Influence of visual processing on spatial memory and navigation in young and older adulthood

PhD Defence

9th of November 2023

Marion Durteste

Supervised by Angelo Arleo & Stephen Ramanoël

In front of a jury composed of:

Dr Iris Groen, reviewer
Dr Ineke van der Ham, reviewer

Dr Anne-Lise Paradis, examiner
Dr Matthias Kliegel, examiner

Dr Stephen Ramanoël, supervisor
Dr Angelo Arleo, director

Spatial navigation in healthy ageing

Going
to work

Meeting
a friend

Spatial navigation in healthy ageing

Going to work

Meeting a friend

Moffat, 2009, *Neuropsychol. Rev.*; Lester et al., 2017, *Neuron*; Burns, 1999, *J. Gerontol.*

Spatial navigation in healthy ageing

Going to work

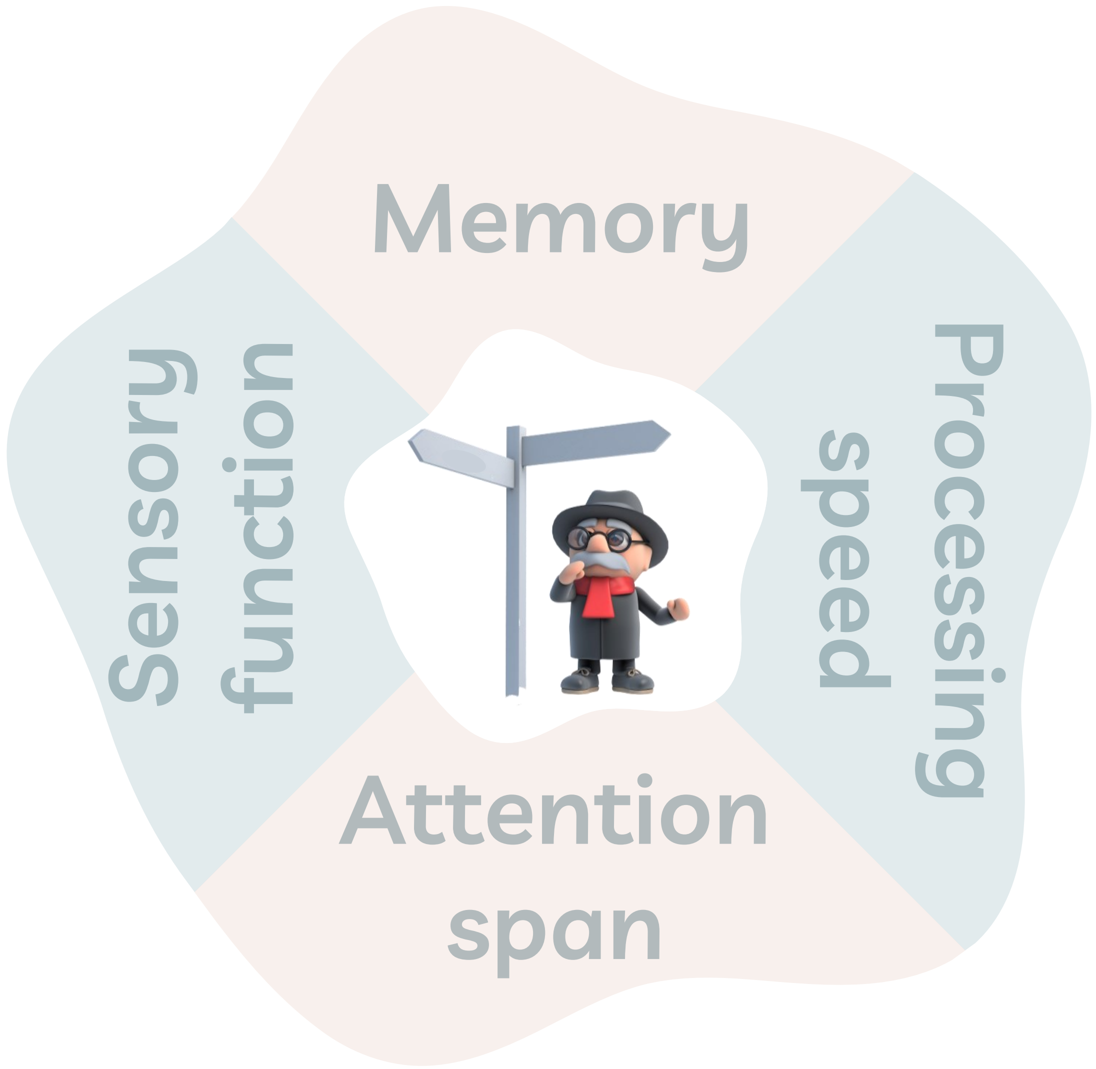
Meeting a friend

- Prominent navigation deficits
- Negative impact on mobility and quality of life
- Increased risk of cognitive decline

Moffat, 2009, *Neuropsychol. Rev.*; Lester et al., 2017, *Neuron*; Burns, 1999, *J. Gerontol.*

