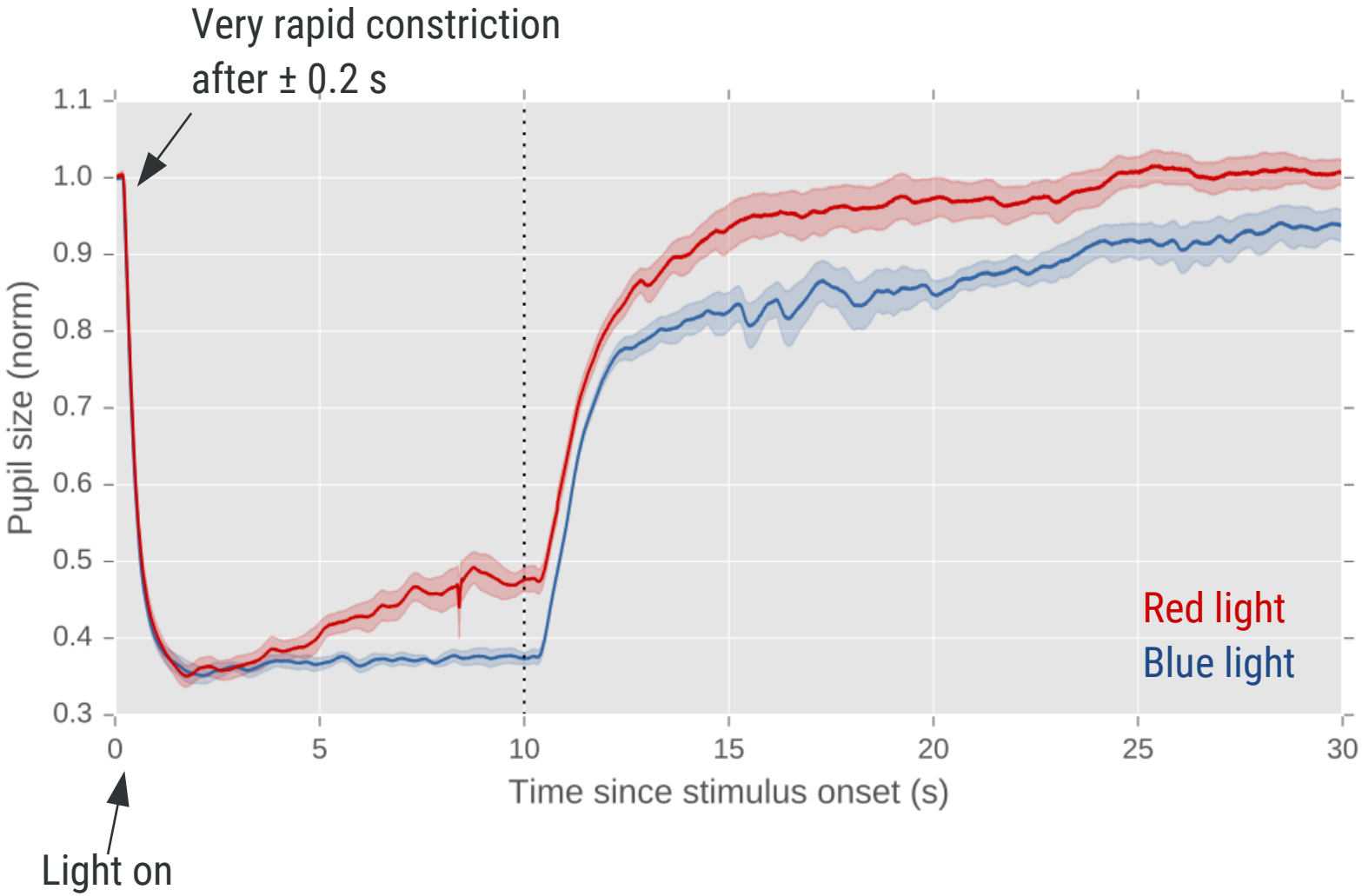

Rapid constriction
Pupil size (norm)
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0
5
10
15
20
25
30
Time since cue (s)
Cue to focus nearby
Cue to focus far away

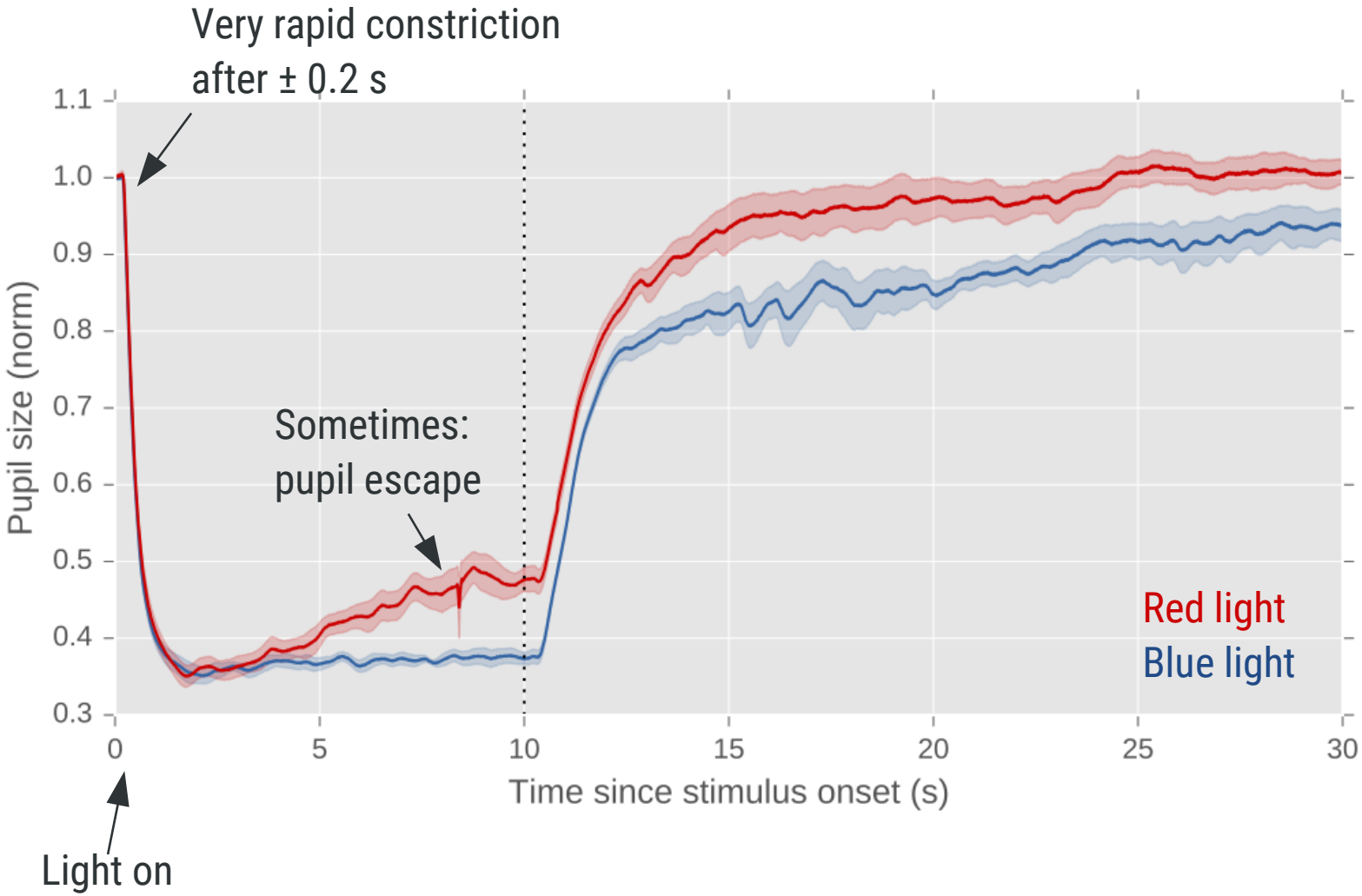

Rapid constriction
Gradual dilation
Pupil size (norm)
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0
5
10
15
20
25
30
Time since cue (s)
Cue to focus nearby
Cue to focus far away

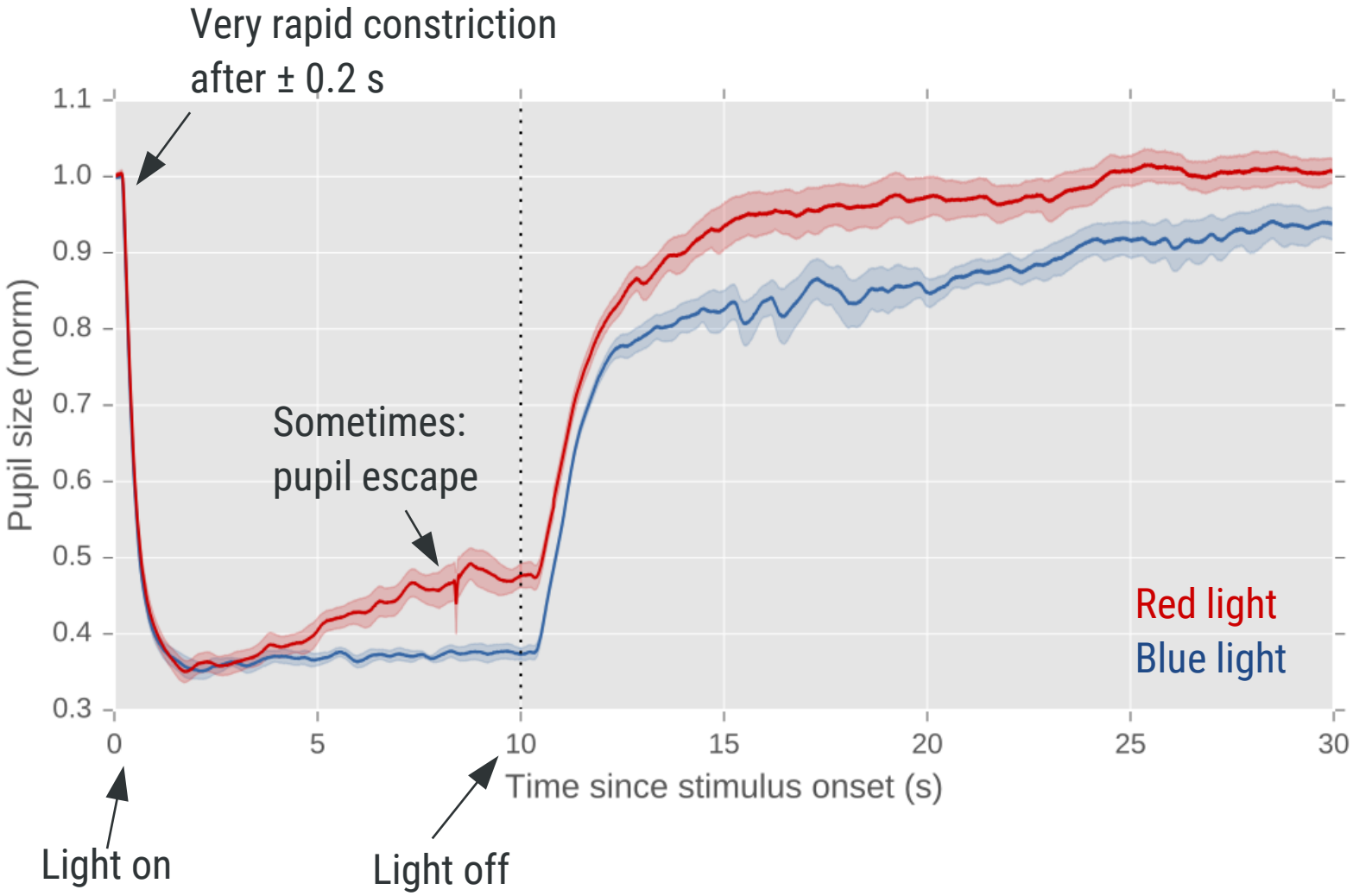

Light.

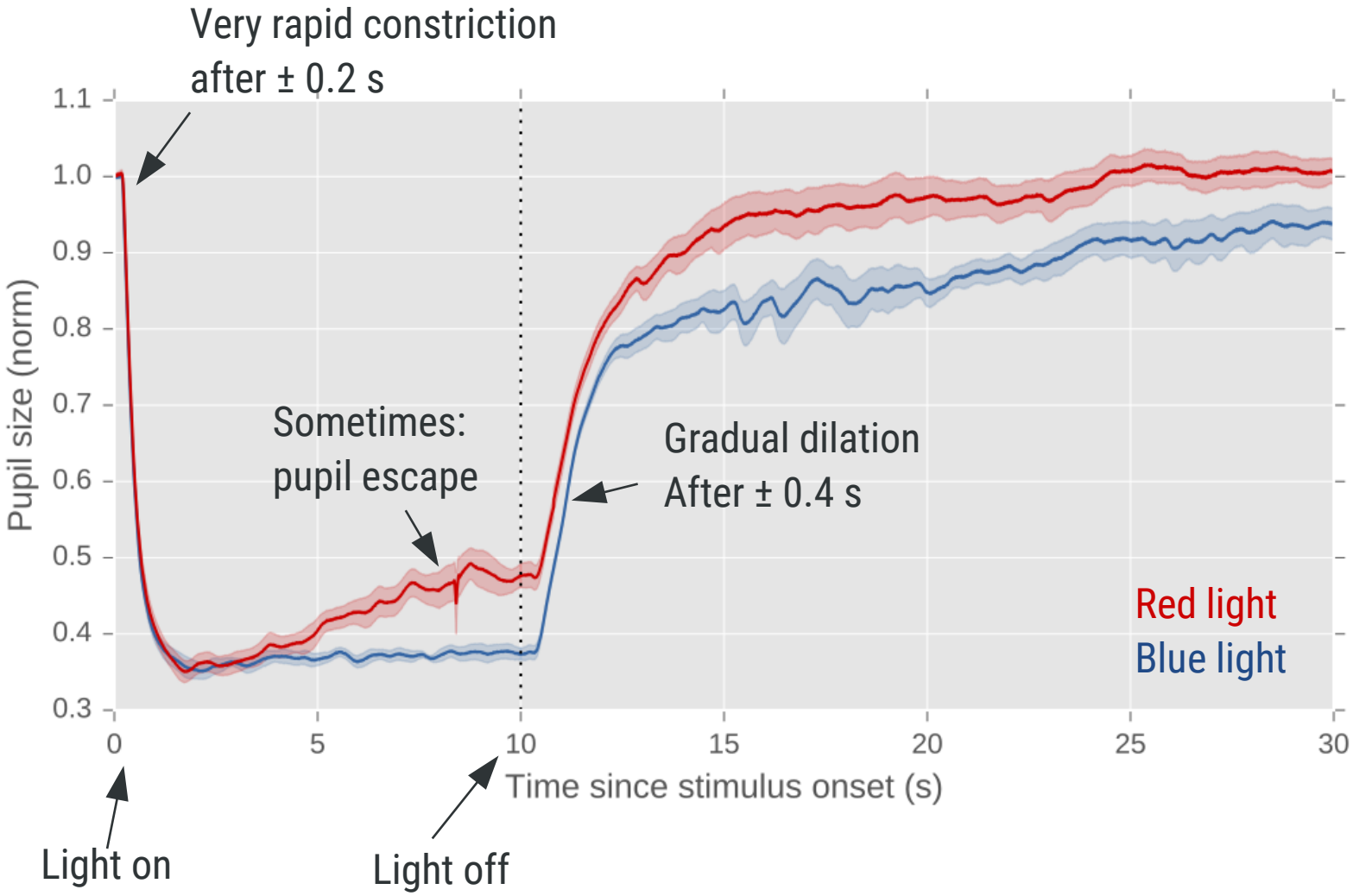

1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
Pupil size (norm)
0
5
10
15
20
25
30
Time since stimulus onset (s)
Red light
Blue light

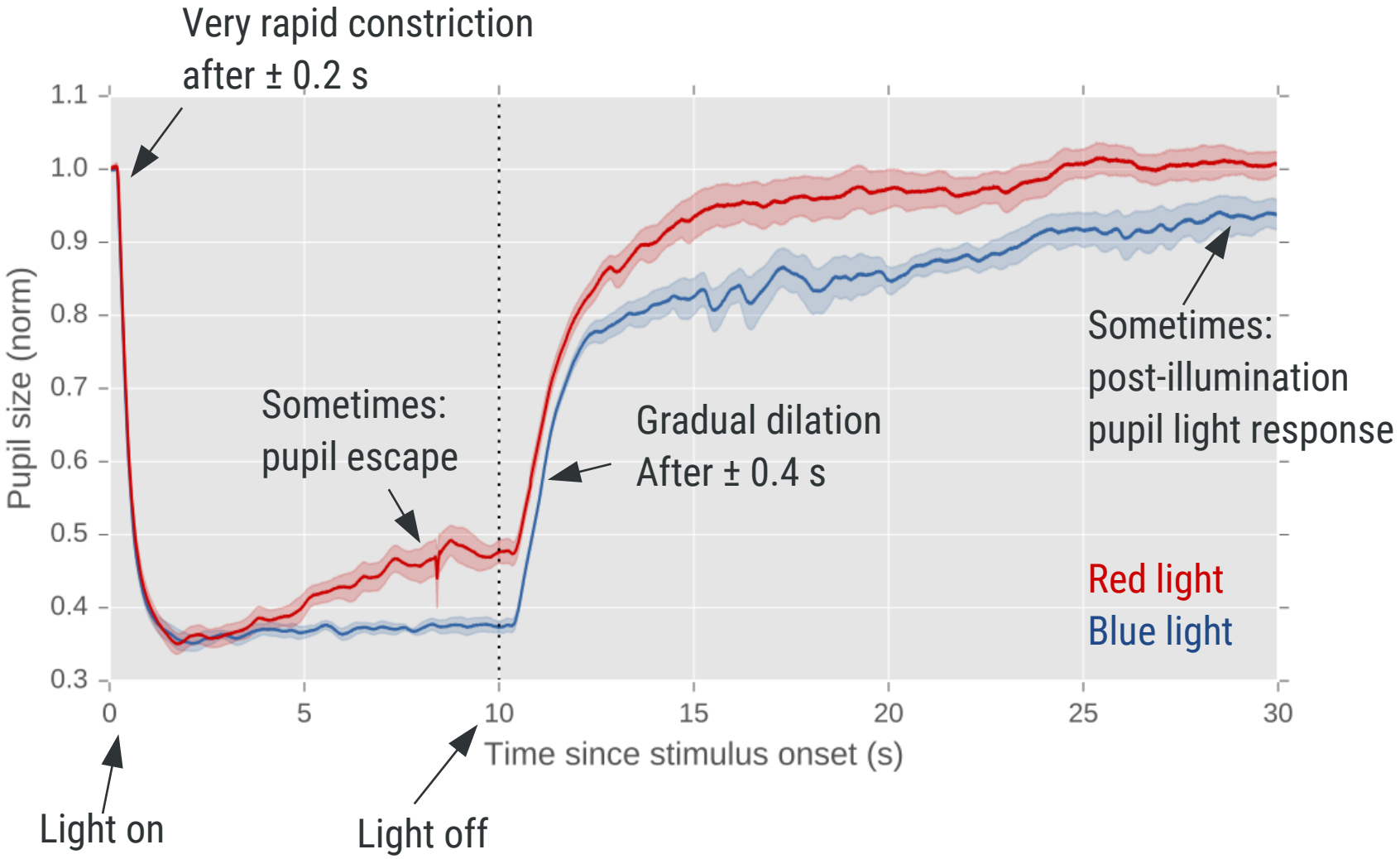

1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
Pupil size (norm)
0
5
10
15
20
25
30
Time since stimulus onset (s)
Red light
Blue light
Light on

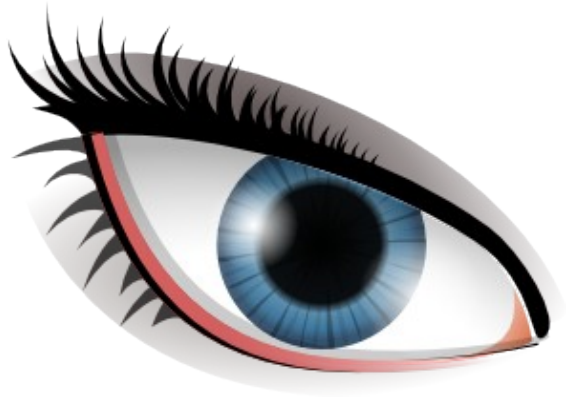

Very rapid constriction
after ± 0.2 s
Pupil size (norm)
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0
5
10
15
20
25
30
Time since stimulus onset (s)
Red light
Blue light
Light on

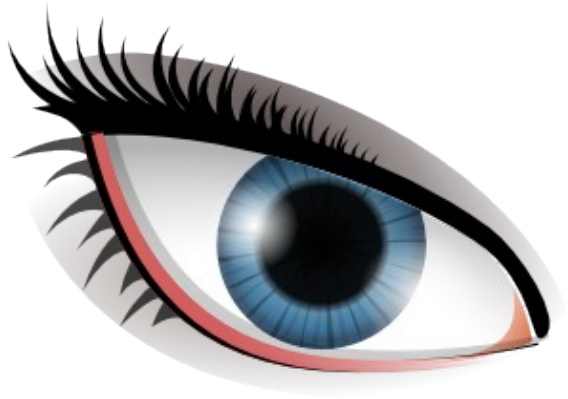

Very rapid constriction
after ± 0.2 s
Sometimes:
pupil escape
Light on
Red light
Blue light
Pupil size (norm)
Time since stimulus onset (s)
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0
5
10
15
20
25
30


Very rapid constriction
after ± 0.2 s
Sometimes:
pupil escape
Red light
Blue light
Pupil size (norm)
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0
5
10
15
20
25
30
Time since stimulus onset (s)
Light on
Light off

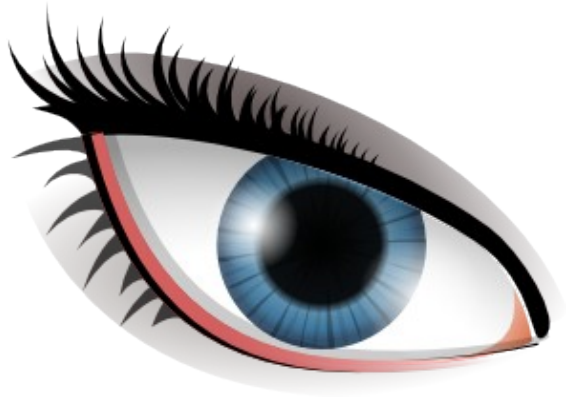

Very rapid constriction
after ± 0.2 s
Sometimes:
pupil escape
Gradual dilation
After ± 0.4 s
Red light
Blue light
Pupil size (norm)
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0
5
10
15
20
25
30
Time since stimulus onset (s)
Light on
Light off


Very rapid constriction
after ± 0.2 s
Sometimes:
pupil escape
Gradual dilation
After ± 0.4 s
Sometimes:
post-illumination
pupil light response
Red light
Blue light
Pupil size (norm)
Time since stimulus onset (s)
Light on
Light off