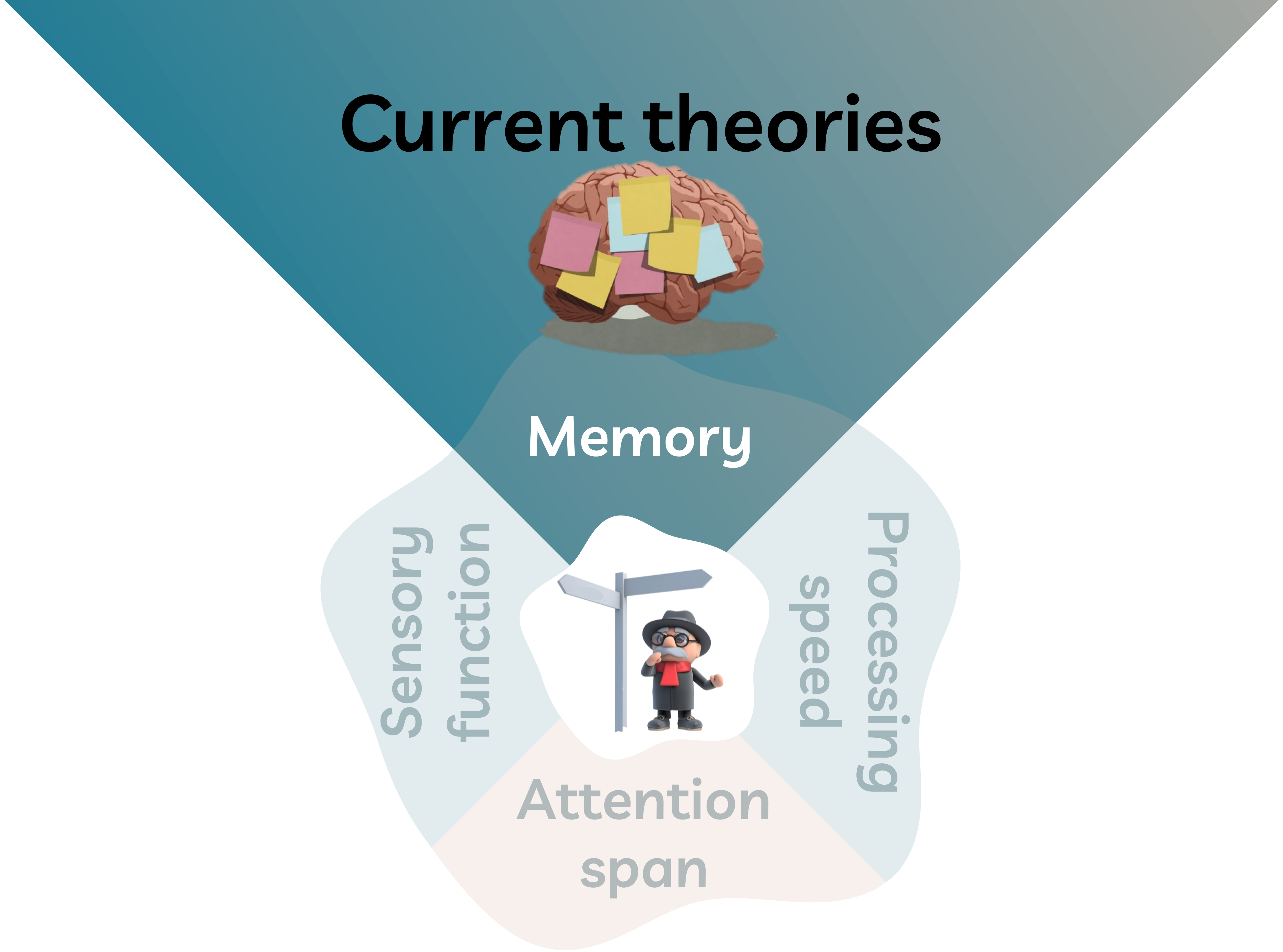
Current theories

Pinpointing the source of age-related navigational decline



Colombo et al., 2017, *Neurosci. Biobehav. Rev.*; Lester et al., 2017, *Neuron*