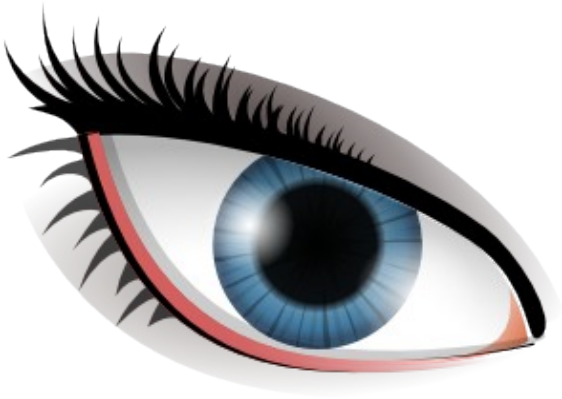


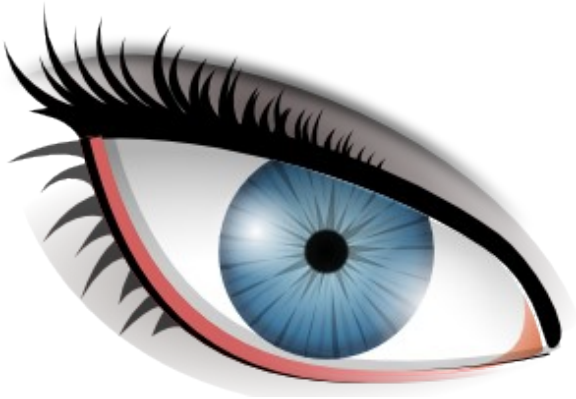
Captures lots of light



Captures lots of light

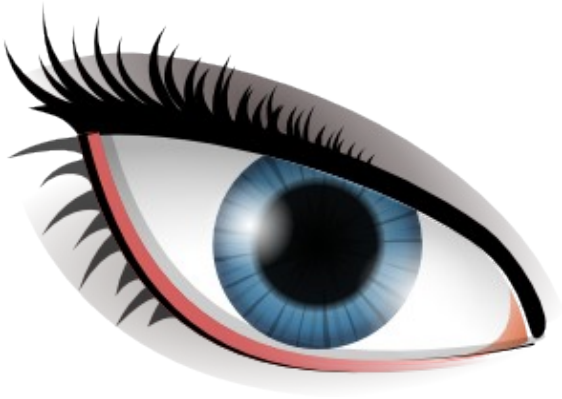
Has lots of optical distortions

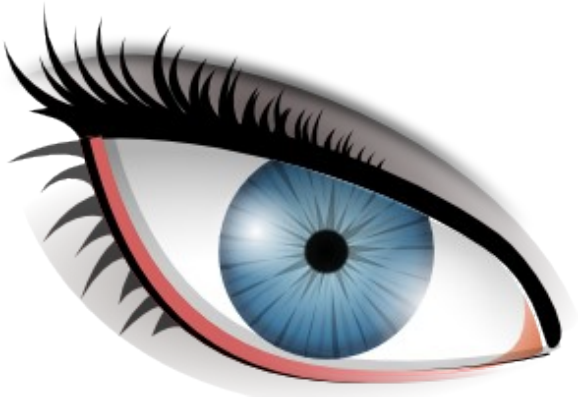




Captures lots of light

Has lots of optical distortions

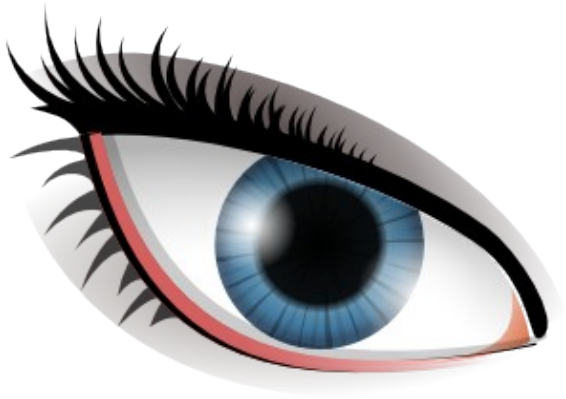


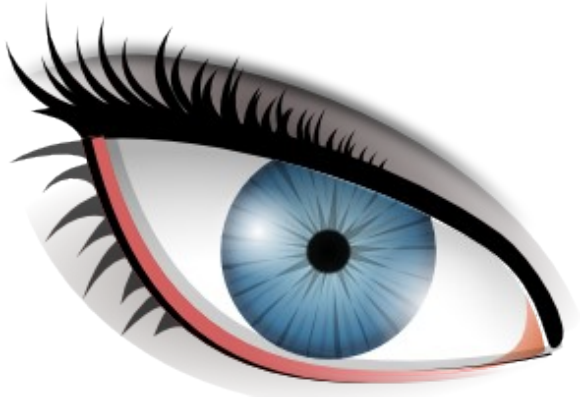


Captures lots of light

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

[1] Reviewed in Mathôt & Van der Stigchel (2015)

The pupil light response

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- Recent studies show cognitive influences[1]

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- Today: The pupillary light response in

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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

[1] Reviewed in Mathôt & Van der Stigchel (2015)

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

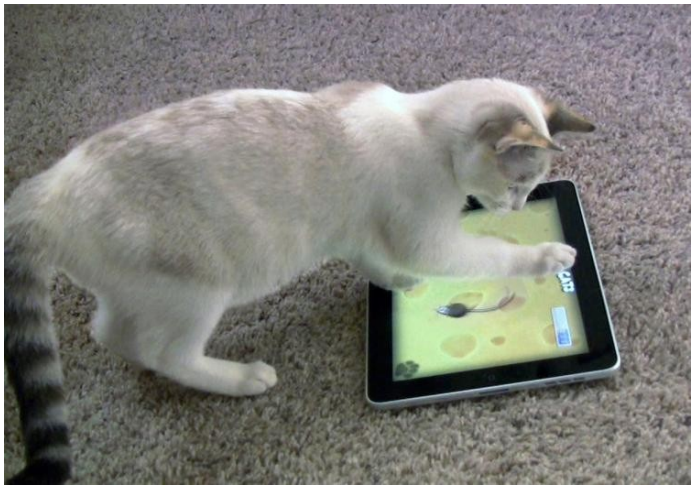
[1] Reviewed in Mathôt & Van der Stigchel (2015)

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

[1] Reviewed in Mathôt & Van der Stigchel (2015)

The pupillary light response and visual attention



Mathôt, Dalmaijer, Grainger, & Van der Stigchel (2014)
http://doi.org/10.1167/14.14.7

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

[1] Yantis & Jonides (1984)

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

[1] Yantis & Jonides (1984)

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

[1] Yantis & Jonides (1984)

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]

[1] Posner and Cohen (1984) [2] Klein (2000)

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]

[1] Posner and Cohen (1984) [2] Klein (2000)

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

[1] Posner and Cohen (1984) [2] Klein (2000)

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:

[1] Posner and Cohen (1984) [2] Klein (2000)

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?

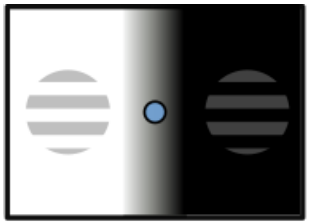
[1] Posner and Cohen (1984) [2] Klein (2000)

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?

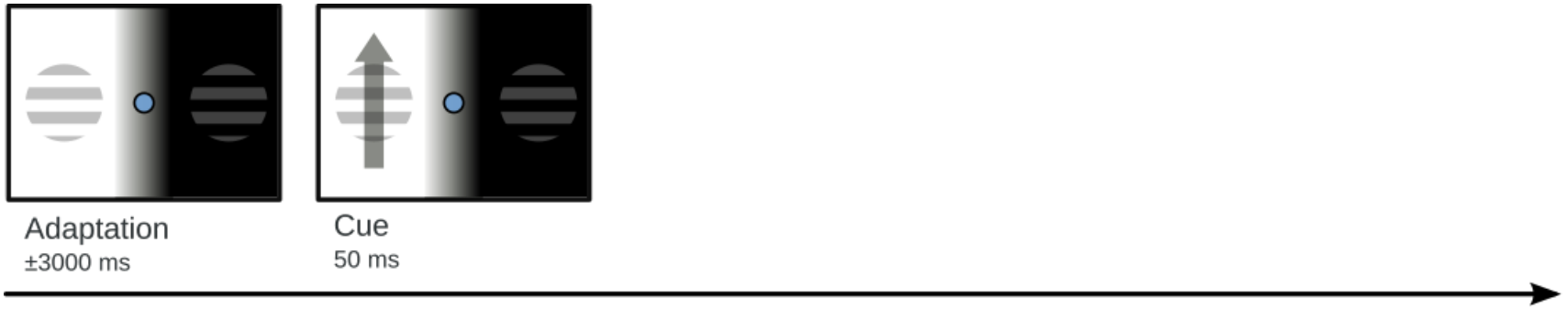
[1] Posner and Cohen (1984) [2] Klein (2000)

Methods

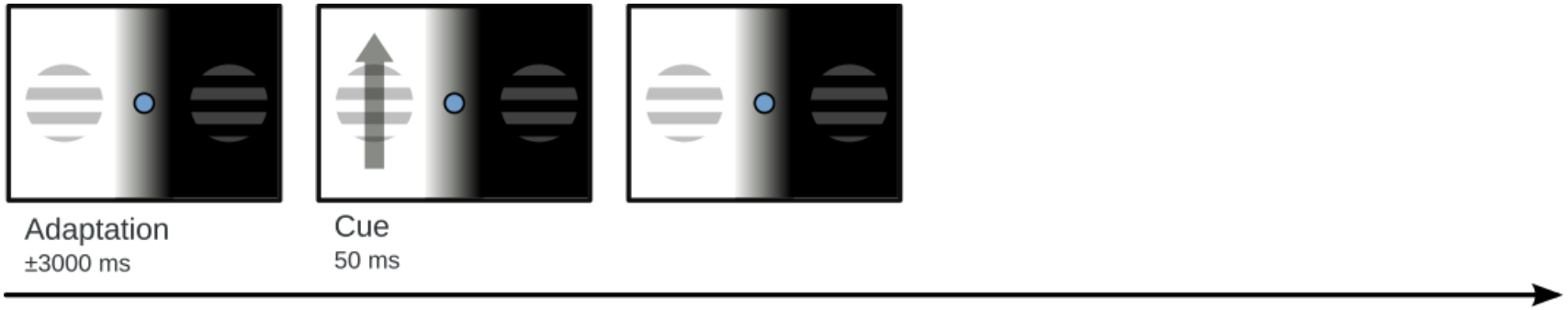


Adaptation
±3000 ms

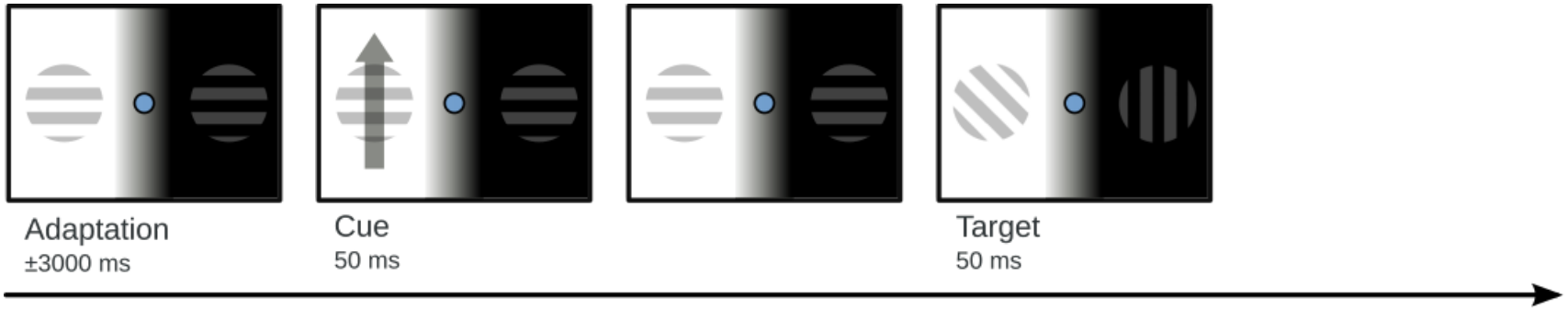
Methods



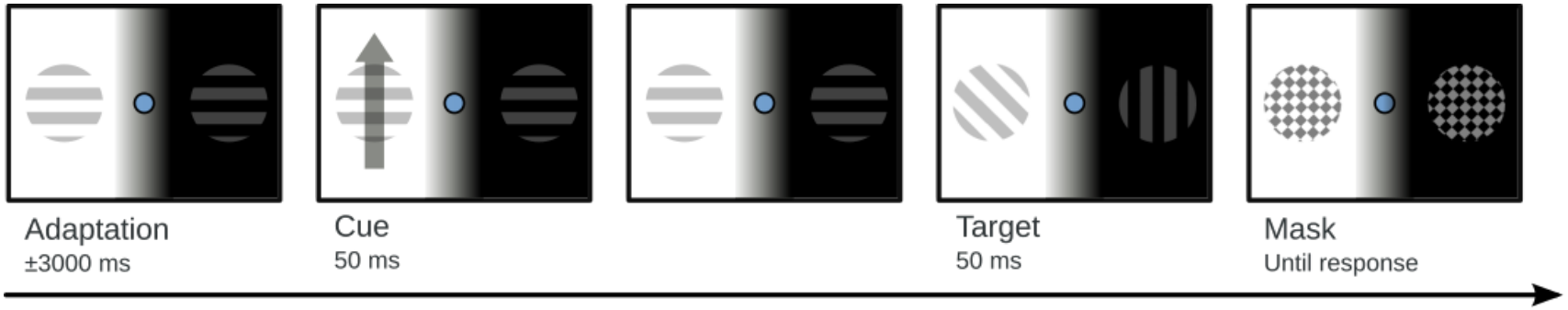
Methods



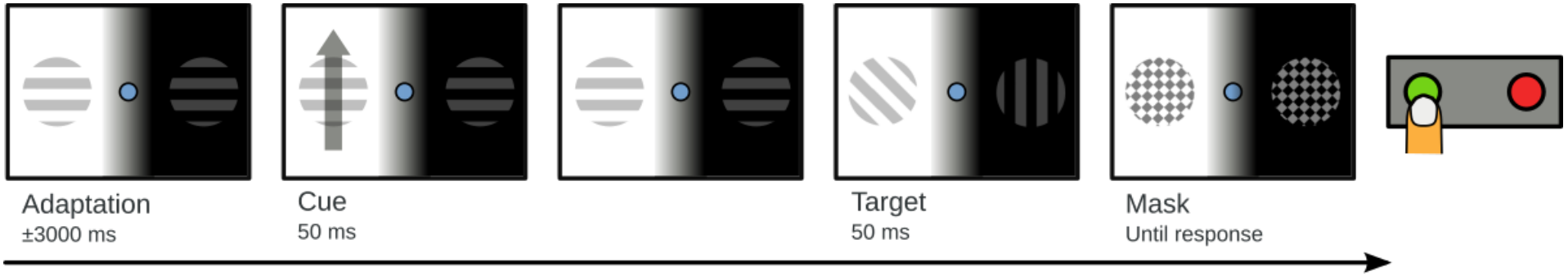
Methods



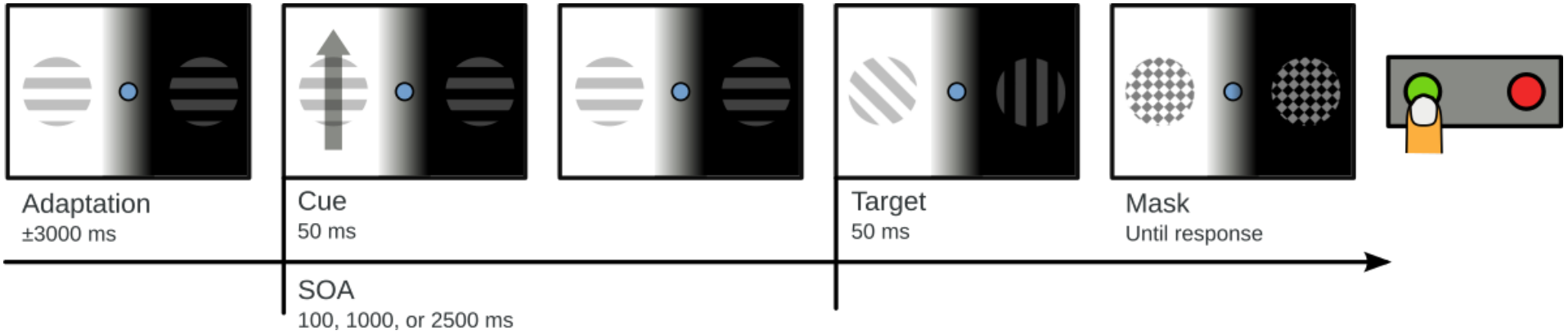
Methods


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

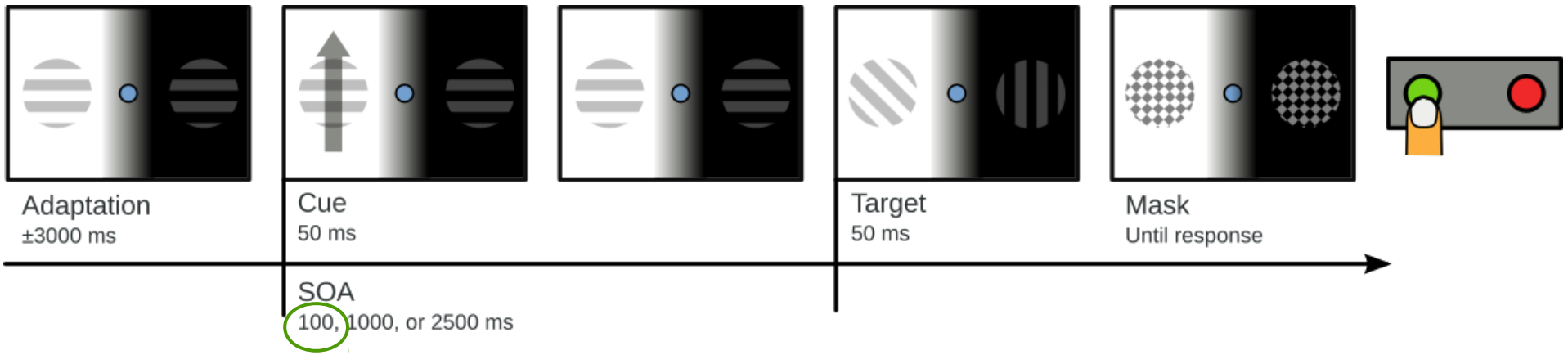
Methods


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

Methods

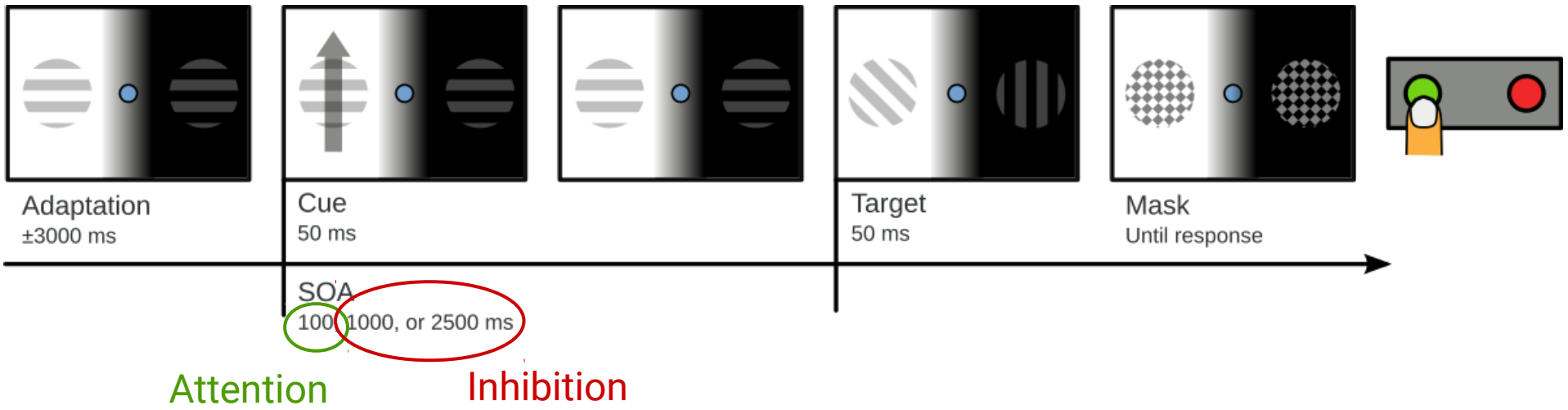

Adaptation
±3000 ms
Cue
50 ms
SOA
100, 1000, or 2500 ms
Target
50 ms
Mask
Until response

Methods

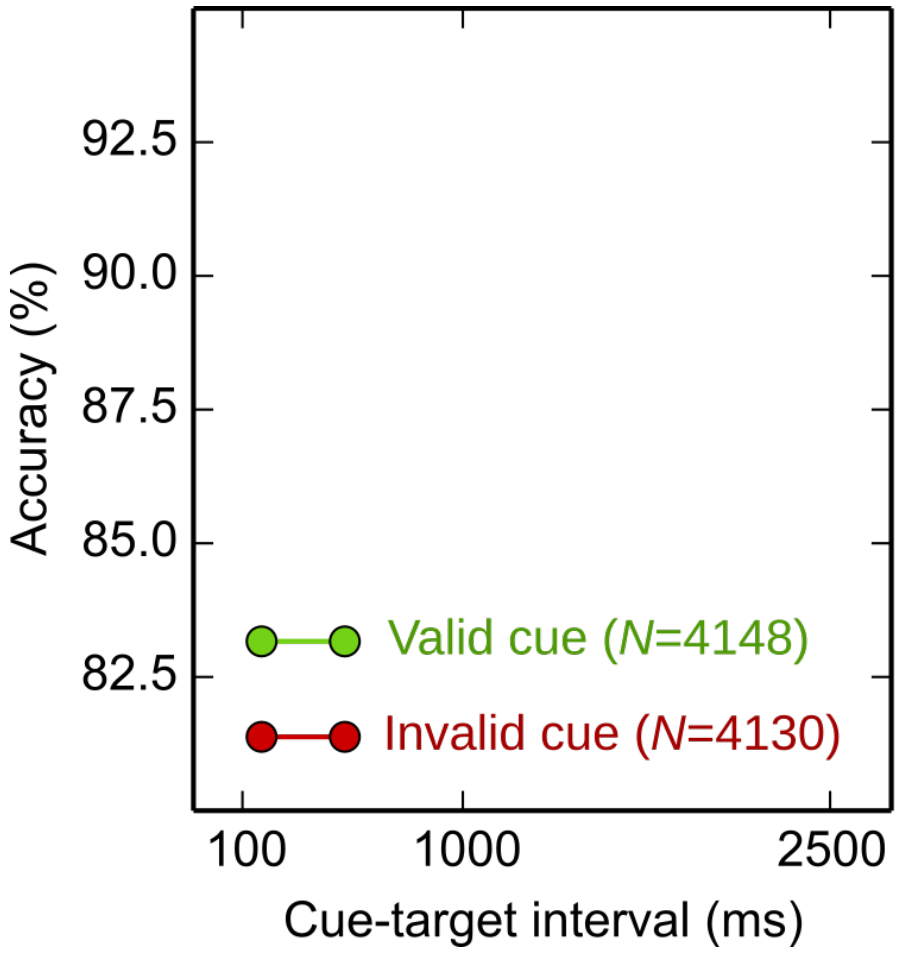


Attention

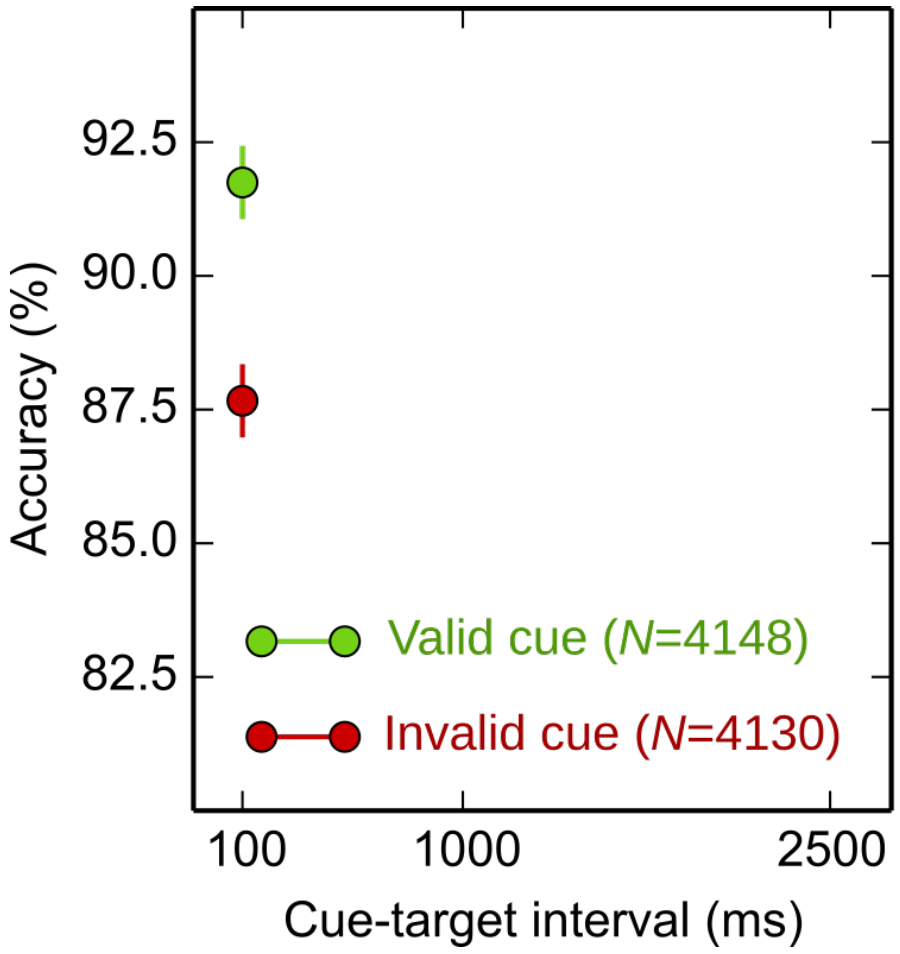
Methods


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

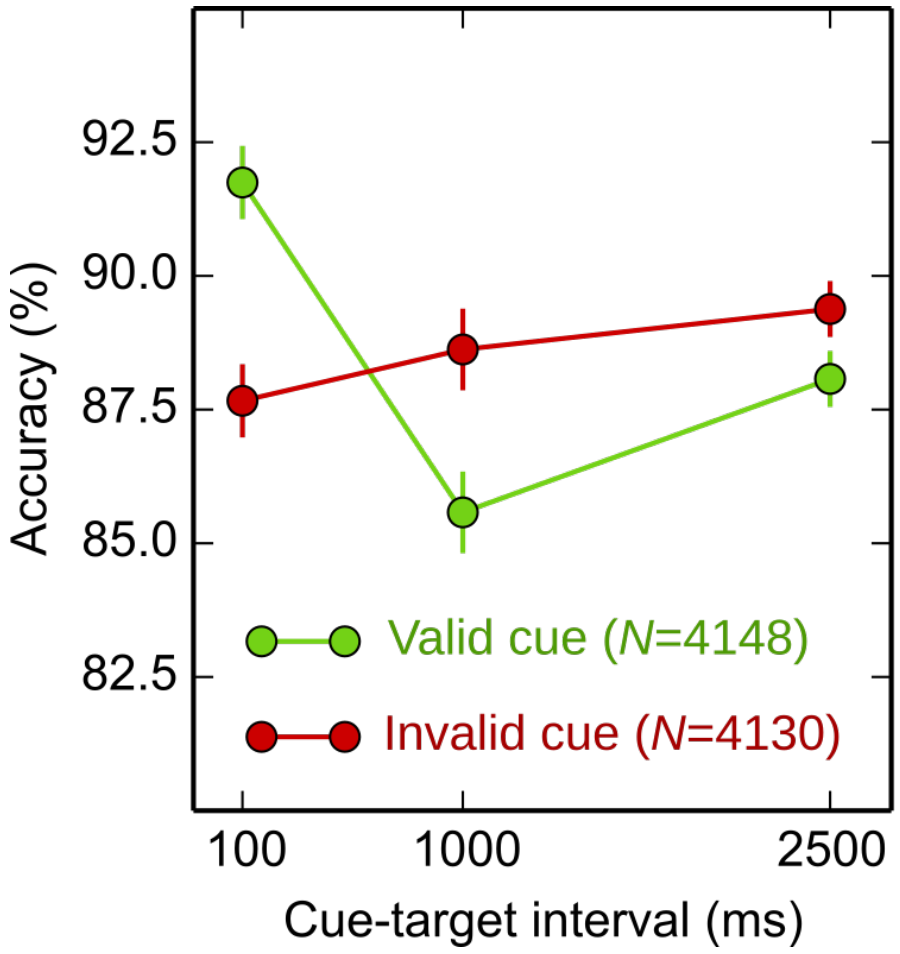
Results


92.5
90.0
87.5
85.0
82.5
Accuracy (%)
Valid cue (N=4148)
Invalid cue (N=4130)
100
1000
2500
Cue-target interval (ms)

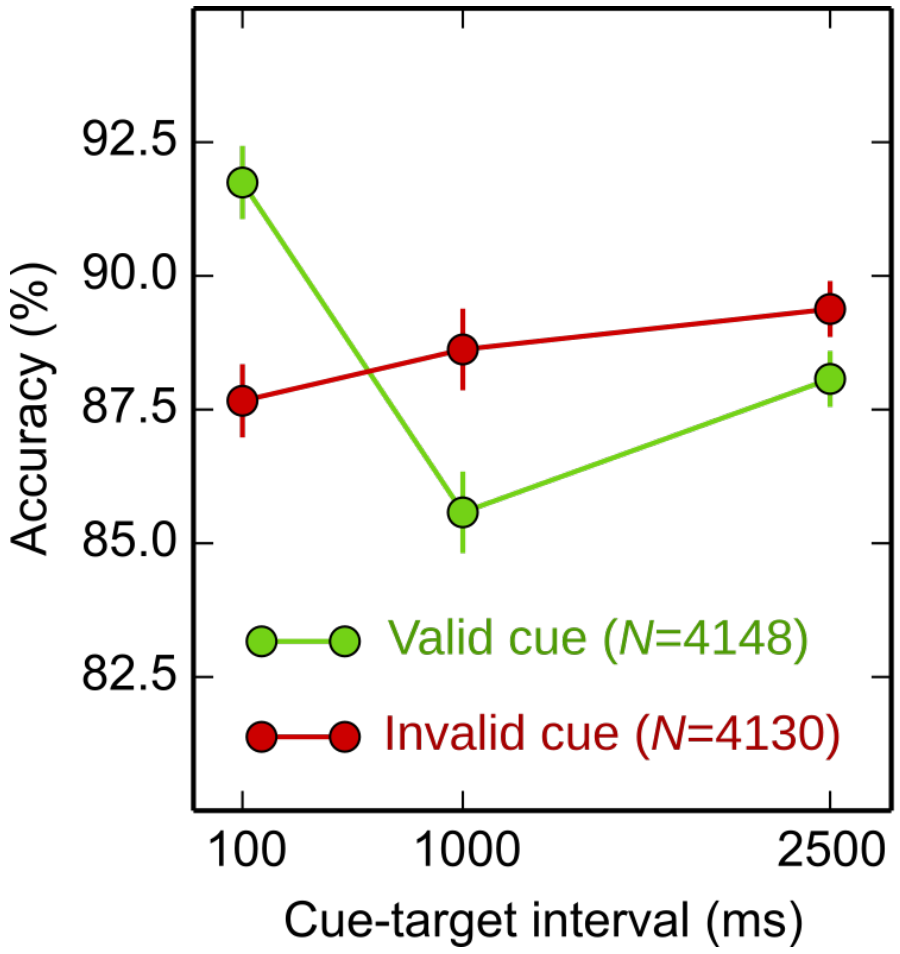
Results

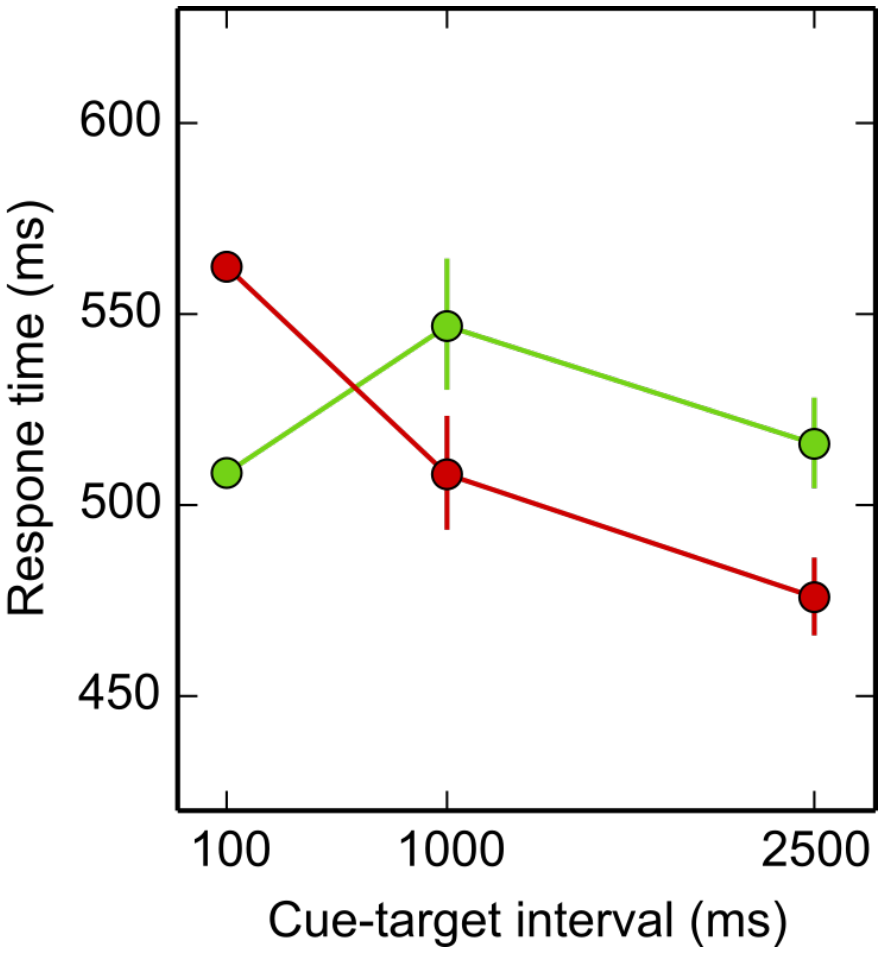

92.5
90.0
87.5
85.0
82.5
Accuracy (%)
Valid cue (N=4148)
Invalid cue (N=4130)
100
1000
2500
Cue-target interval (ms)

Results


92.5
90.0
87.5
85.0
82.5
Accuracy (%)
Valid cue (N=4148)
Invalid cue (N=4130)
100
1000
2500
Cue-target interval (ms)

Results


92.5
90.0
87.5
85.0
82.5
Accuracy (%)
Valid cue (N=4148)
Invalid cue (N=4130)
100
1000
2500
Cue-target interval (ms)

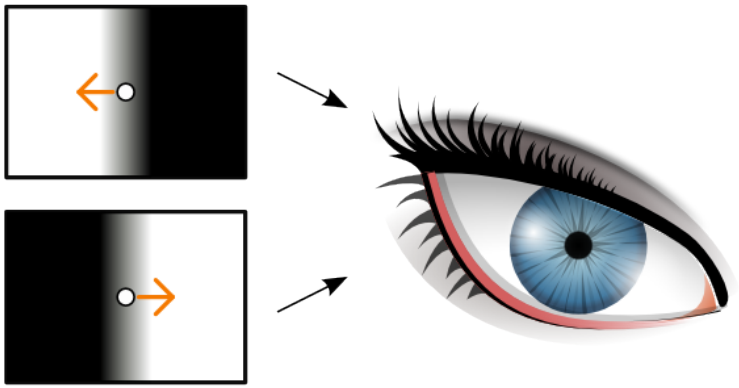

600
550
500
450
Respone time (ms)
100
1000
2500
Cue-target interval (ms)