Current theories



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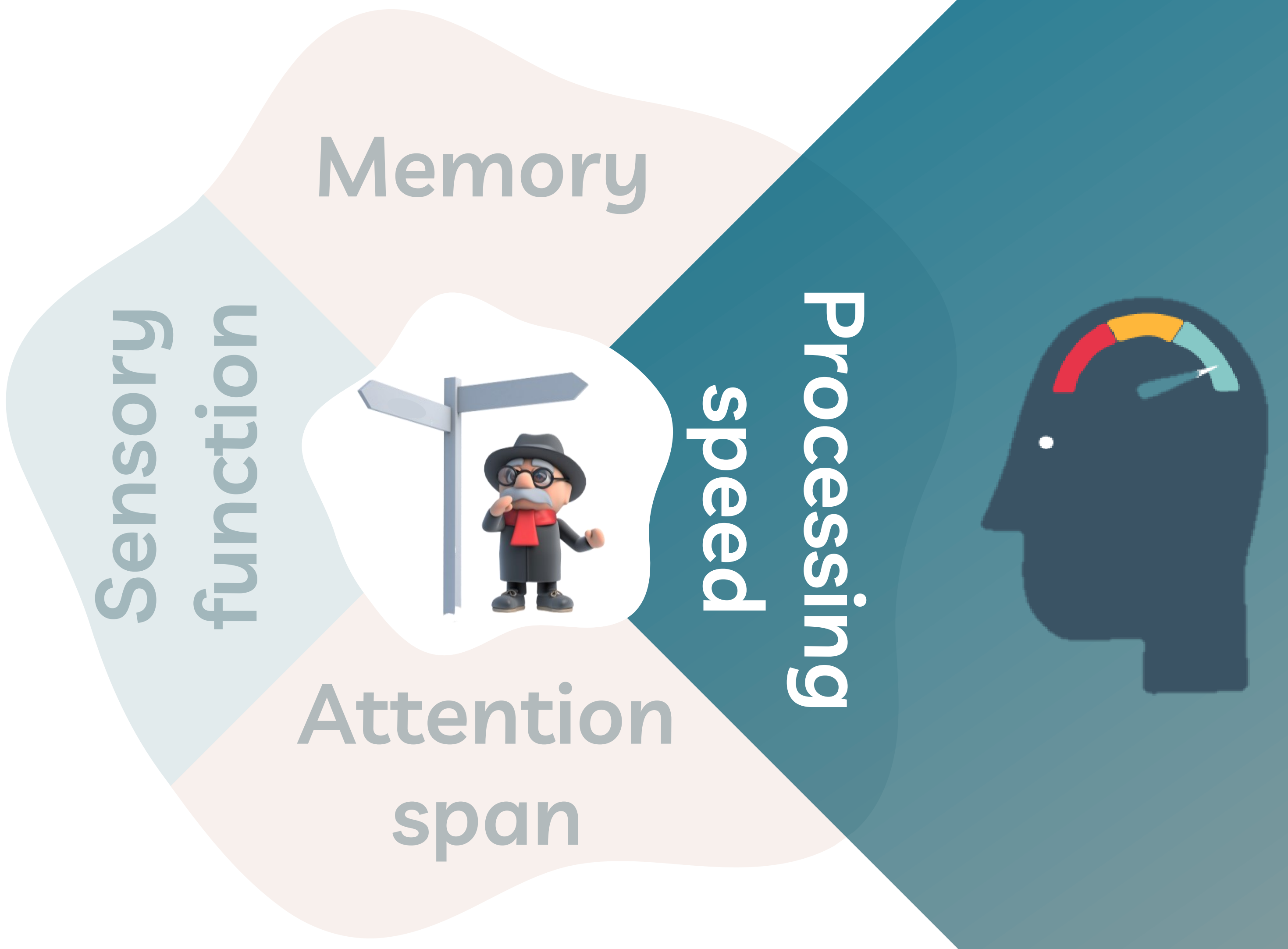

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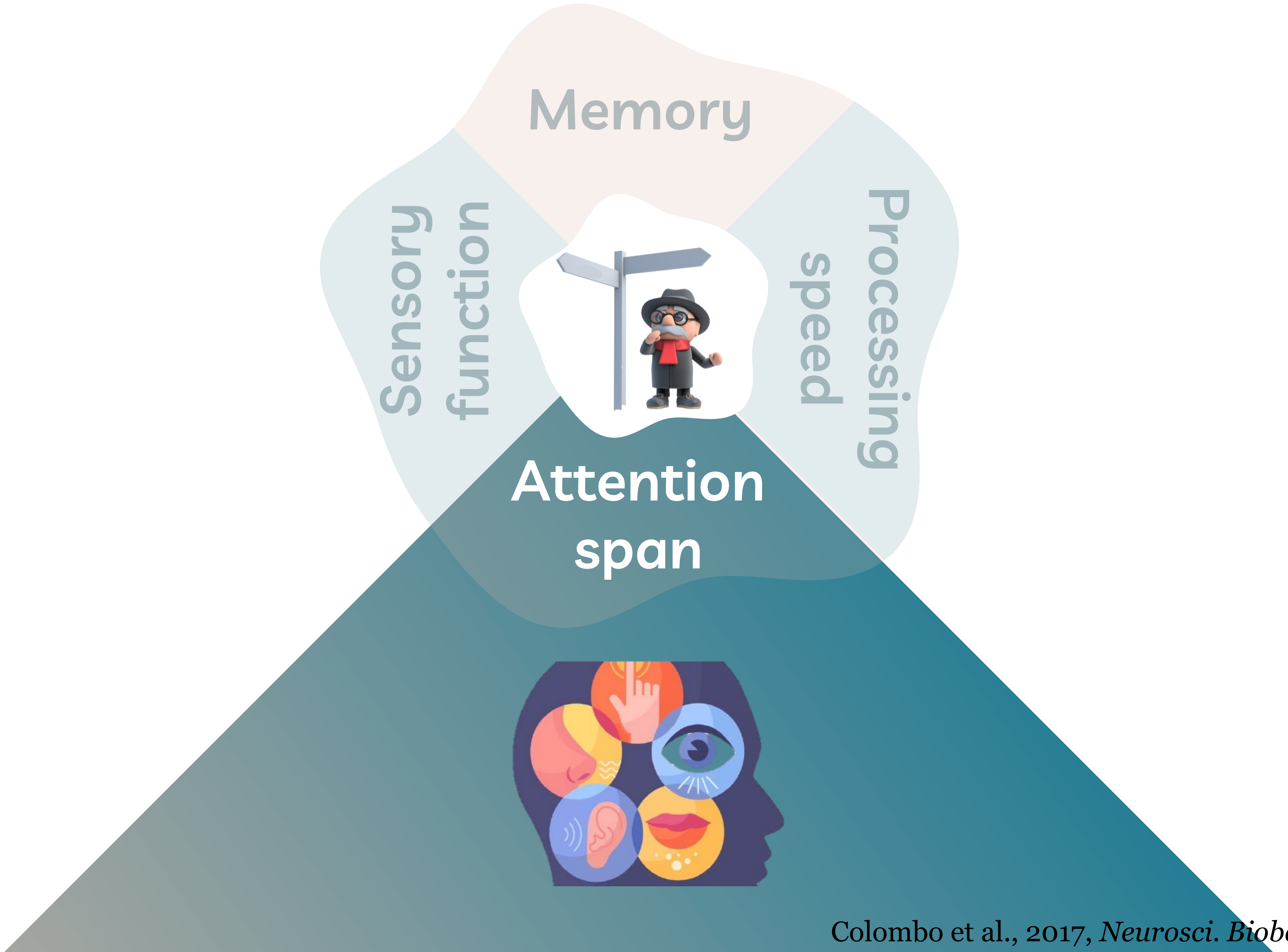

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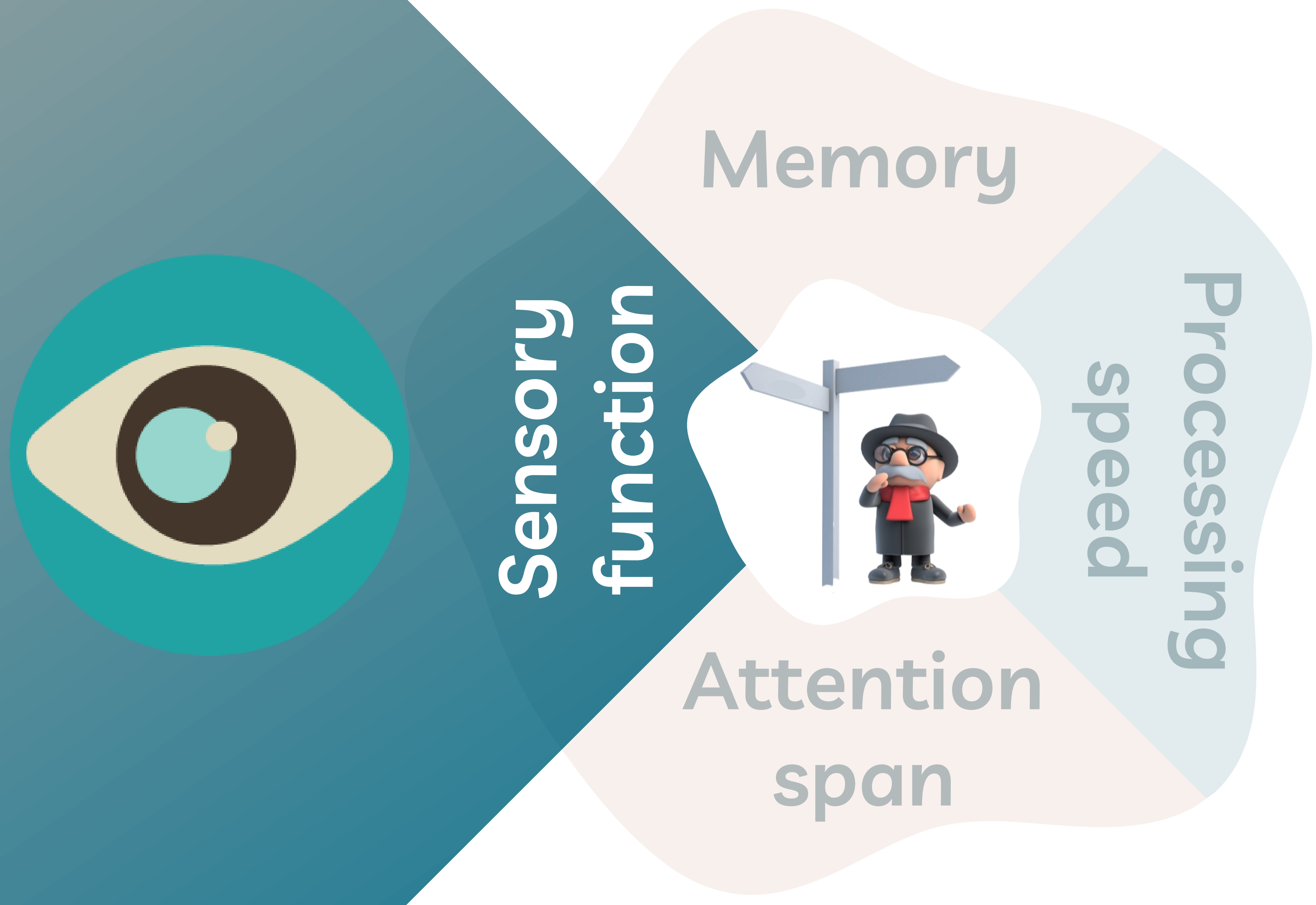