Prediction

Attend bright

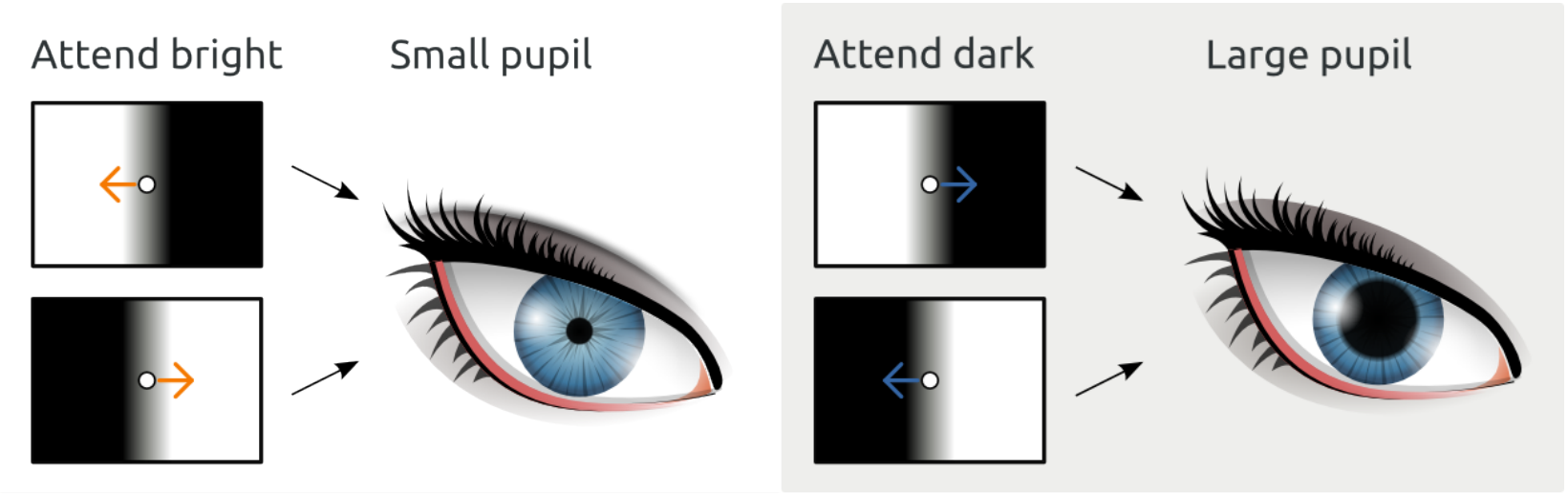
Small pupil

Shortly After cue



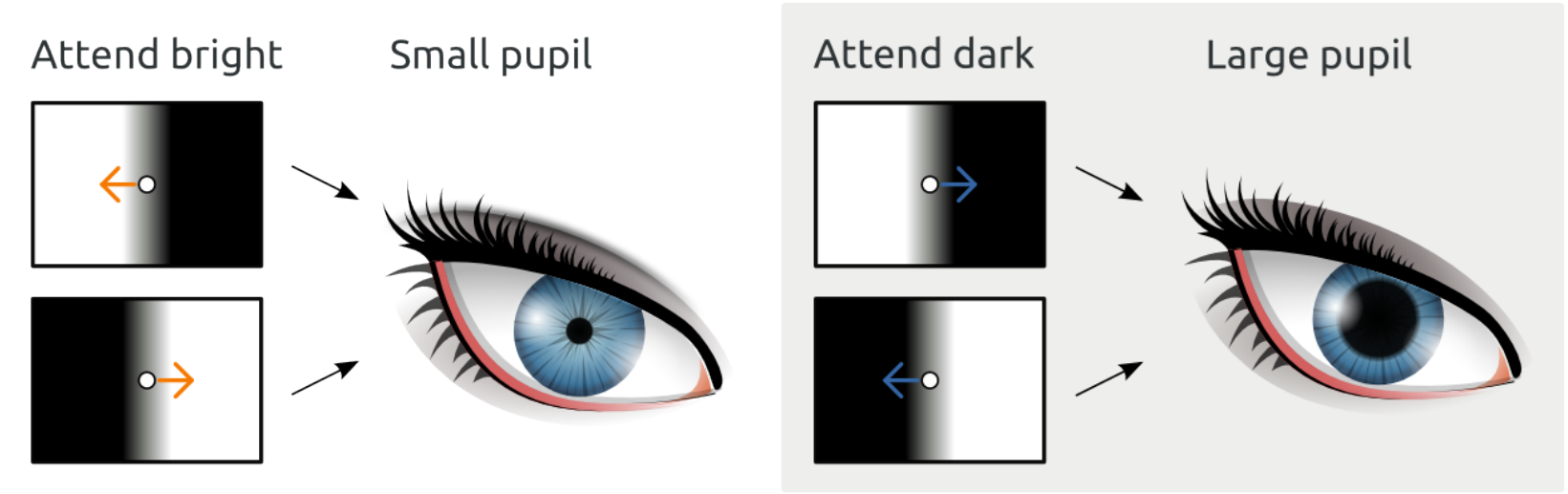
Prediction

Shortly After cue



Prediction

Shortly After cue



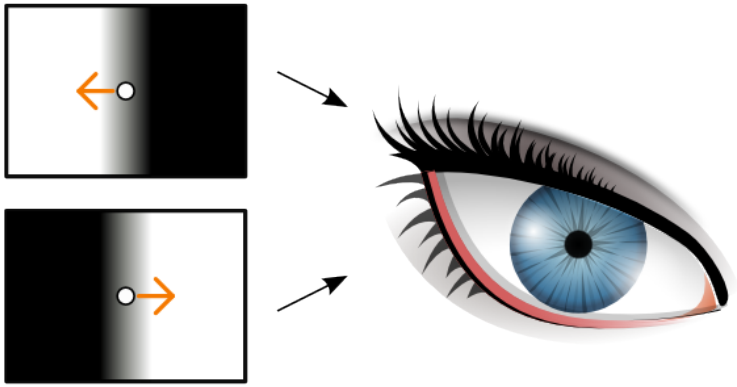
Longer after cue

Prediction

Shortly After cue

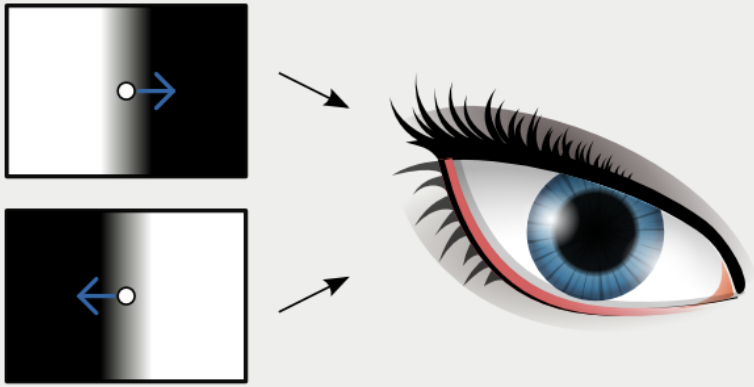
Attend bright

Small pupil



Attend dark

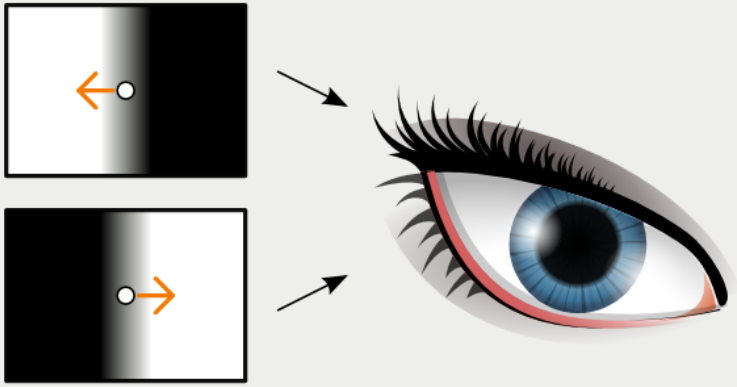
Large pupil



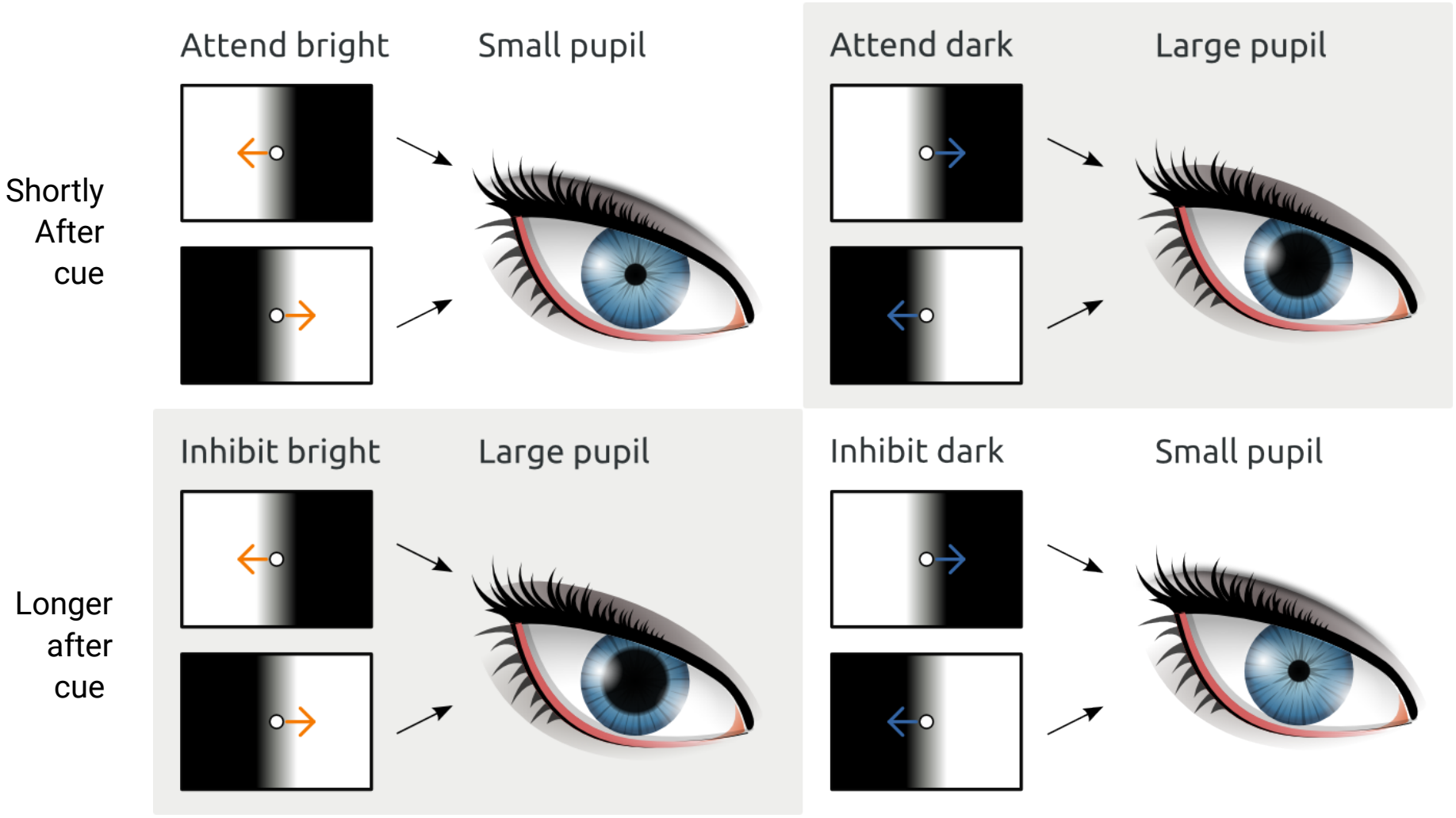
Longer after cue

Inhibit bright

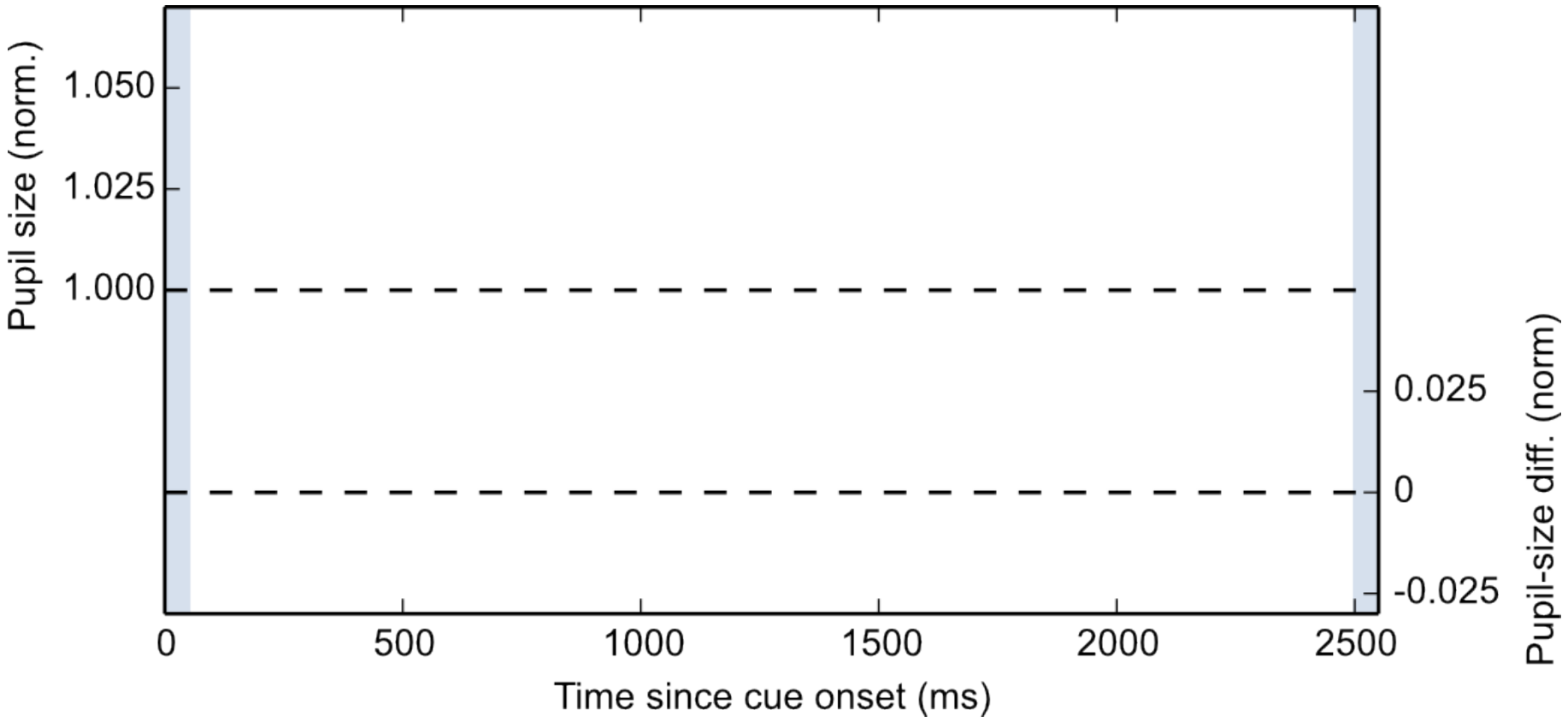
Large pupil



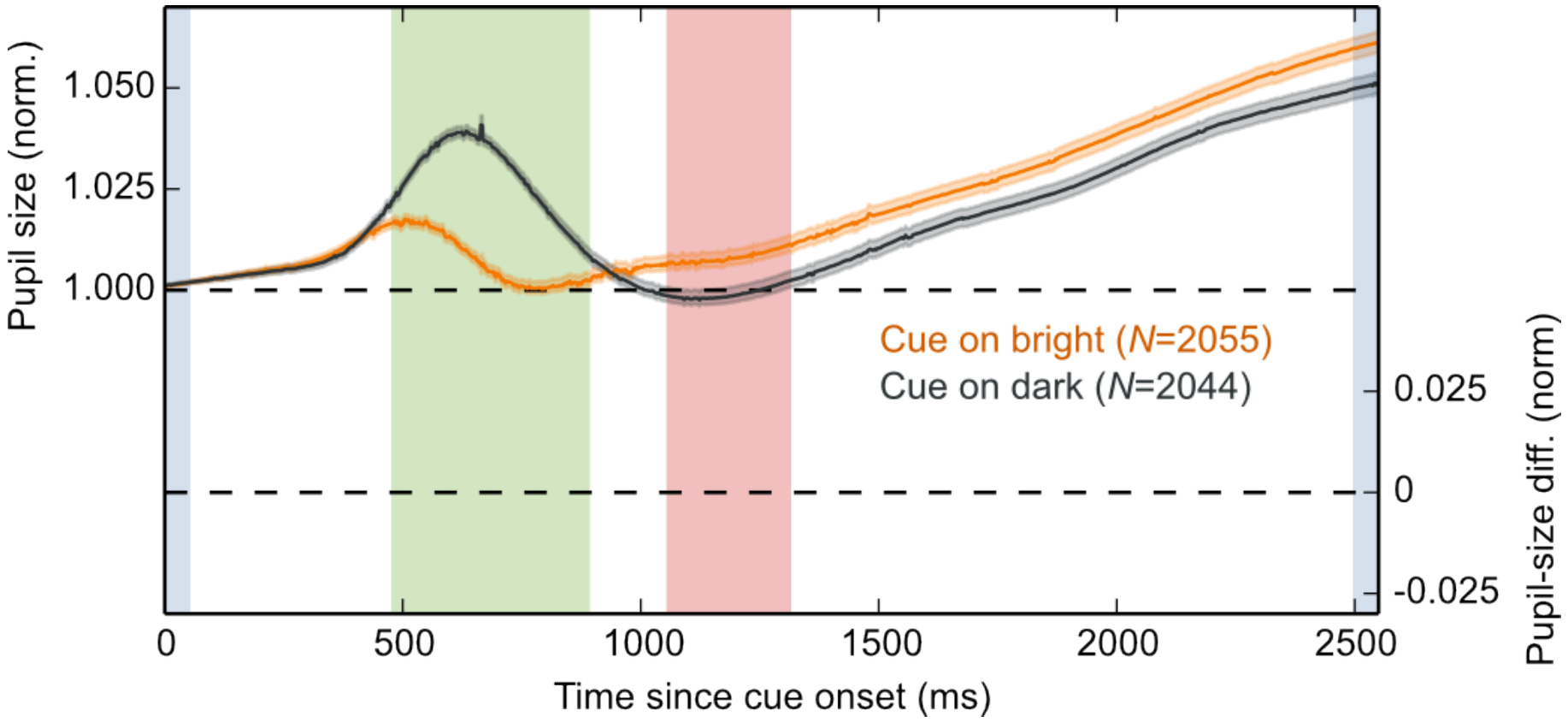
Prediction


Attend bright
Small pupil
Attend dark
Large pupil
Shortly After cue
Inhibit bright
Large pupil
Inhibit dark
Small pupil
Longer after cue

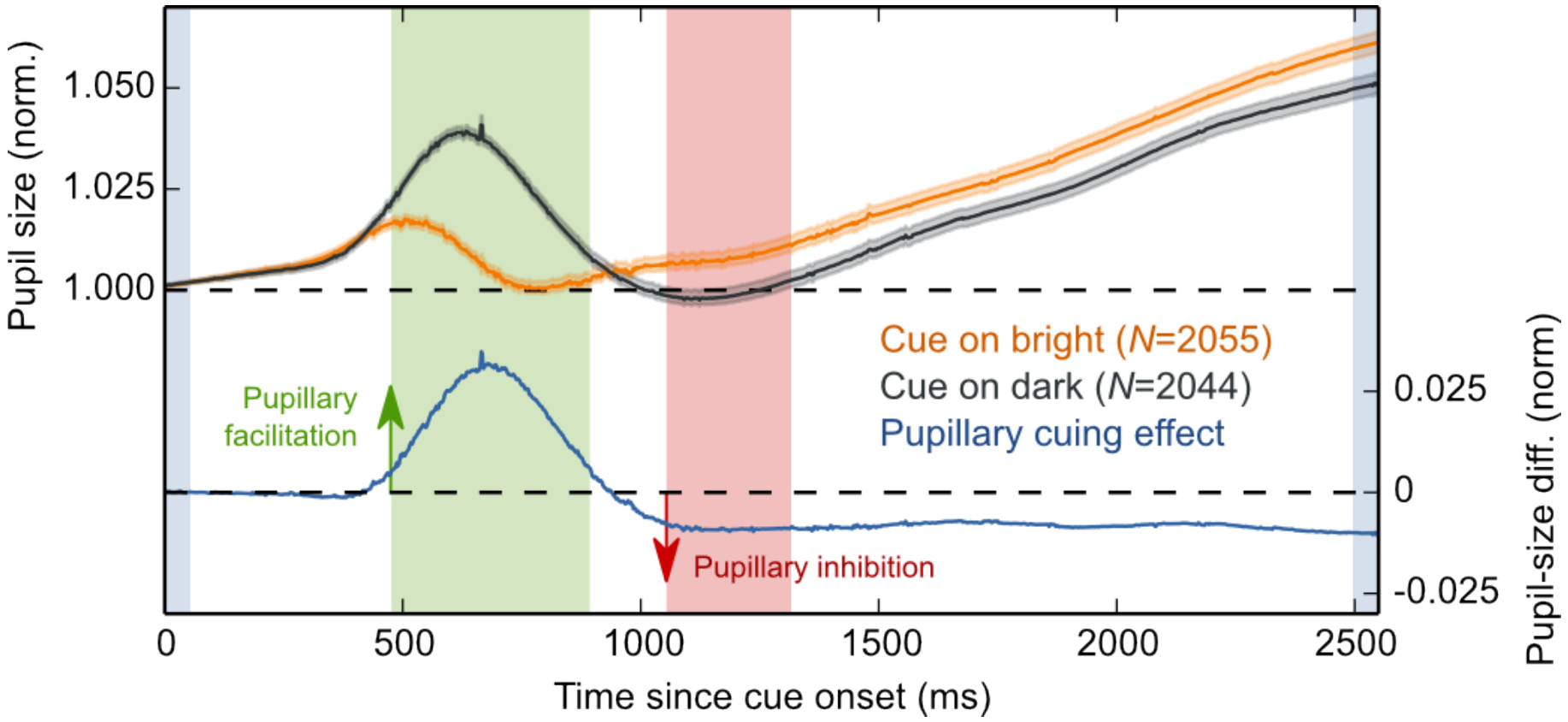
Results


Pupil size (norm.)
1.050
1.025
1.000
0.025
0
-0.025
Pupil-size diff. (norm)
0
500
1000
1500
2000
2500
Time since cue onset (ms)

Results


Pupil size (norm.)
1.050
1.025
1.000
Cue on bright (N=2055)
Cue on dark (N=2044)
0.025
0
-0.025
Pupil-size diff. (norm)
0
500
1000
1500
2000
2500
Time since cue onset (ms)

Results


Pupil size (norm.)
1.050
1.025
1.000
Cue on bright (N=2055)
Cue on dark (N=2044)
Pupillary cuing effect
Pupillary facilitation
Pupillary inhibition
0.025
0
-0.025
Pupil-size diff. (norm)
0
500
1000
1500
2000
2500
Time since cue onset (ms)

Interim discussion

Interim discussion

- Pupil size reflects reflexive attention

Interim discussion

- Pupil size reflects reflexive attention

  … and subsequent inhibition of return

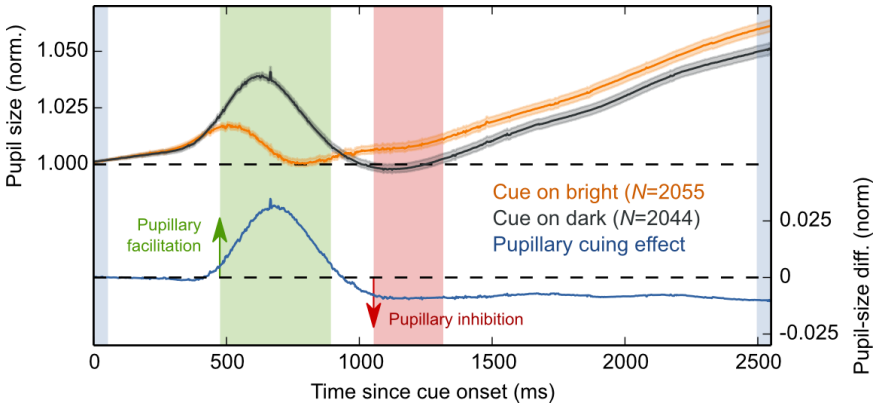
Interim discussion

- Pupil size reflects reflexive attention

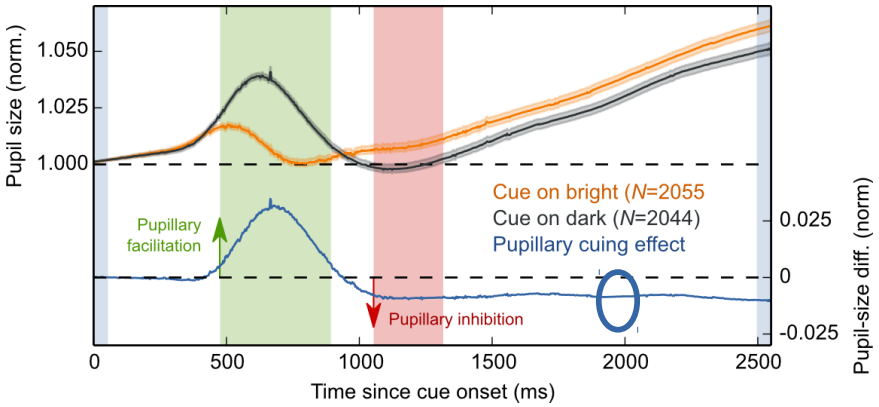
  … and subsequent inhibition of return

- Can we link this to behavior?
  - Strong behavioral effect → Strong pupillary effect

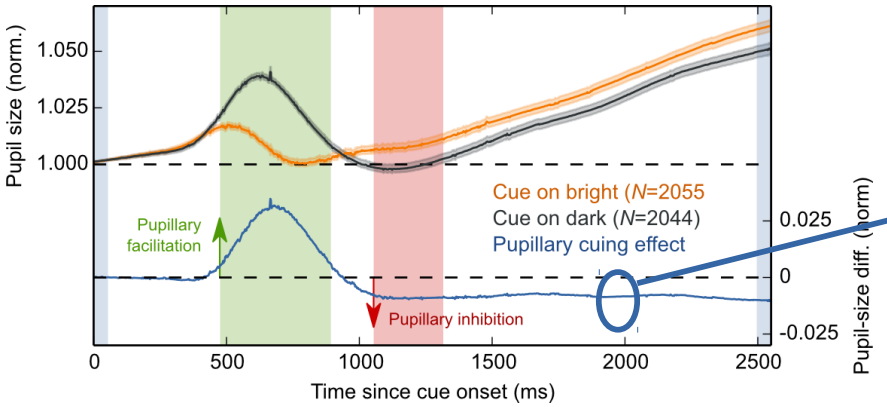
Results

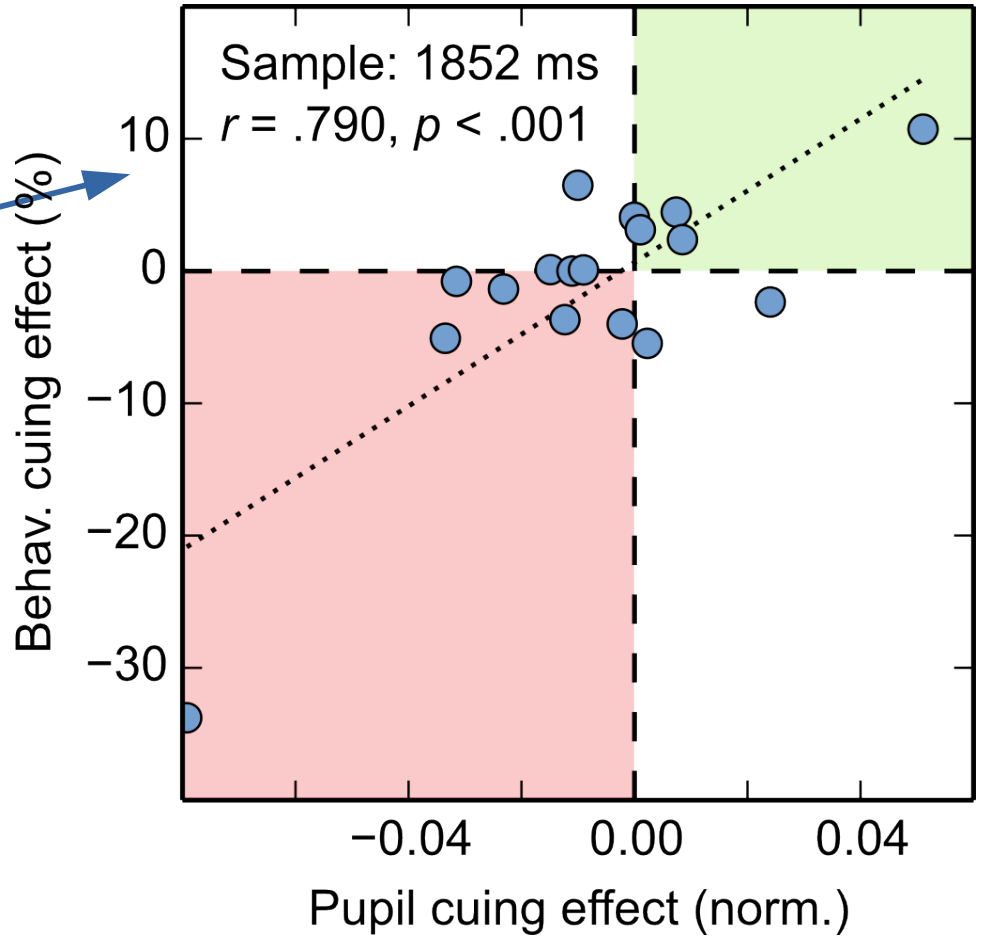

Pupil size (norm.)
1.050
1.025
1.000
Cue on bright (N=2055
Cue on dark (N=2044)
Pupillary cuing effect
Pupillary facilitation
Pupillary inhibition
0.025
0
-0.025
Pupil-size diff. (norm)
0
500
1000
1500
2000
2500
Time since cue onset (ms)

Results

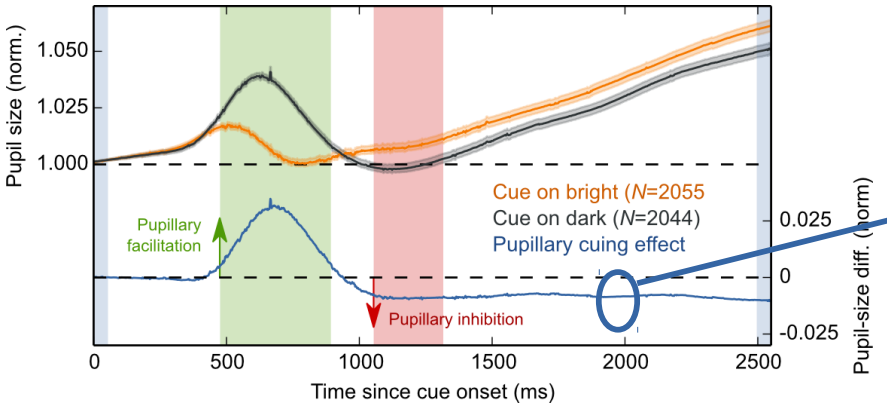

Pupil size (norm.)
1.050
1.025
1.000
Cue on bright (N=2055
Cue on dark (N=2044)
Pupillary cuing effect
Pupillary facilitation
Pupillary inhibition
0.025
0
-0.025
Pupil-size diff. (norm)
0
500
1000
1500
2000
2500
Time since cue onset (ms)

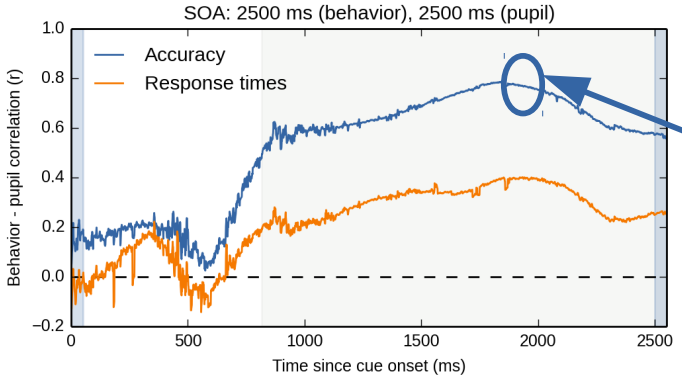
Results

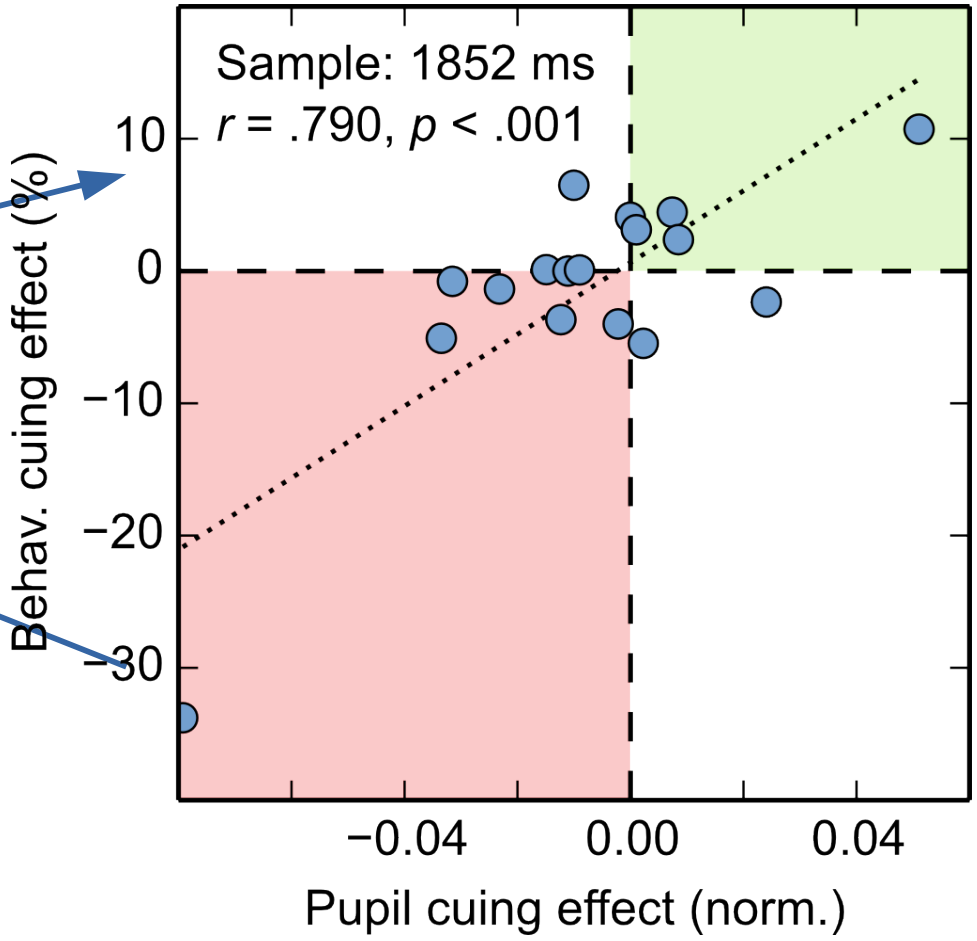

Pupil size (norm.)
1.050
1.025
1.000
Pupillary facilitation
Pupillary inhibition
Cue on bright (N=2055
Cue on dark (N=2044)
Pupillary cuing effect
0.025
0
-0.025
Pupil-size diff. (norm)
0
500
1000
1500
2000
2500
Time since cue onset (ms)


Sample: 1852 ms
r = .790, p < .001
Behav. cuing effect (%)
10
0
−10
−20
−30
−0.04
0.00
0.04
Pupil cuing effect (norm.)