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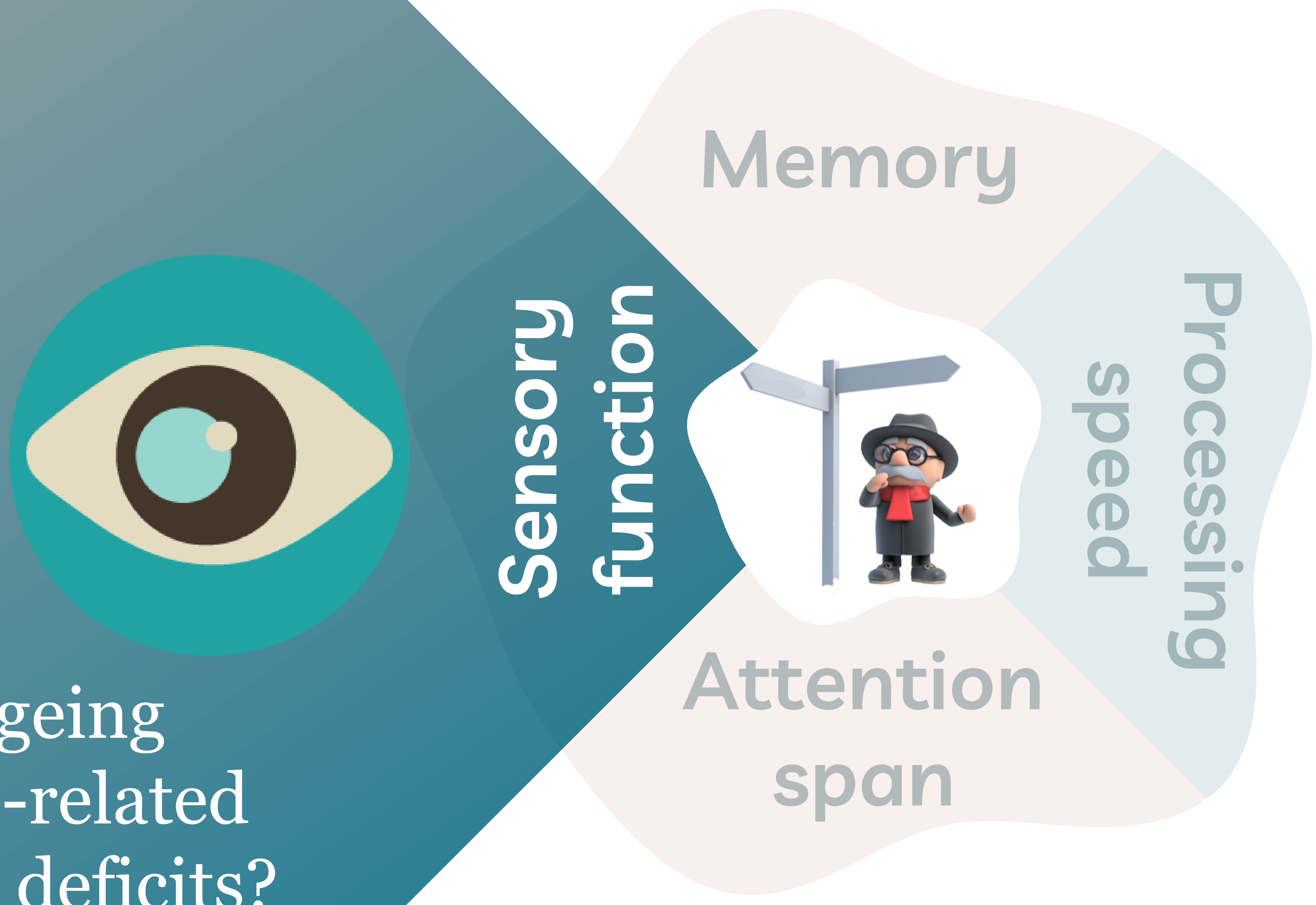


Could visual ageing contribute to age-related spatial navigation deficits?

Colombo et al., 2017, *Neurosci. Biobehav. Rev.*; Lester et al., 2017, *Neuron*

The visual ageing hypothesis

Ekstrom, 2015, *Hippocampus*; Burnett et al. 2001, *Contemp. Ergo.*; Auger et al., 2012, *Plos One*

The visual ageing hypothesis

Landmarks

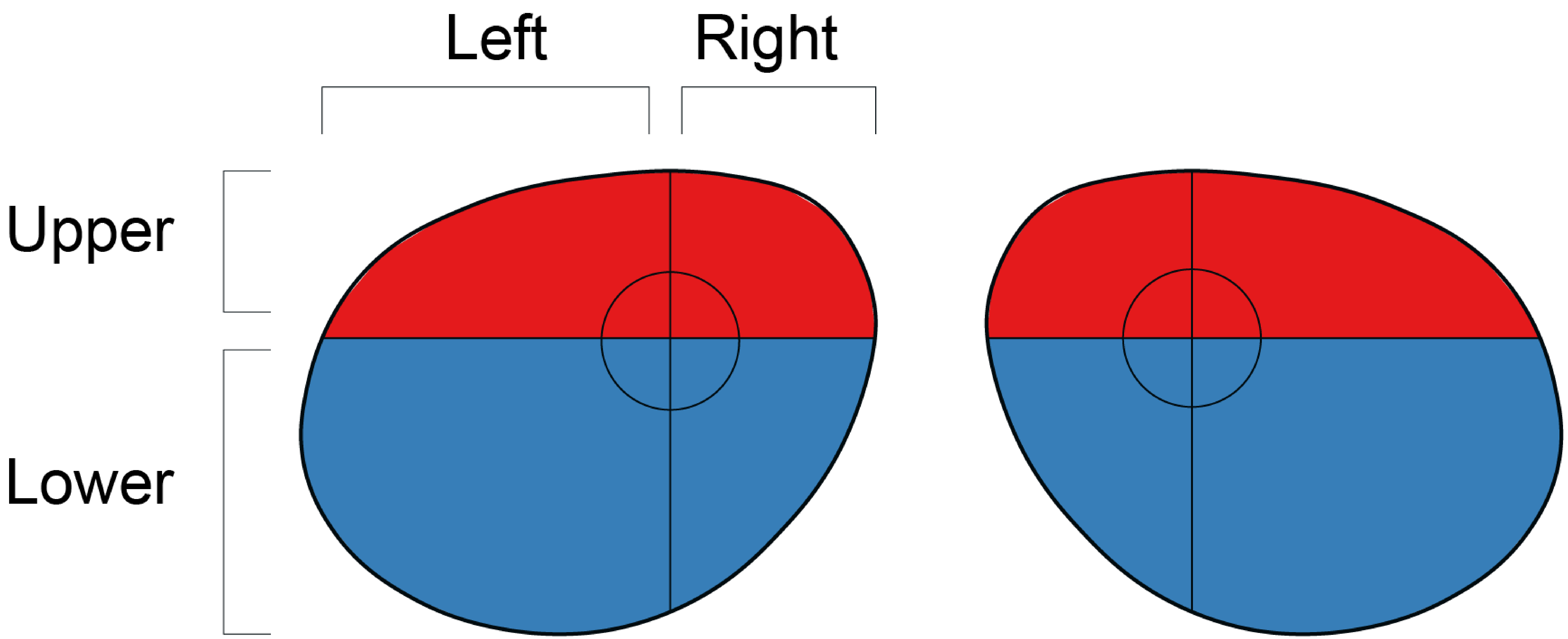
Geometry

Features

Ekstrom, 2015, *Hippocampus*; Burnett et al. 2001, *Contemp. Ergo.*; Auger et al., 2012, *Plos One*