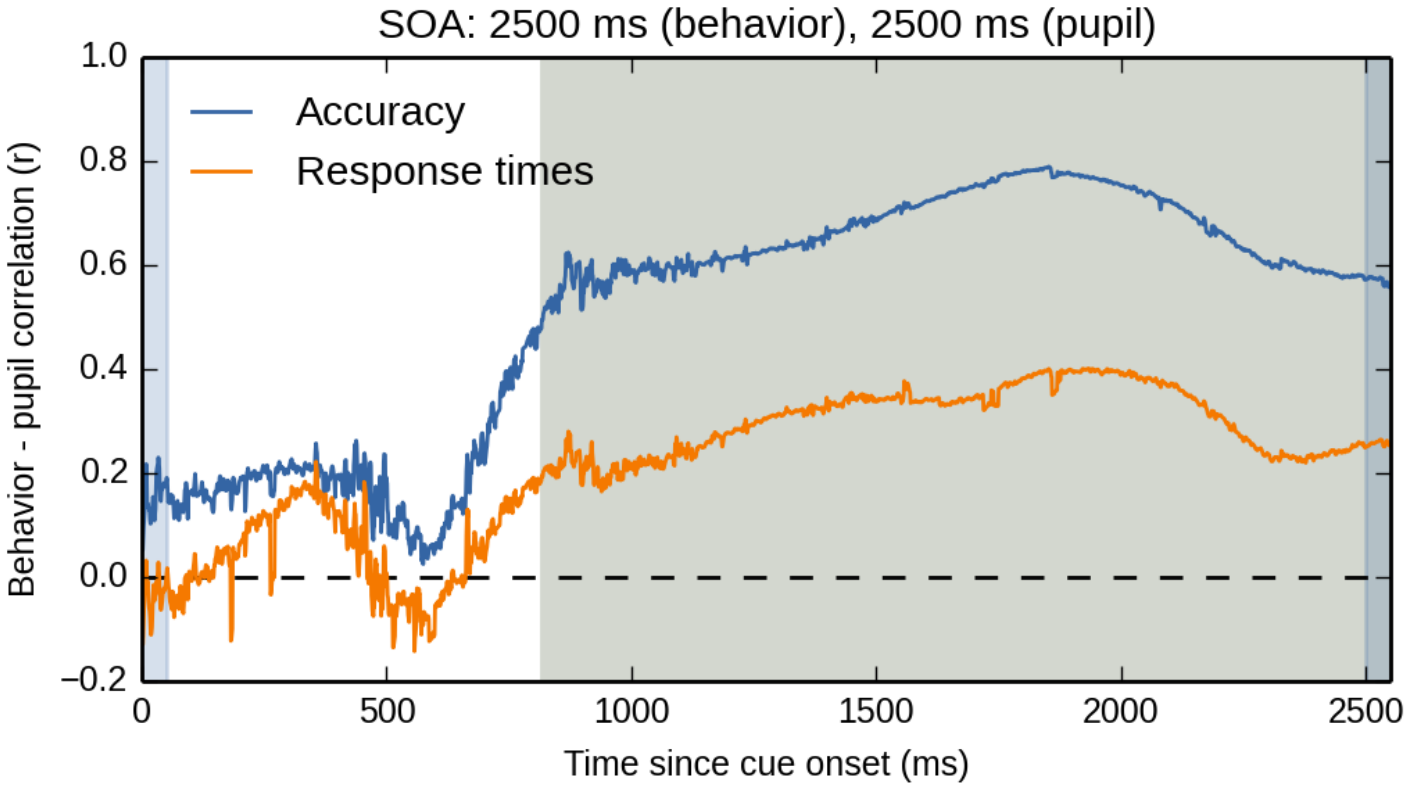
Results


Pupil size (norm.)
1.050
1.025
1.000
Cue on bright (N=2055
Cue on dark (N=2044)
Pupillary cuing effect
Pupillary facilitation
Pupillary inhibition
0.025
0
-0.025
Pupil-size diff. (norm)
0
500
1000
1500
2000
2500
Time since cue onset (ms)


SOA: 2500 ms (behavior), 2500 ms (pupil)
Accuracy
Response times
Behavior - pupil correlation (r)
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
0
500
1000
1500
2000
2500
Time since cue onset (ms)


Sample: 1852 ms
r = .790, p < .001
Behav. cuing effect (%)
10
0
−10
−20
−30
−0.04
0.00
0.04
Pupil cuing effect (norm.)

Results


SOA: 2500 ms (behavior), 2500 ms (pupil)
Accuracy
Response times
Behavior - pupil correlation (r)
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
0
500
1000
1500
2000
2500
Time since cue onset (ms)

Discussion

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- Pupil inhibition is related to behavioral inhibition of return

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  … suggesting that both reflect the same mechanism

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  … 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

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

[1] Olivers et al. (2006) [2] Van der Stigchel et al. (2007) [3] Postle (2006)

Attention and working memory

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

[1] Olivers et al. (2006) [2] Van der Stigchel et al. (2007) [3] Postle (2006)

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  - Things in working memory capture attention[1]
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- General idea:

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- General idea:
  - The same brain areas are used for:

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- General idea:
  - The same brain areas are used for:
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    - Attention

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  - 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

[1] Olivers et al. (2006) [2] Van der Stigchel et al. (2007) [3] Postle (2006)

Attention and working memory

- Attention and working memory are linked
  - Things in working memory capture attention[1]
  - Attention disrupts working memory[2]
- General idea:
  - The same brain areas are used for:
    - Visual perception
    - Attention
    - Working memory
  - “Emergent properties”[3]

[1] Olivers et al. (2006) [2] Van der Stigchel et al. (2007) [3] Postle (2006)

Attention and working memory

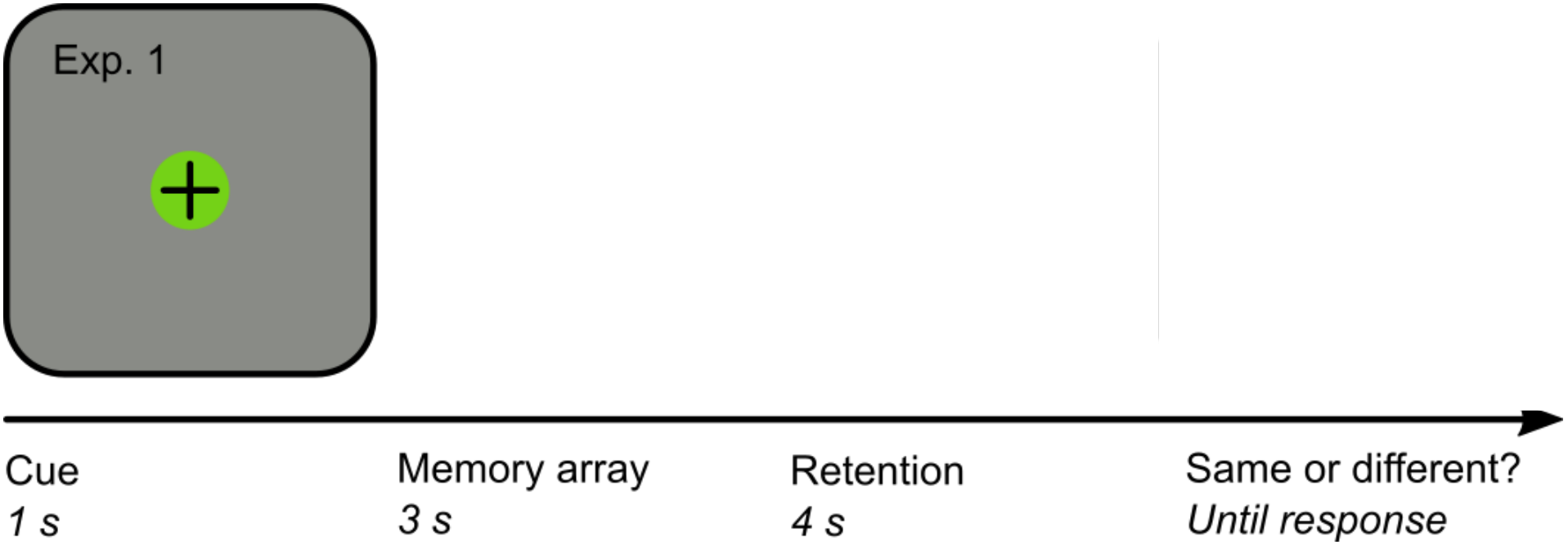
Attention and working memory

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

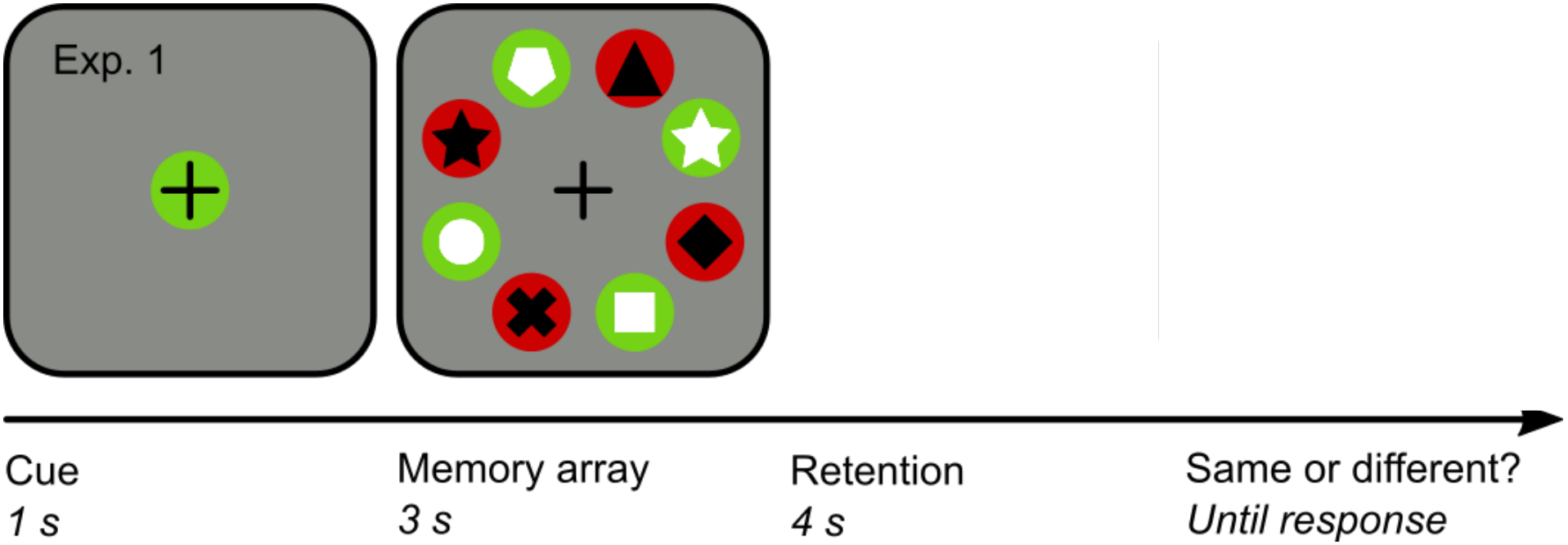
Attention and working memory

- 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?

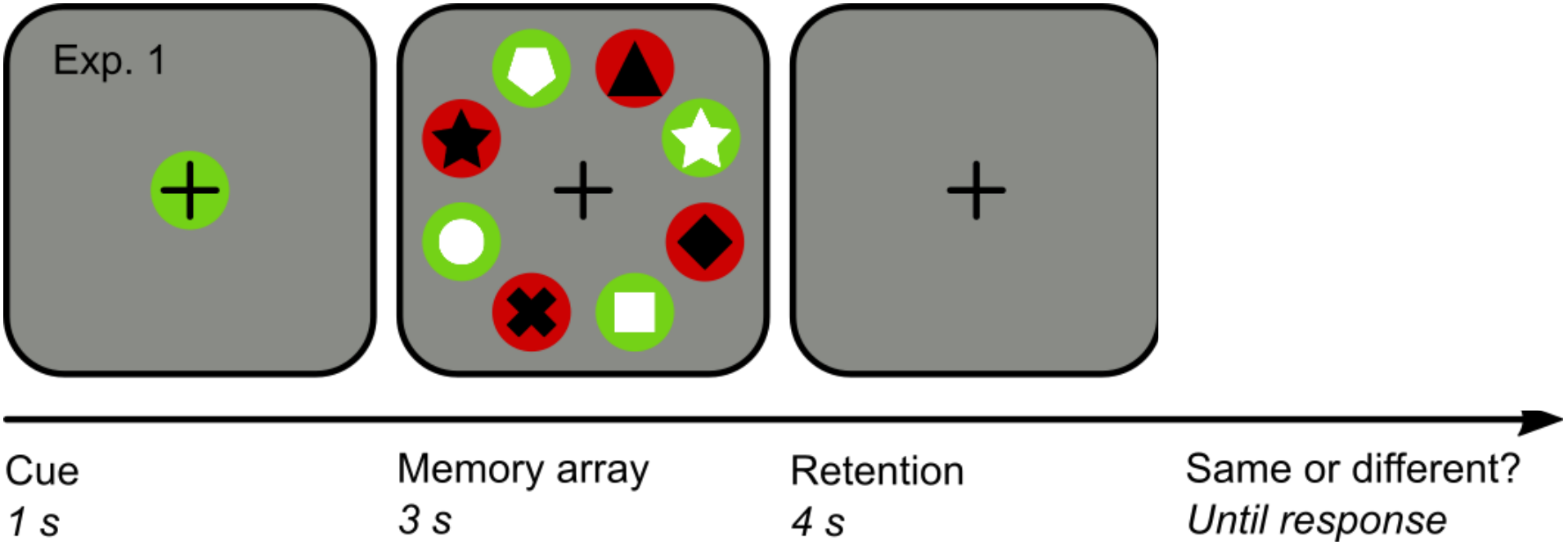
Paradigm


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

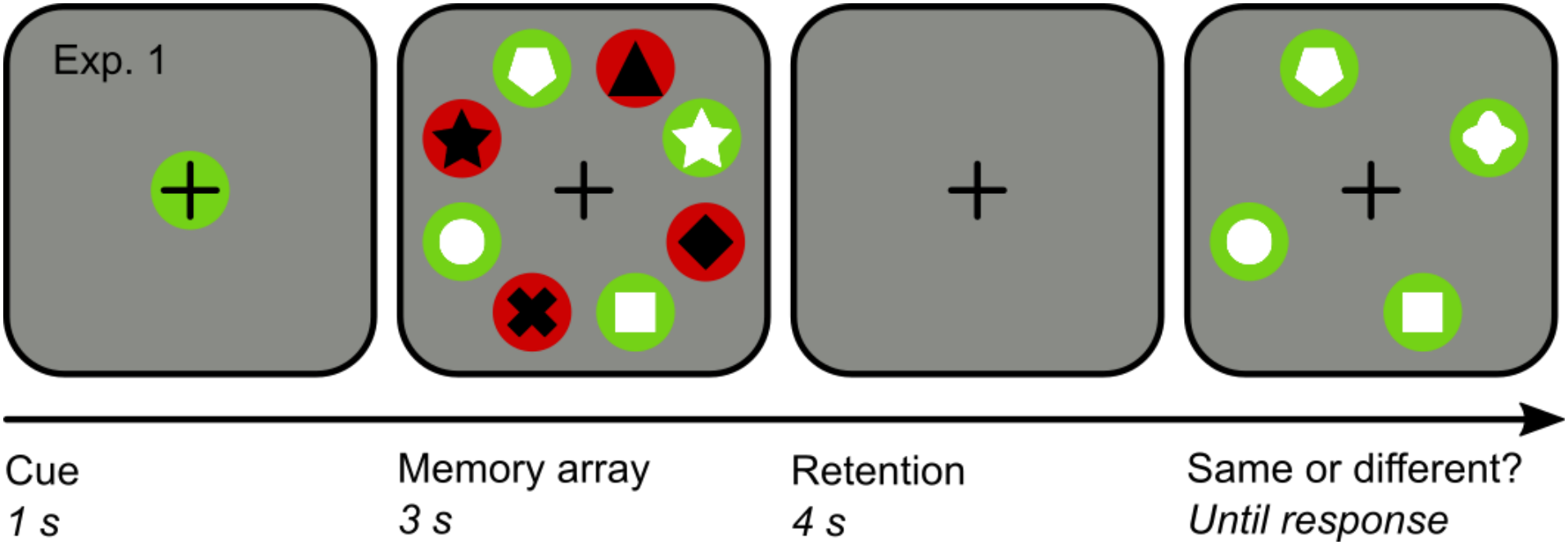
Paradigm


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

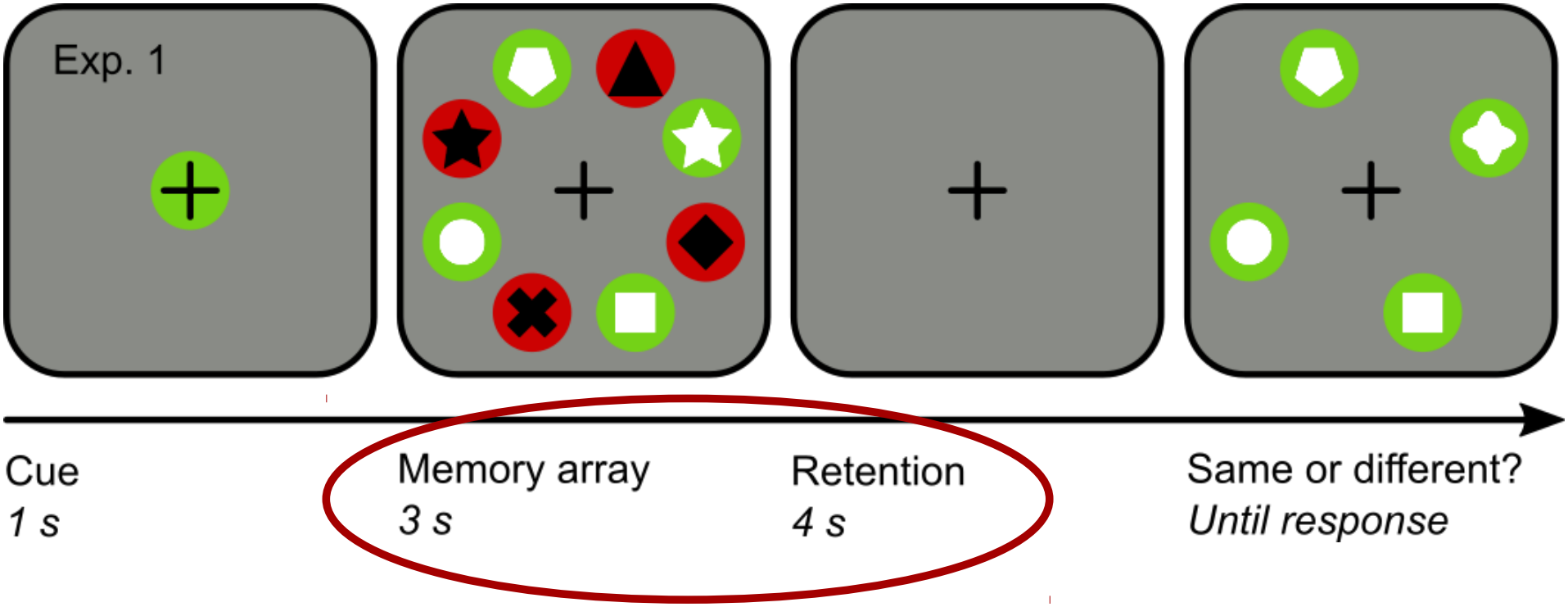
Paradigm


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

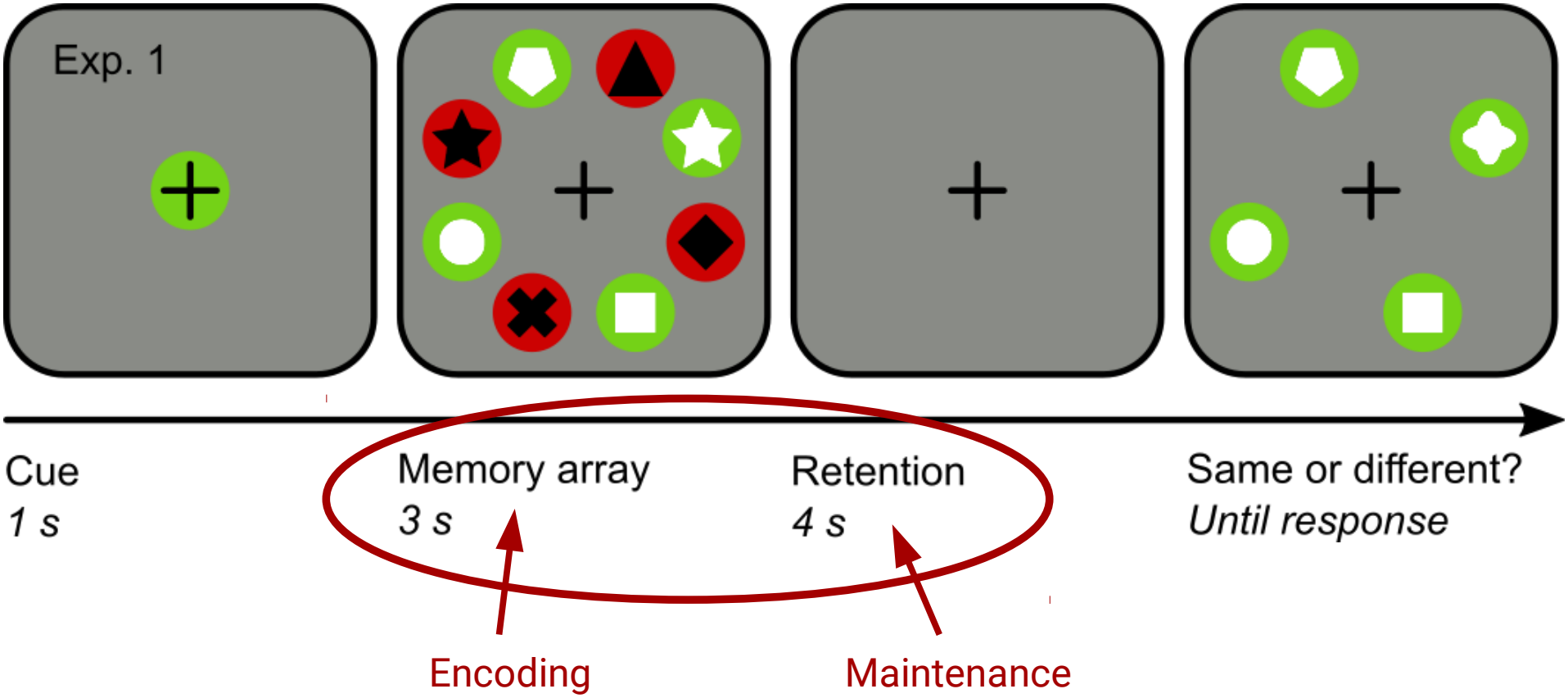
Paradigm


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

Paradigm

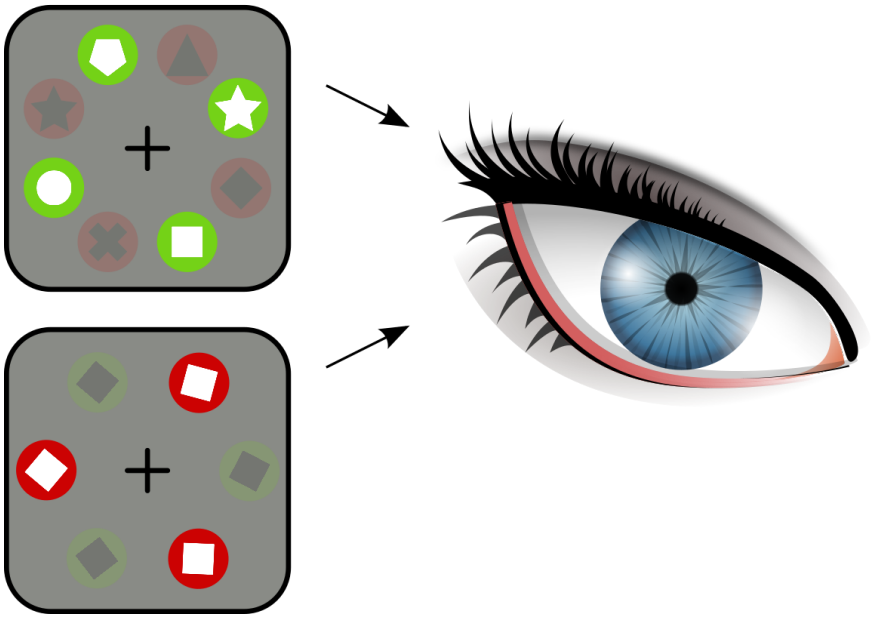

Exp. 1
Cue
1 s
Memory array
3 s
Retention
4 s
Same or different?
Until response

Paradigm

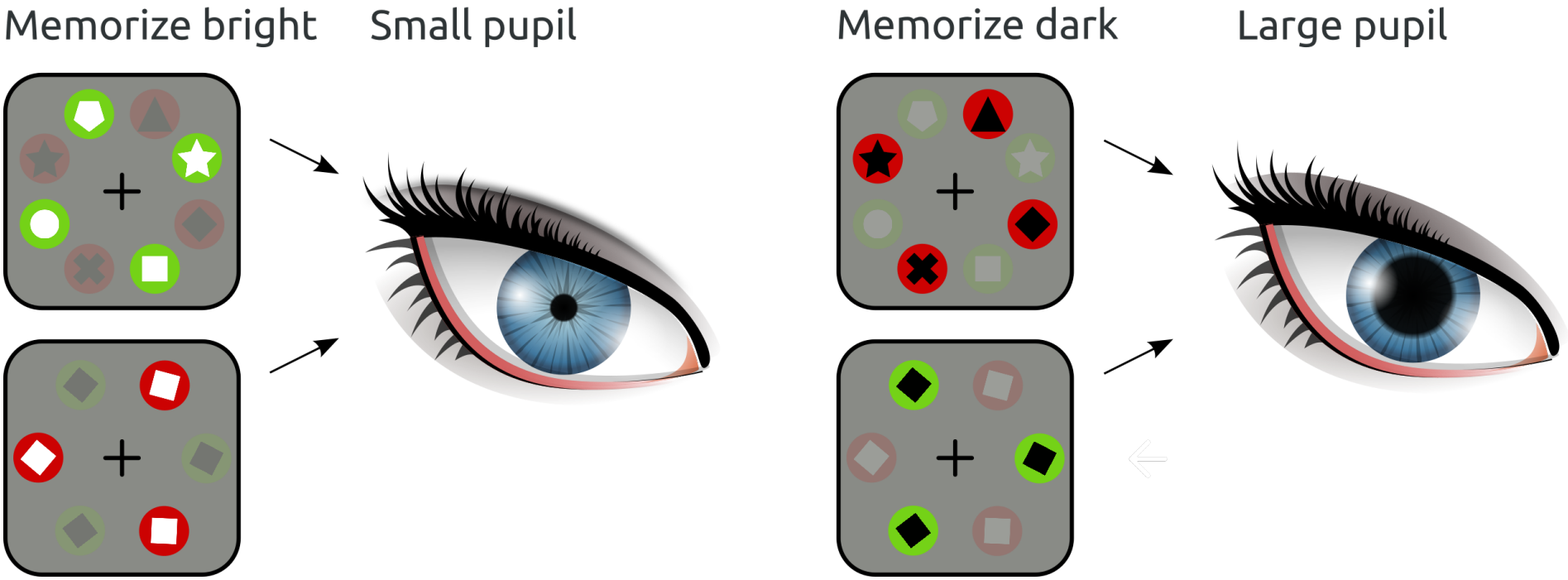

Exp. 1
Cue
1 s
Memory array
3 s
Retention
4 s
Same or different?
Until response
Encoding
Maintenance

Prediction

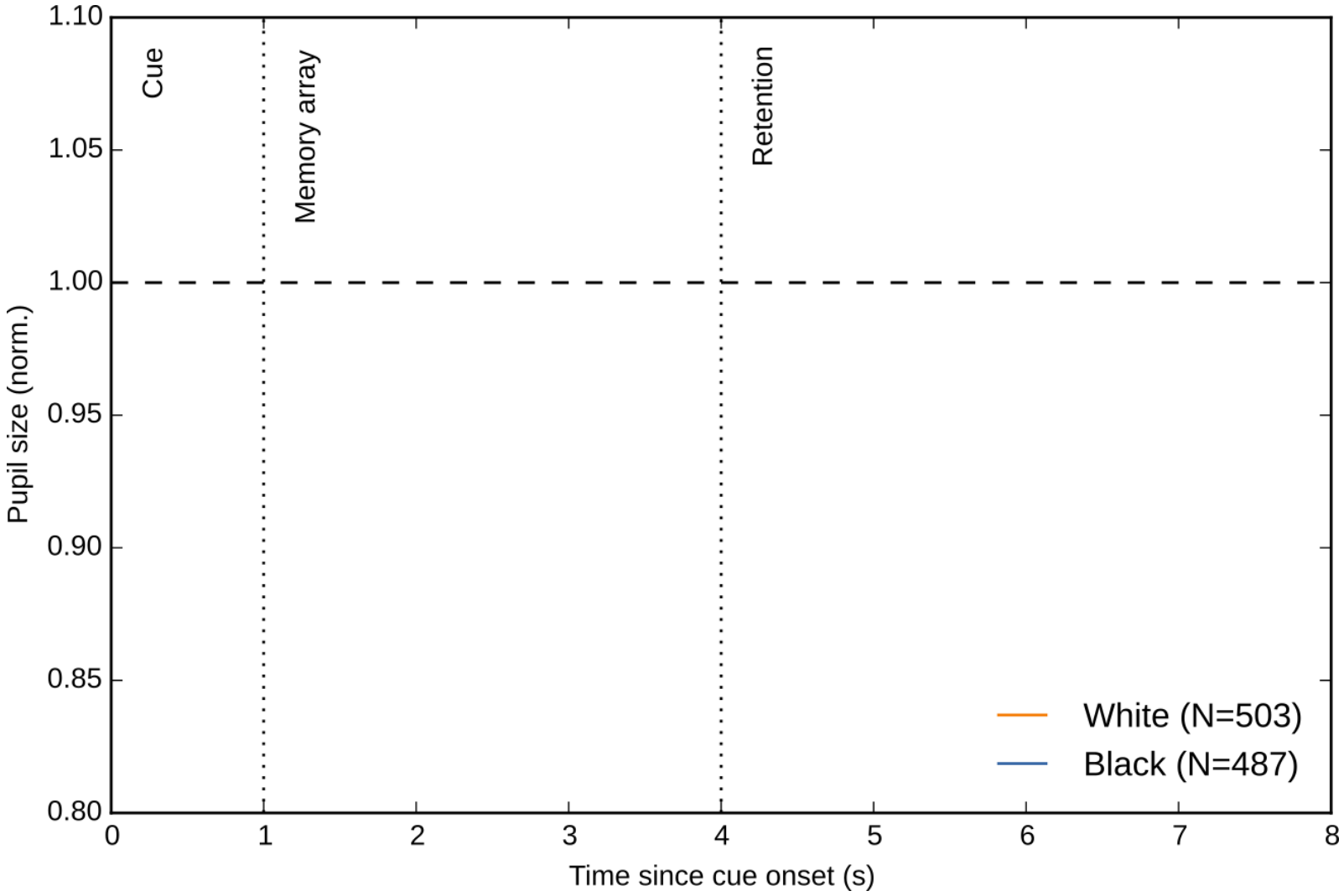
Memorize bright Small pupil



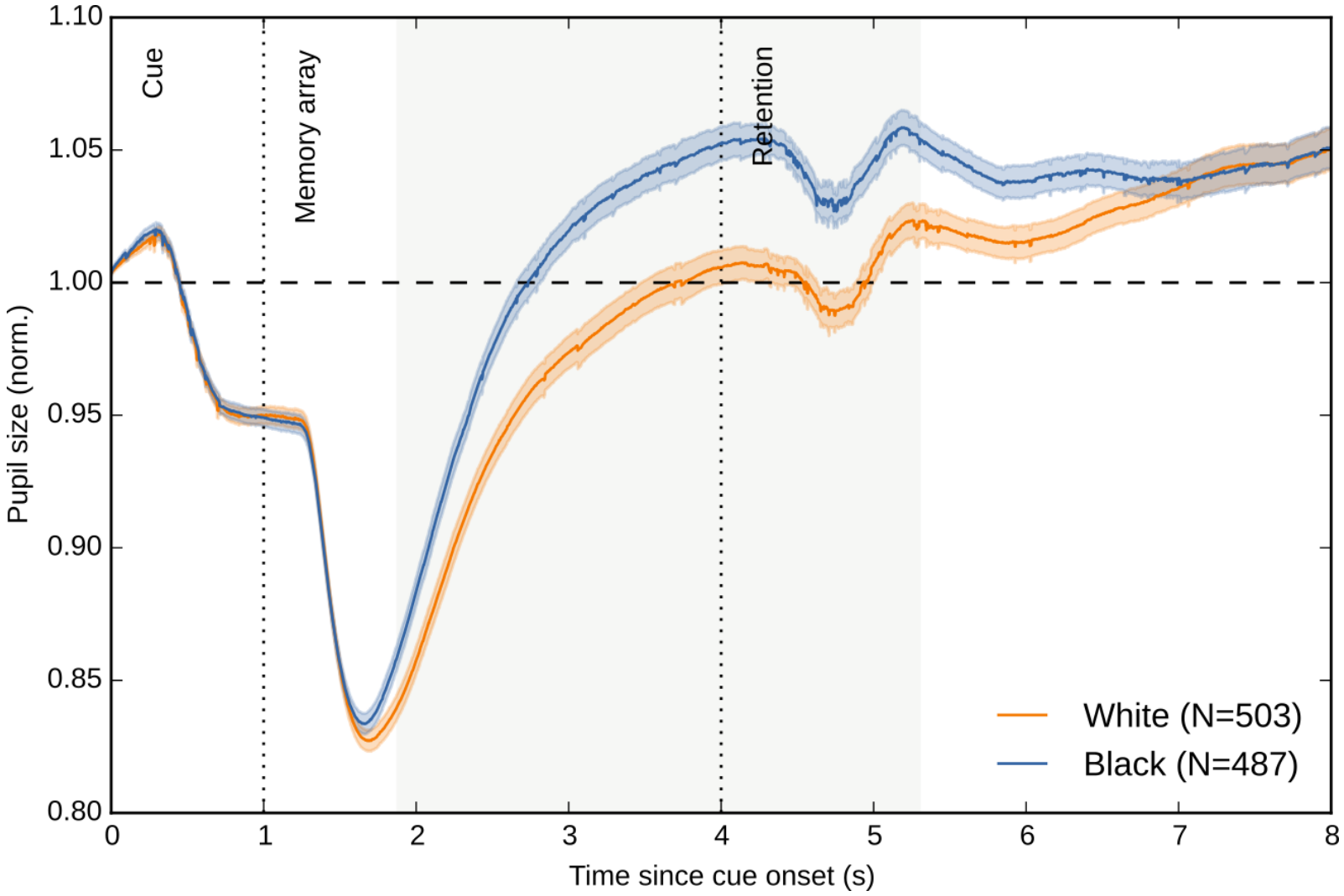
Prediction



Results


Cue
Memory array
Retention
Pupil size (norm.)
1.10
1.05
1.00
0.95
0.90
0.85
0.80
0
1
2
3
4
5
6
7
8
Time since cue onset (s)
White (N=503)
Black (N=487)

Results


Cue
Memory array
Retention
Pupil size (norm.)
Time since cue onset (s)
1.10
1.05
1.00
0.95
0.90
0.85
0.80
0
1
2
3
4
5
6
7
8
White (N=503)
Black (N=487)