The visual ageing hypothesis

Position within the visual field



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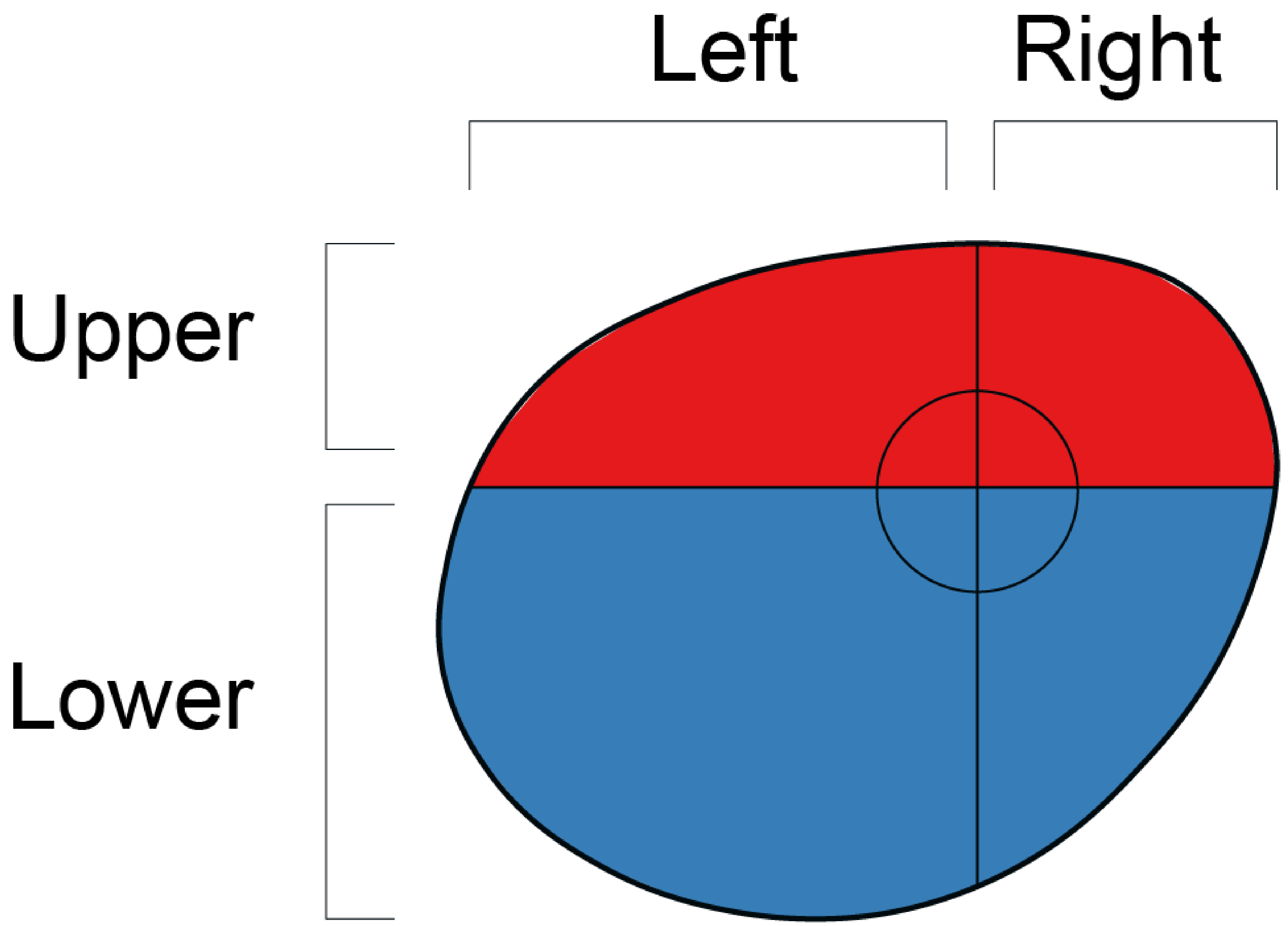

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The visual ageing hypothesis

- Wide array of visual deficits are associated with ageing

Owsley, 2016, *Annu. Rev. Vis. Sci.*; Bécu et al., 2020, *Nat. Hum. Behav.*; Bécu et al., 2023, *eLife*

The visual ageing hypothesis

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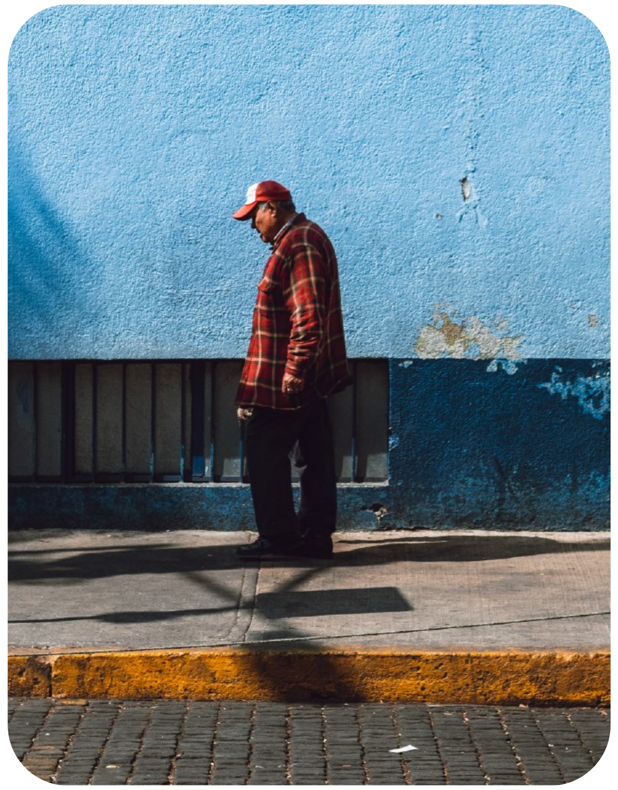
- Older adults focus on lower portions of scenes whilst locomoting



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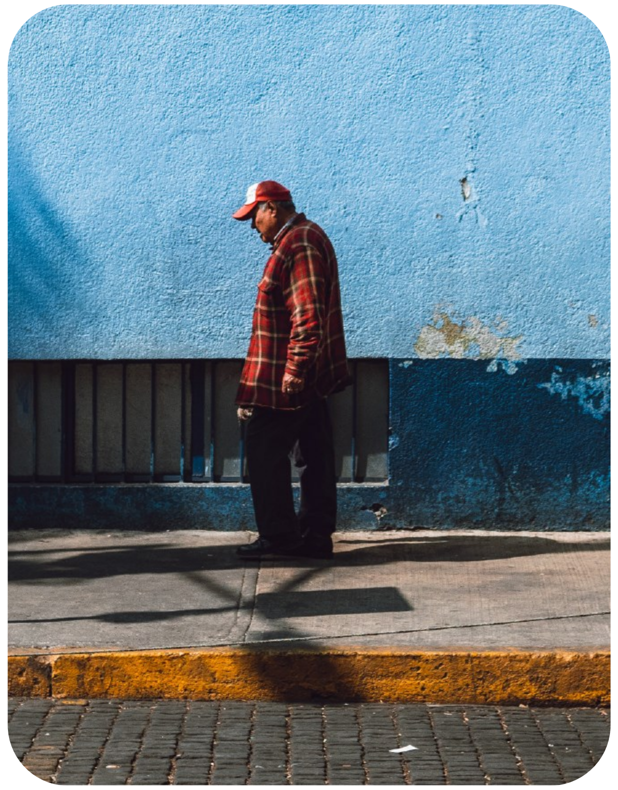
The visual ageing hypothesis