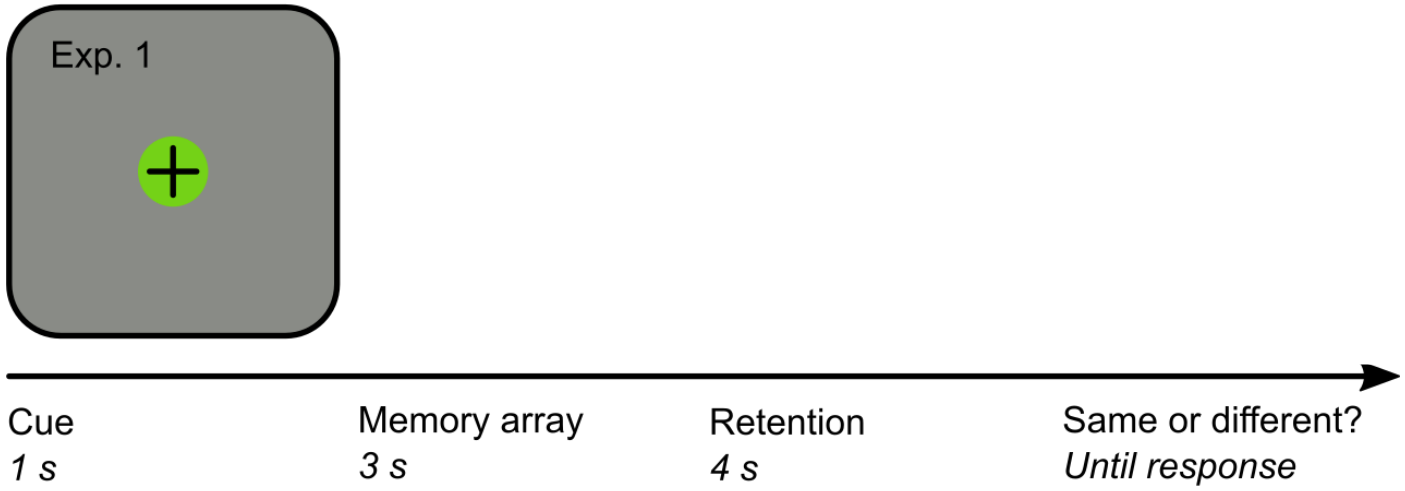
But first …

… Let's compare this to an attention-only condition

Paradigm

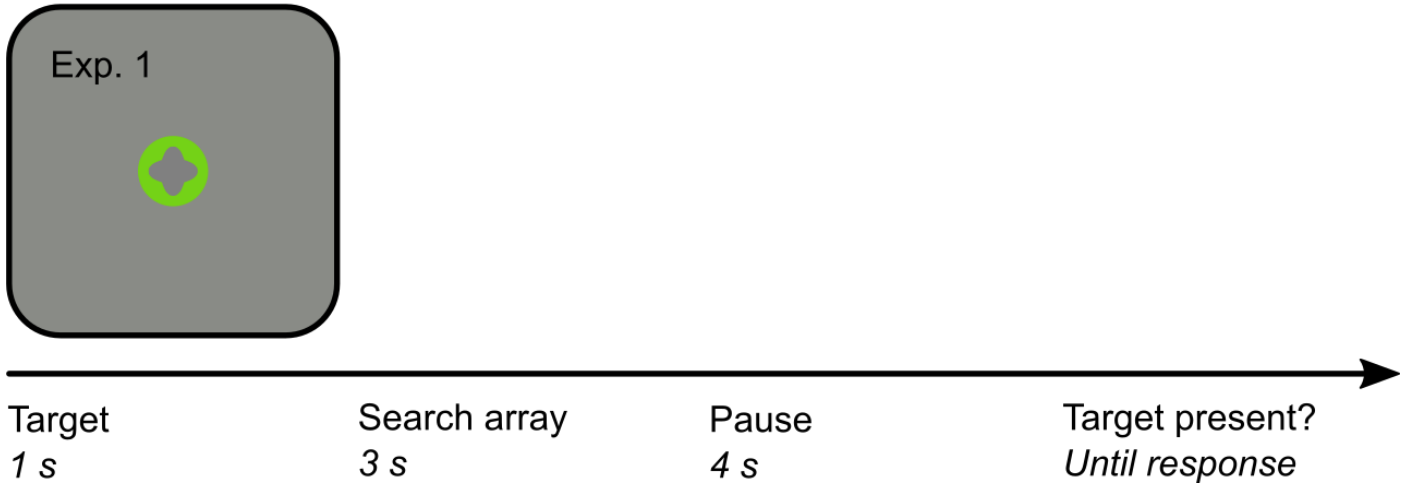
What you just saw →

Working-memory condition



To see the effect of attention alone →

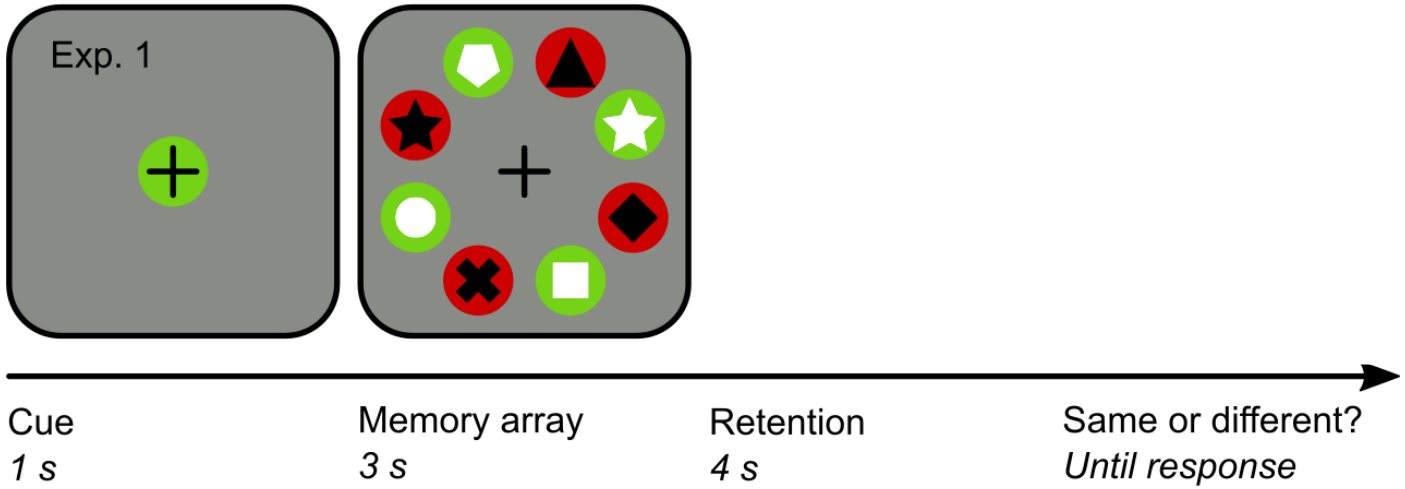
Attention condition



Paradigm

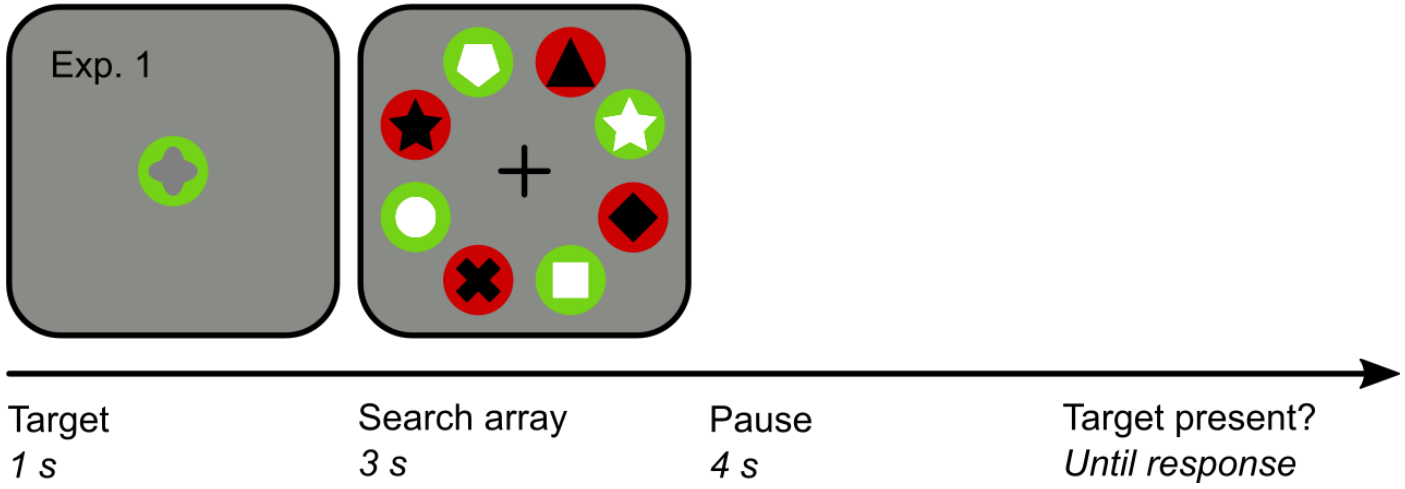
What you just saw →

Working-memory condition



Attention condition

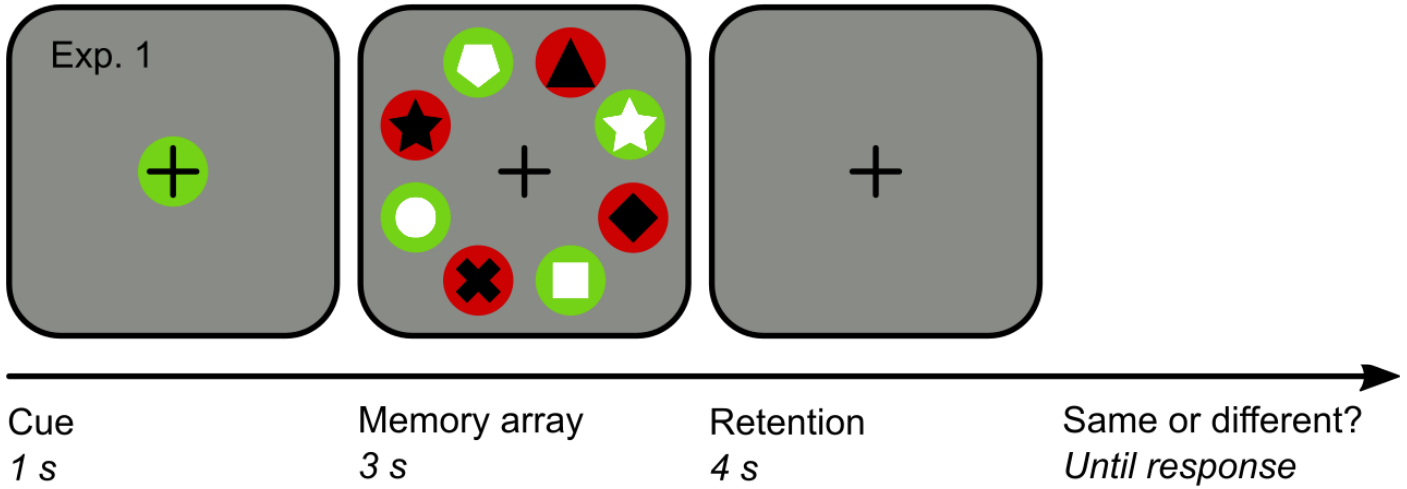
To see the effect of attention alone →



Paradigm

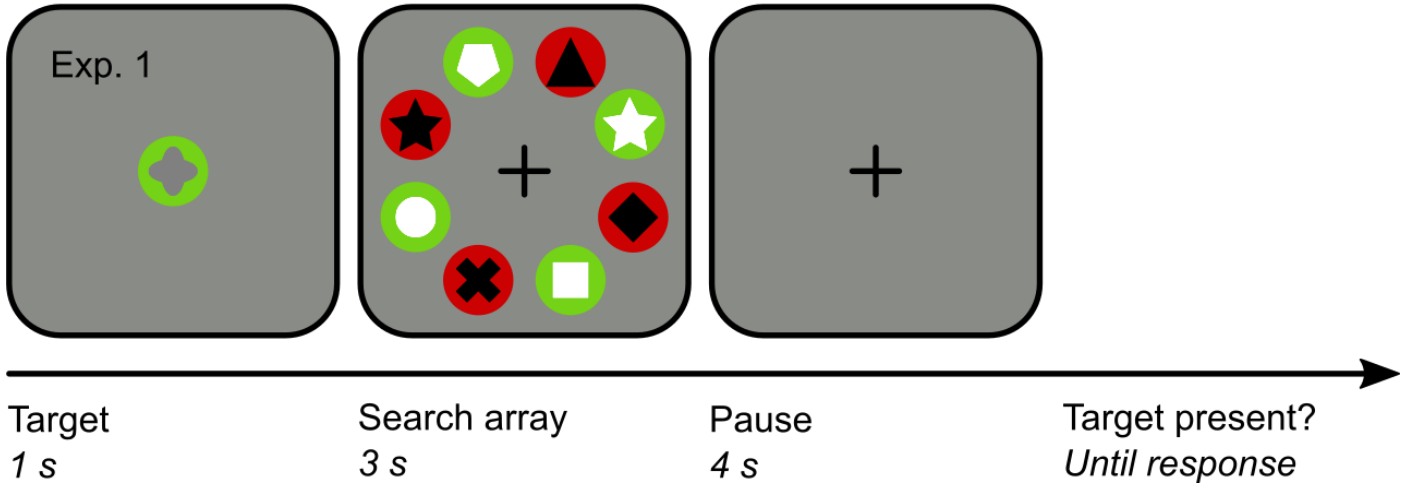
What you just saw →

Working-memory condition



Attention condition

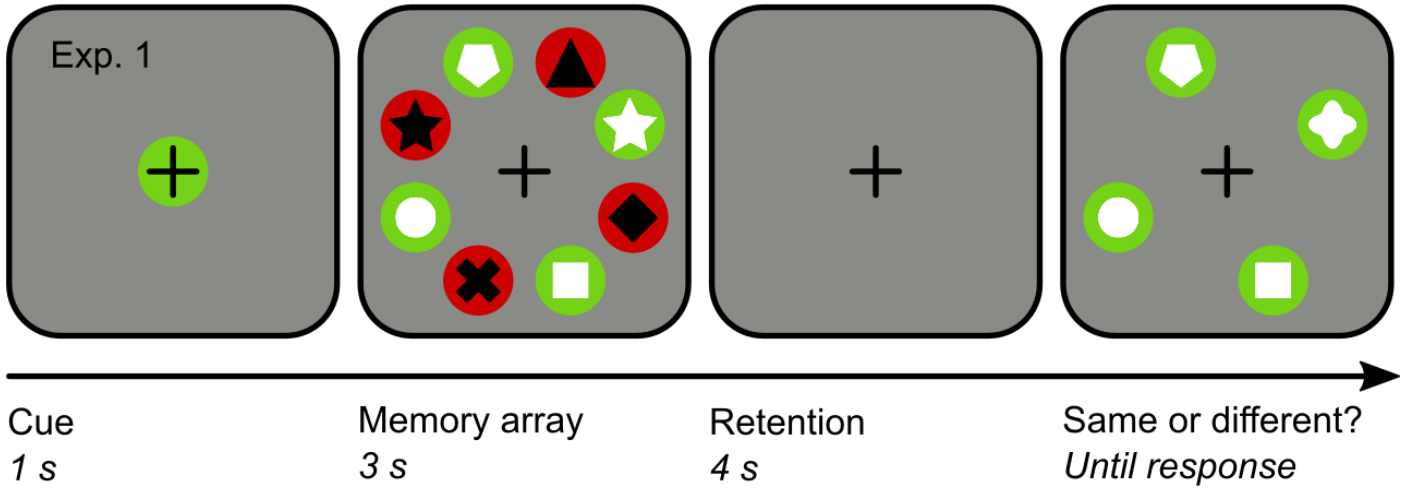
To see the effect of attention alone →



Paradigm

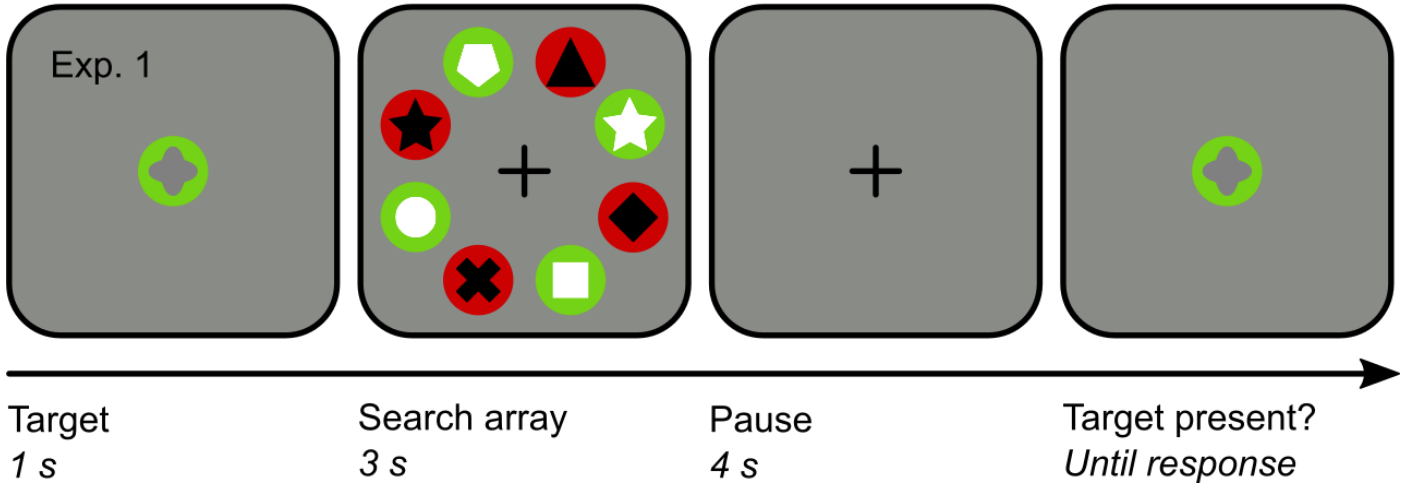
What you just saw →

Working-memory condition



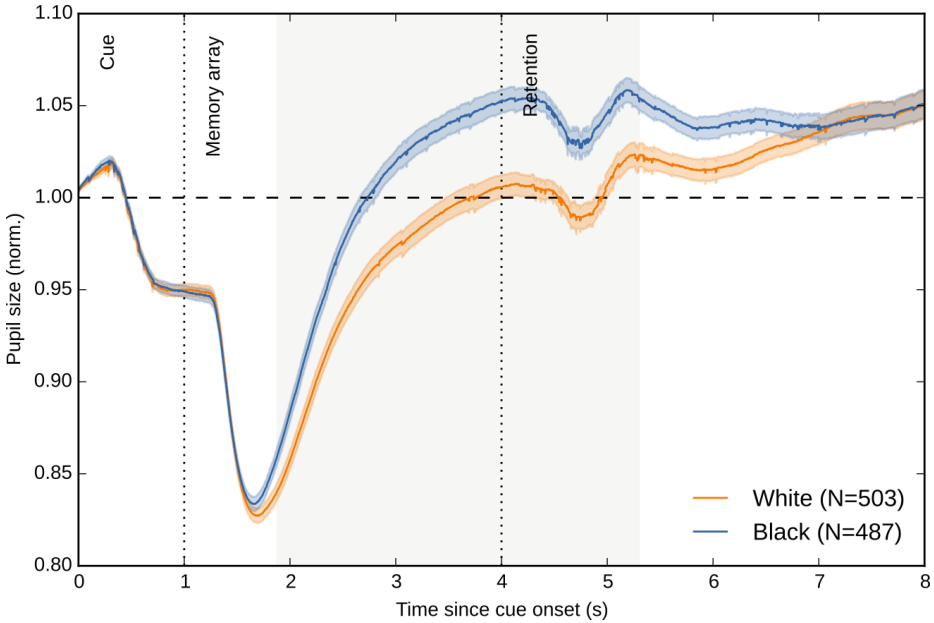
Attention condition

To see the effect of attention alone →



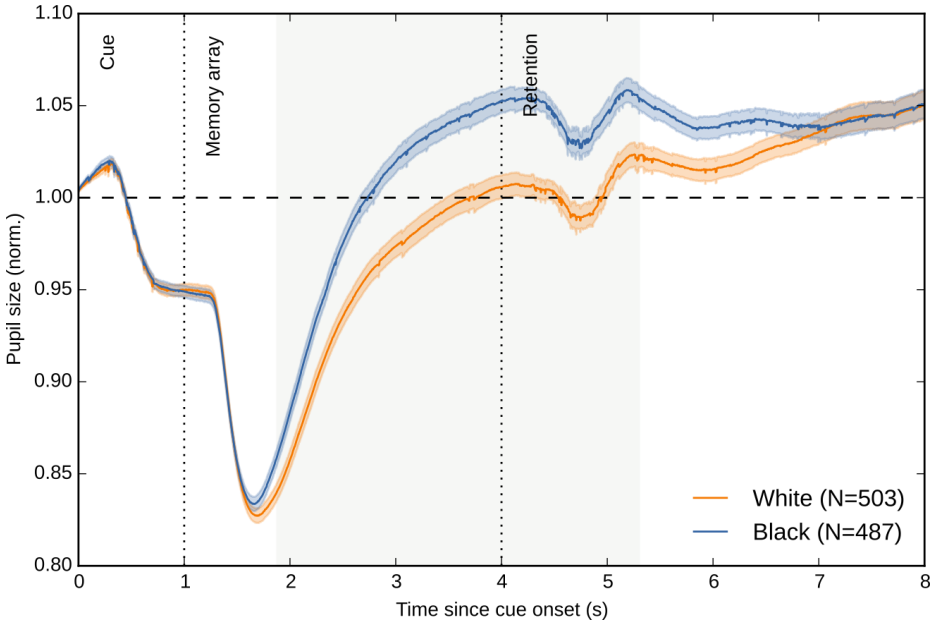
Results

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

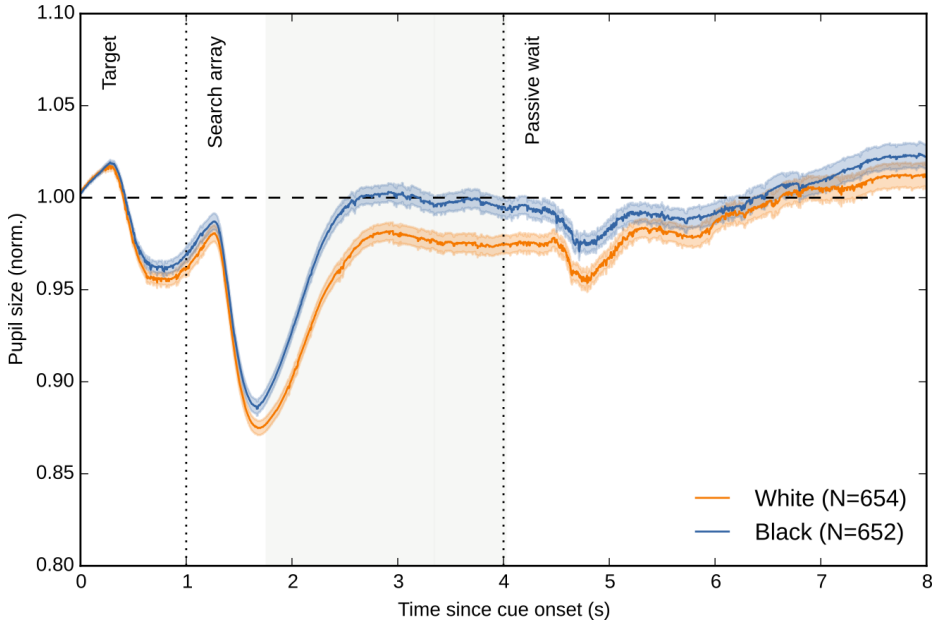


Results

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 (≈attention)
  - But not maintenance of working memory

Results

- The pupillary light response reflects
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- Perhaps

Results

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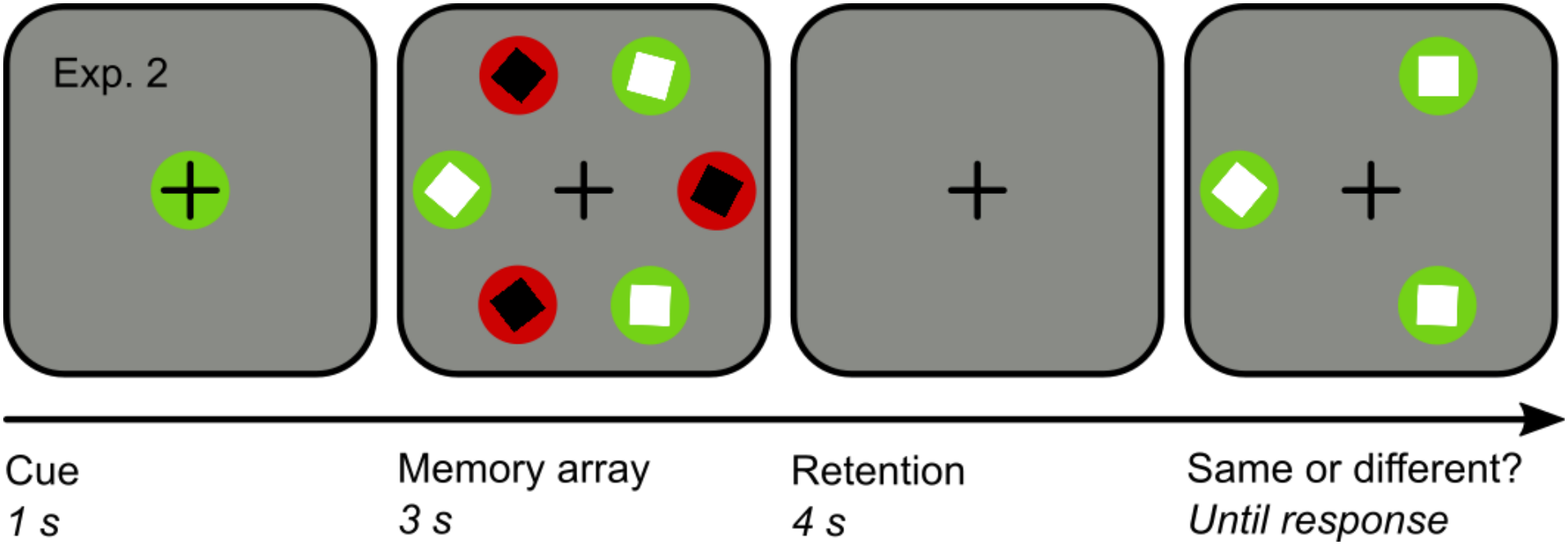
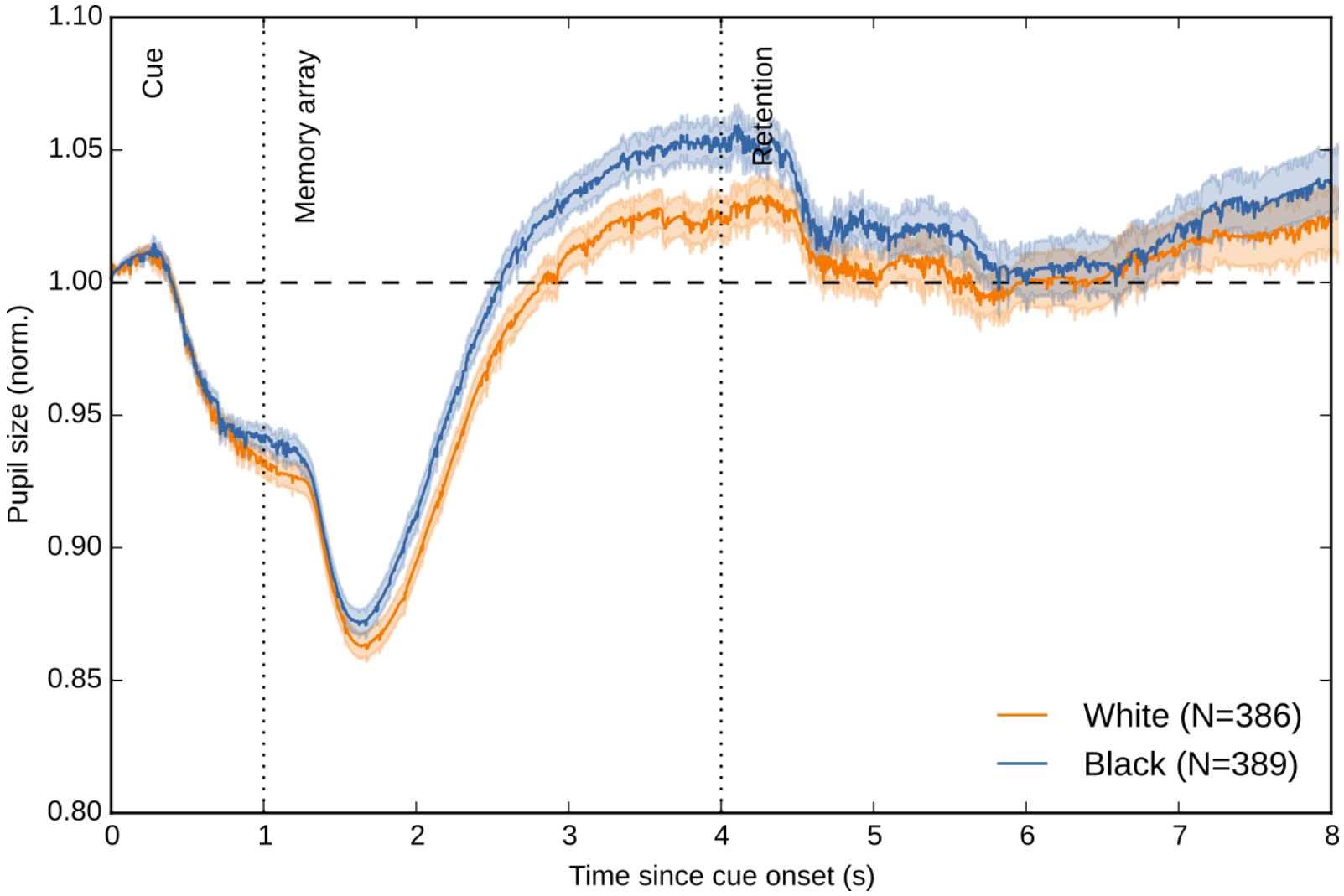
  - Encoding of working memory (≈attention)
  - But not maintenance of working memory
- Perhaps
  - Participants verbalized the stimuli?

Paradigm


Exp. 2
Cue
1 s
Memory array
3 s
Retention
4 s
Same or different?
Until response

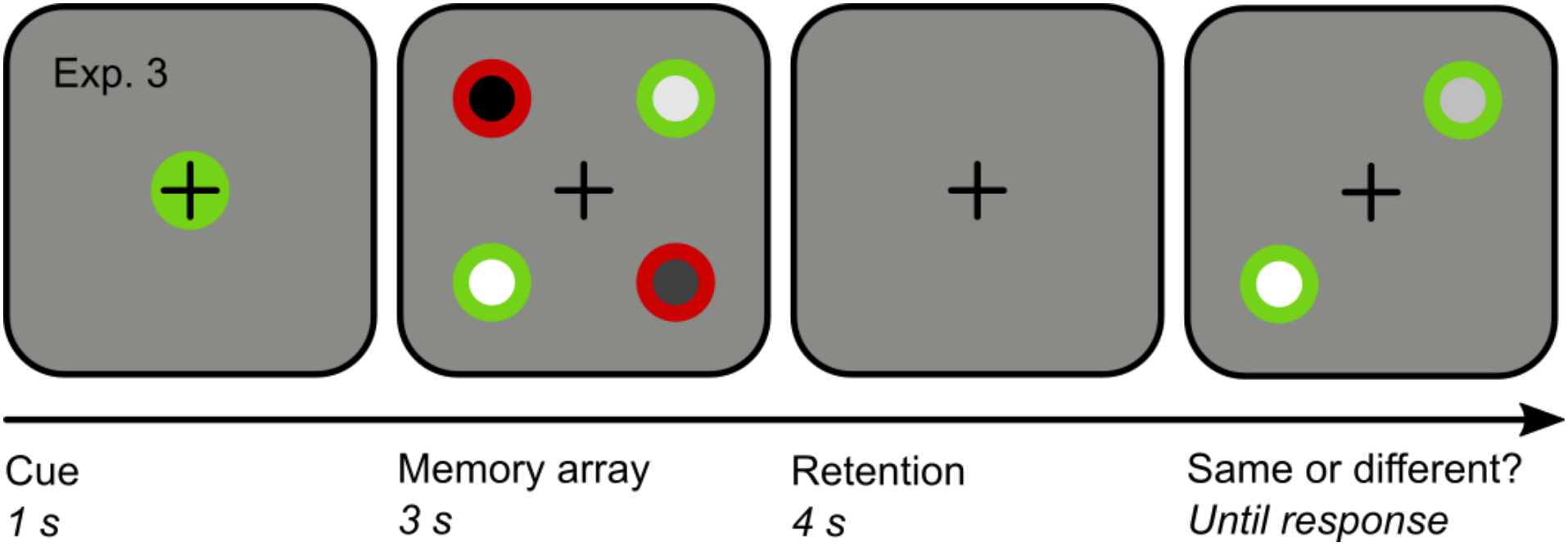
Results


1.10
1.05
1.00
0.95
0.90
0.85
0.80
Pupil size (norm.)
Cue
Memory array
Retention
0
1
2
3
4
5
6
7
8
Time since cue onset (s)
White (N=386)
Black (N=389)

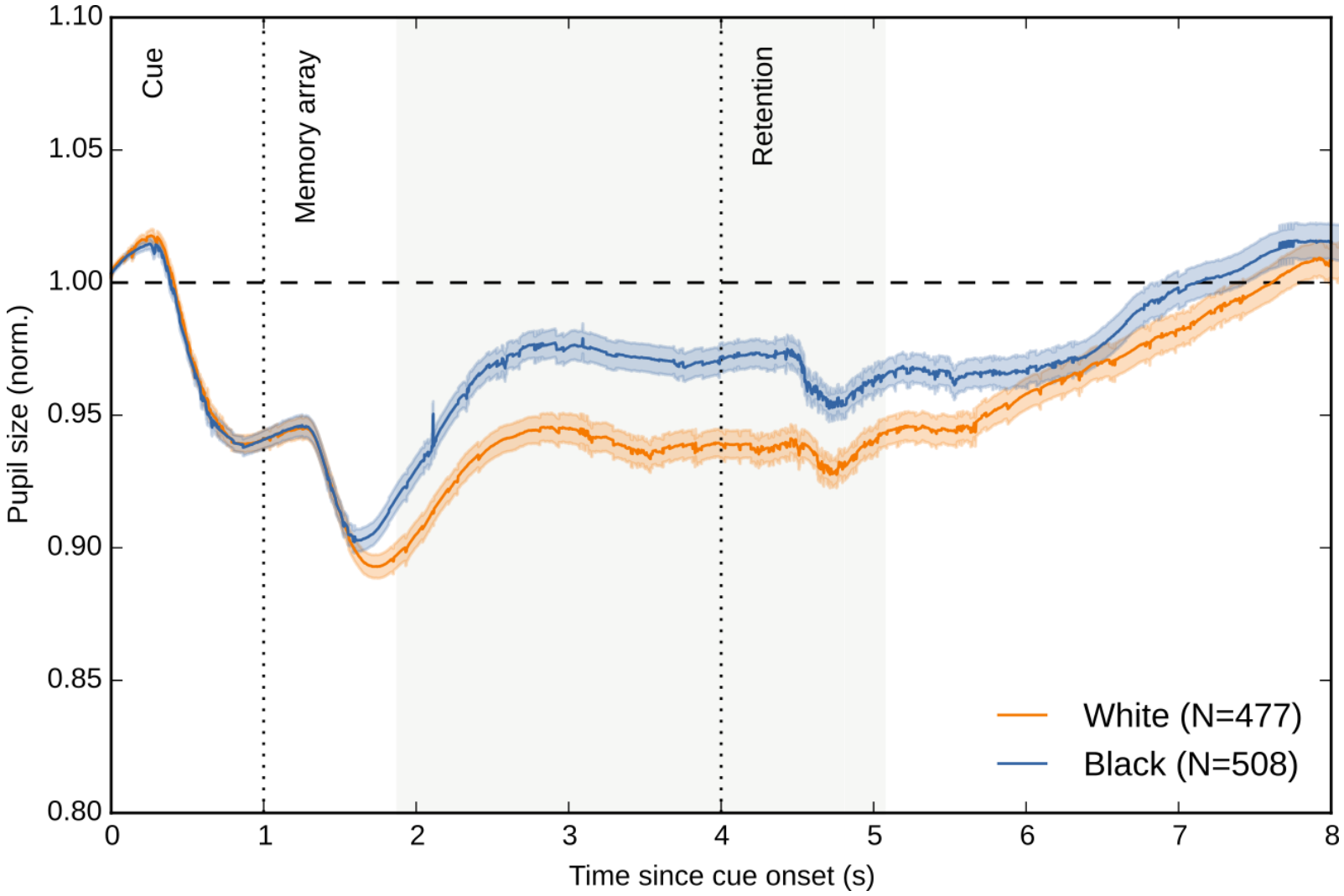
Results

- 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


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

Results


Cue
Memory array
Retention
Pupil size (norm.)
Time since cue onset (s)
White (N=477)
Black (N=508)
1.10
1.05
1.00
0.95
0.90
0.85
0.80
0
1
2
3
4
5
6
7
8

Discussion

- The pupillary light response reflects

[1] Van Moorselaar, Theeuwes, & Olivers (2014)

Discussion

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  - Encoding of working memory (≈attention)

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  - Encoding of working memory (≈attention)
  - But not maintenance of working memory
- Perhaps
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  - ~~Only task-relevant features were encoded?~~
  - Working-memory maintenance and attention are qualitatively different?

[1] Van Moorselaar, Theeuwes, & Olivers (2014)

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]

[1] Van Moorselaar, Theeuwes, & Olivers (2014)

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]

[1] Reviewed in Glenberg & Gallese (2012)

Embodied language

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

[1] Reviewed in Glenberg & Gallese (2012)

Embodied language

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

[1] Reviewed in Glenberg & Gallese (2012)

Embodied language

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

[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?

[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

[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?

[1] Reviewed in Glenberg & Gallese (2012)

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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?

[1] Reviewed in Glenberg & Gallese (2012)

Methods

Methods

- Single word shown for 3 s

Methods

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

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

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- Press key for animal names

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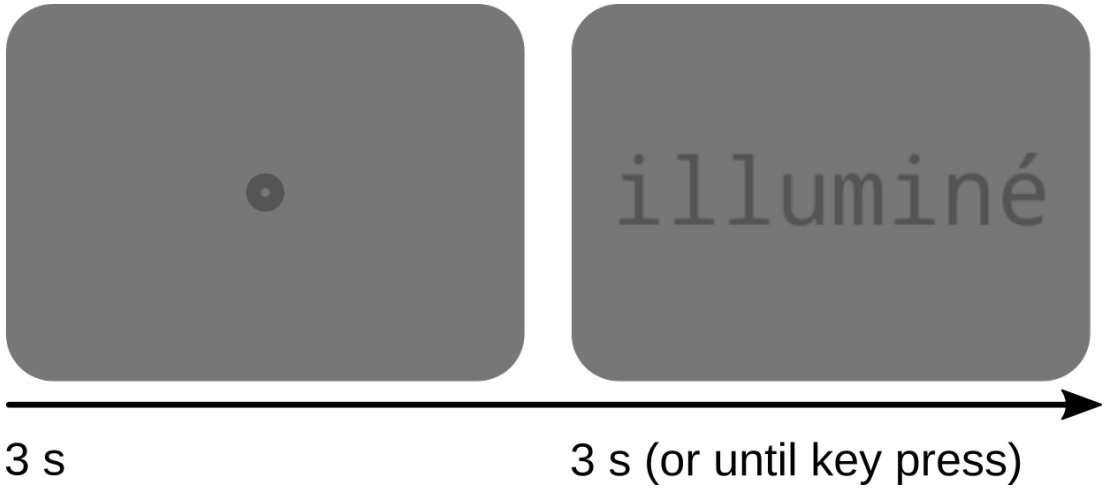
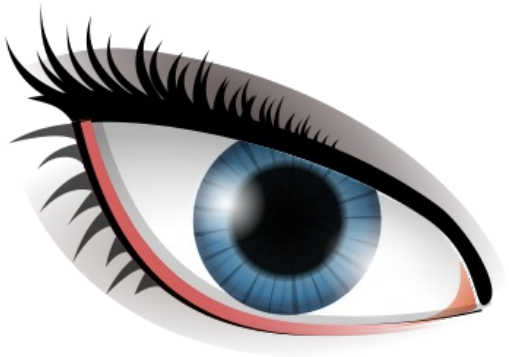
  - Matched on visual and lexical properties
- Press key for animal names



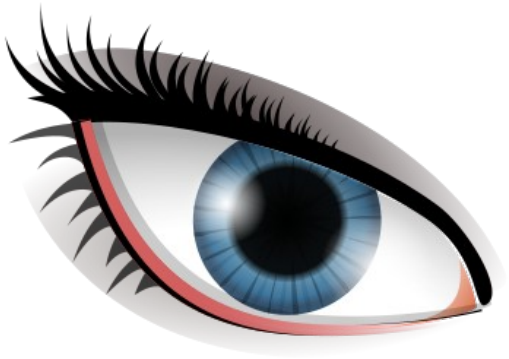
Predictions

Darkness-conveying words

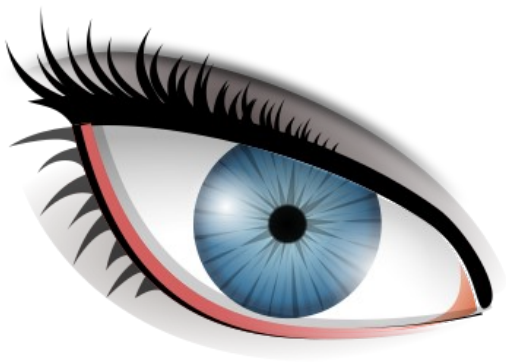


Predictions

Darkness-conveying words

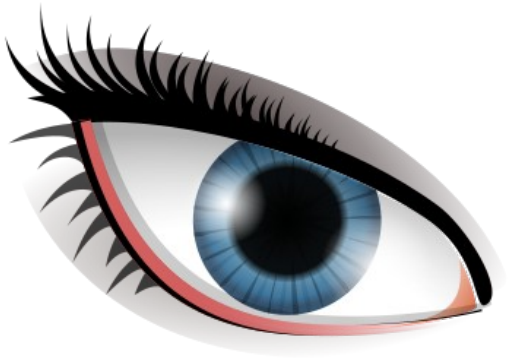


Brightness-conveying words

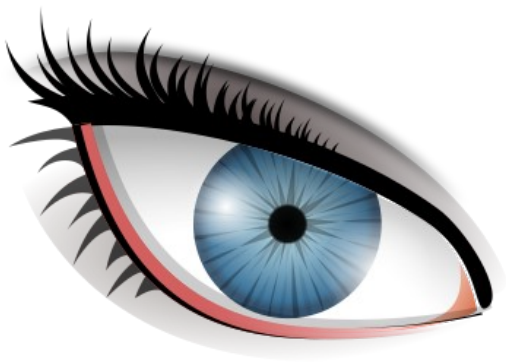


Predictions

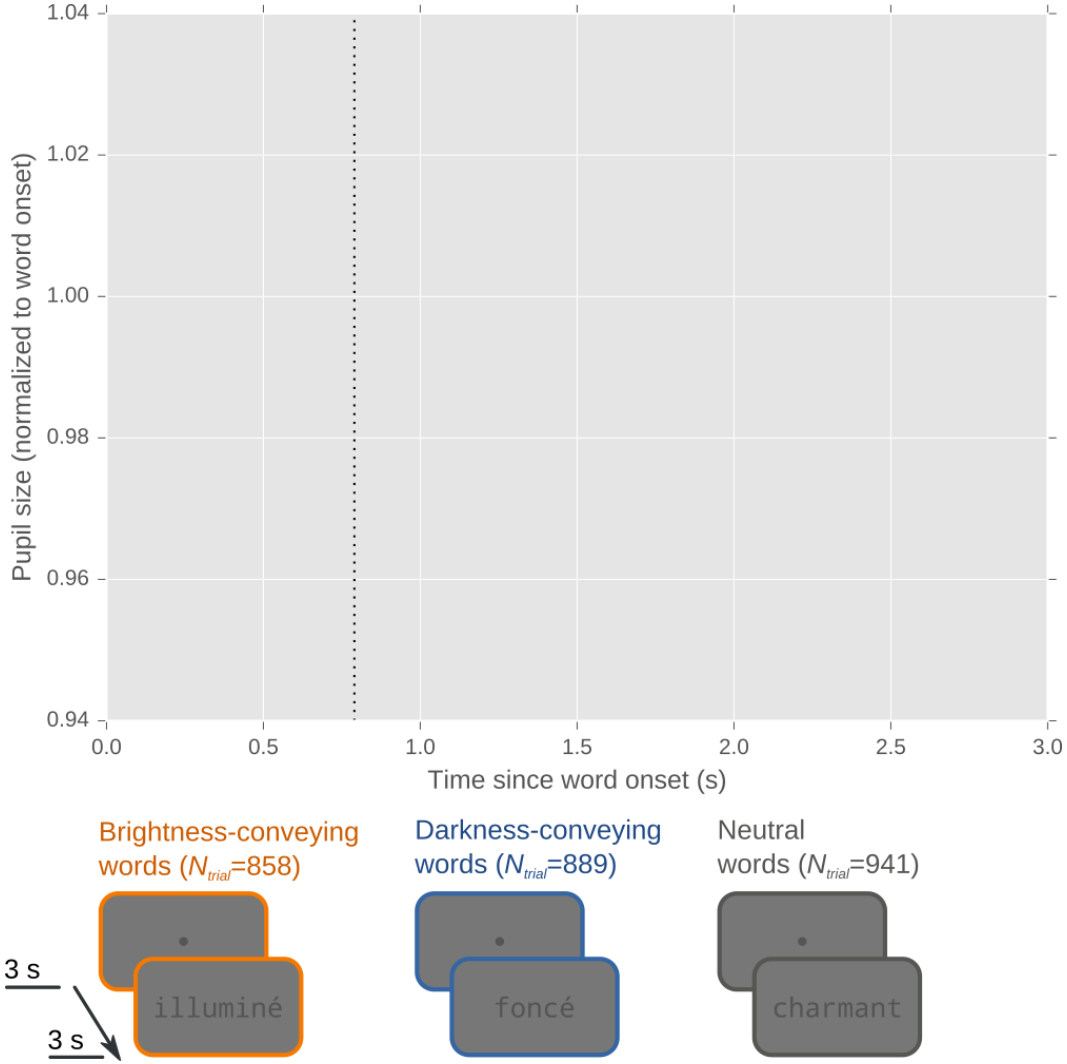
Darkness-conveying words



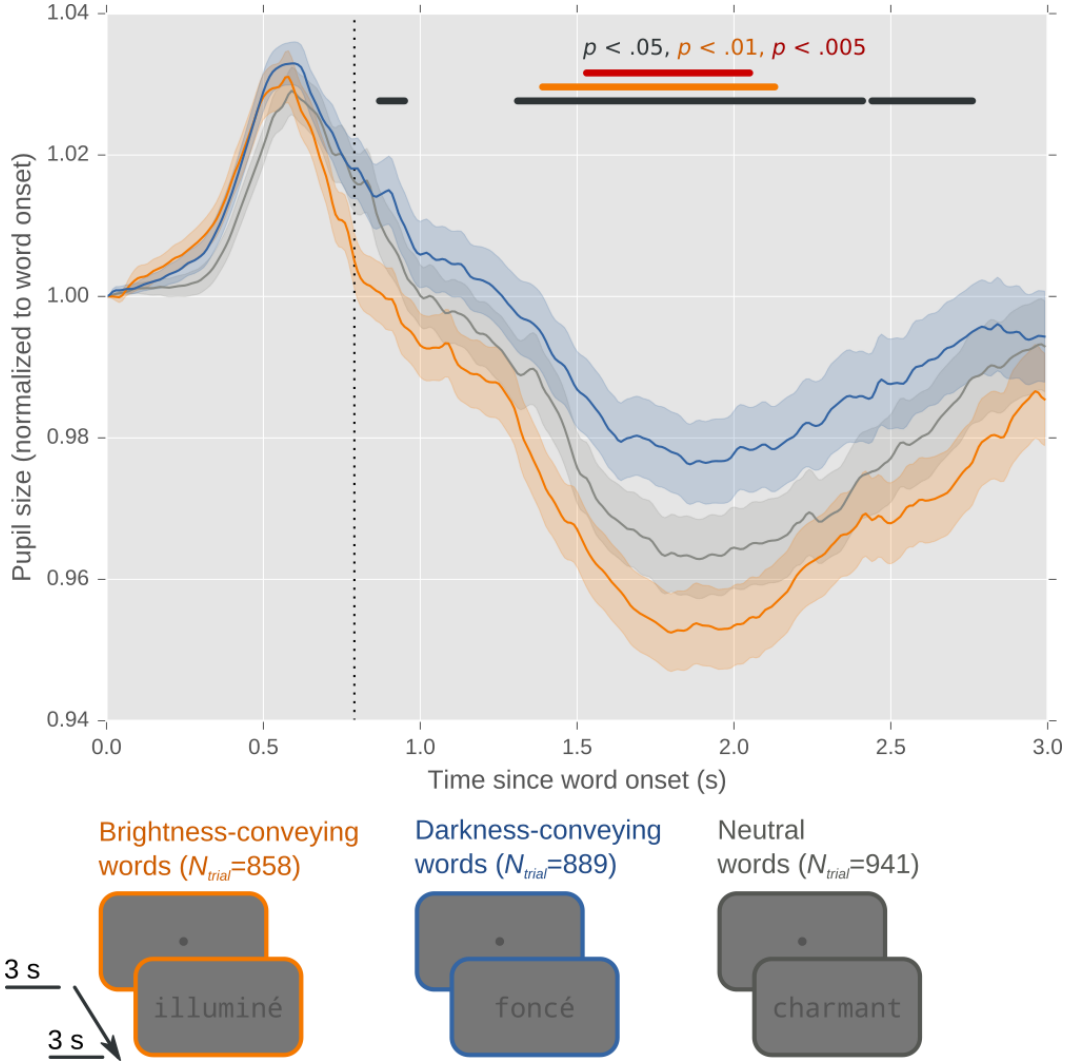
Brightness-conveying words



Results


1.04
1.02
1.00
0.98
0.96
0.94
Pupil size (normalized to word onset)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Time since word onset (s)
Brightness-conveying words (N_{trial}=858)
Darkness-conveying words (N_{trial}=889)
Neutral words (N_{trial}=941)
3 s
3 s
illuminé
foncé
charmant

Results


p < .05, p < .01, p < .005
Pupil size (normalized to word onset)
1.04
1.02
1.00
0.98
0.96
0.94
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Time since word onset (s)
Brightness-conveying words (N_trial=858)
Darkness-conveying words (N_trial=889)
Neutral words (N_trial=941)
3 s
3 s
illuminé
foncé
charmant

Discussion

- Pupil size reflects semantic brightness

Discussion

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

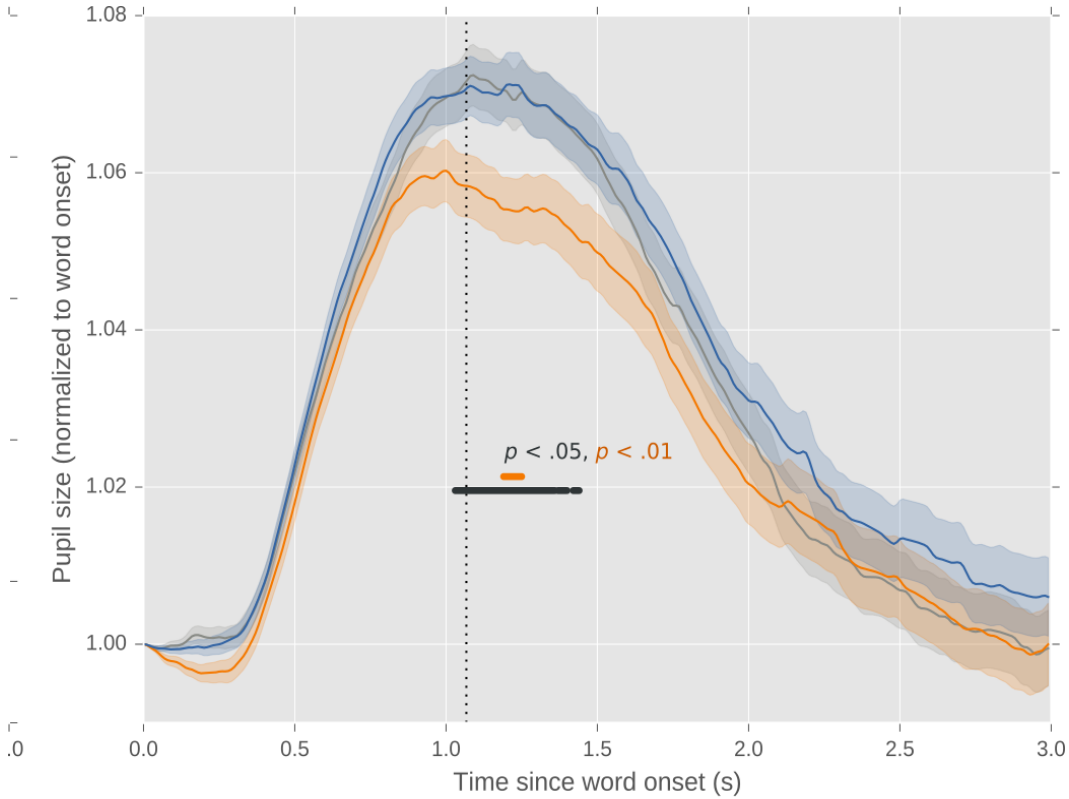
Discussion

- 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


1.08
1.06
1.04
1.02
1.00
.0
Pupil size (normalized to word onset)
p < .05, p < .01
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Time since word onset (s)
Brightness-conveying words (N_trial=936)
Darkness-conveying words (N_trial=971)
Neutral words (N_trial=997)
3 s
3 s
"illuminé"
"foncé"
"charmant"

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

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  - Read or hear “sun” → small pupil
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- Word comprehension activates sensory representations (at least sometimes):

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  - Read or hear “sun” → small pupil
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  - And these affect pupil size

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- 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
  - Embodiment?

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
  - Embodiment?
  - Or preparation?

Conclusion

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- Pupillary responses are not passive reflexes

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  … but are types of eye movements that reflect high-level visual processing

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- “External attention”

Conclusion

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- “External attention”
  - Directing your attention to something out there

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”

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

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


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