- Wide array of visual deficits are associated with ageing
- Older adults focus on lower portions of scenes whilst locomoting
- Recent work points towards an age-related preference for geometric over landmark cues



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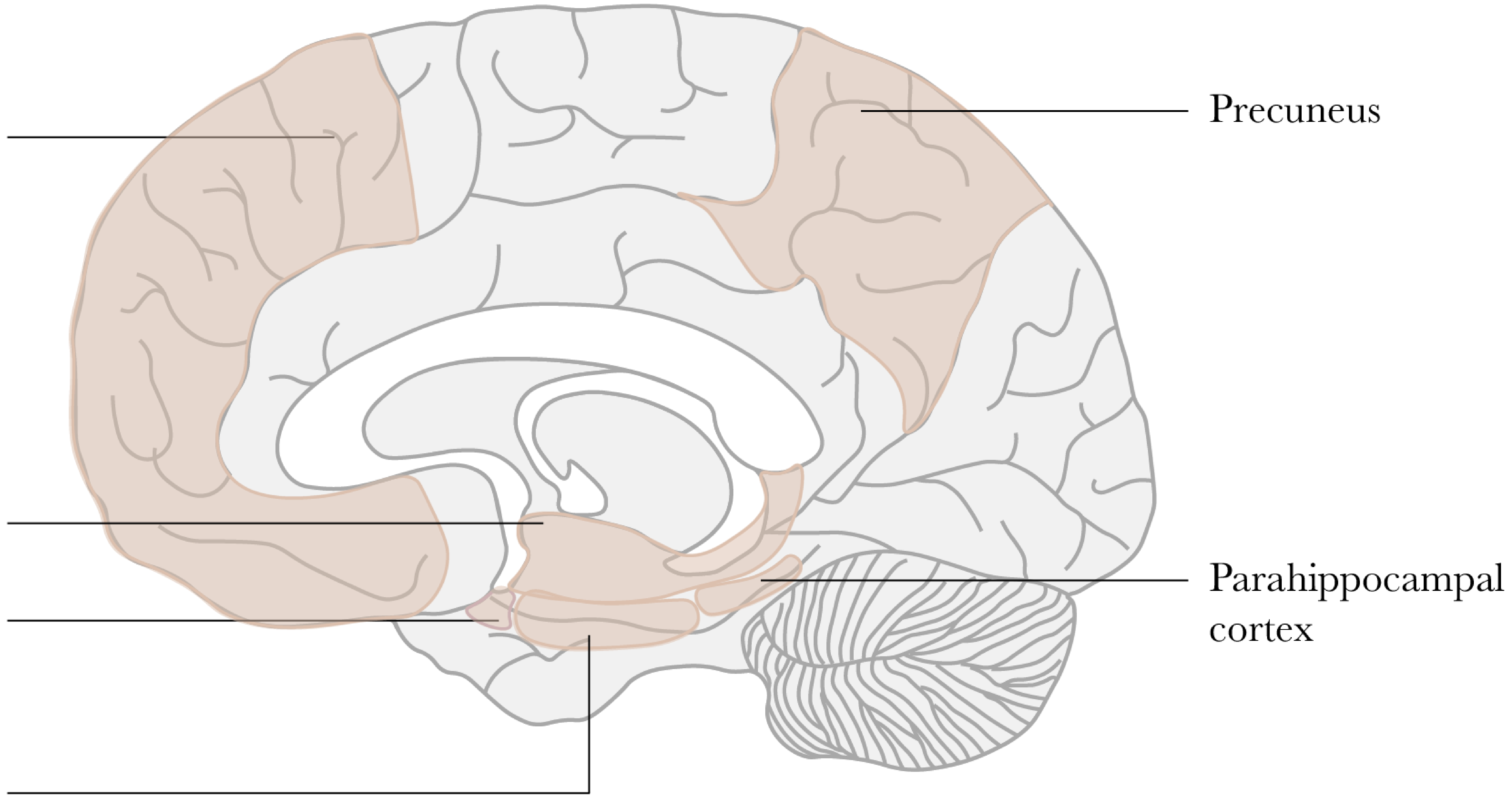
Neural correlates of navigation deficits



Storsve et al, 2014, *J. Neurosci.*; Li and King, 2019, *Neurosci. Biobehav. Rev.*

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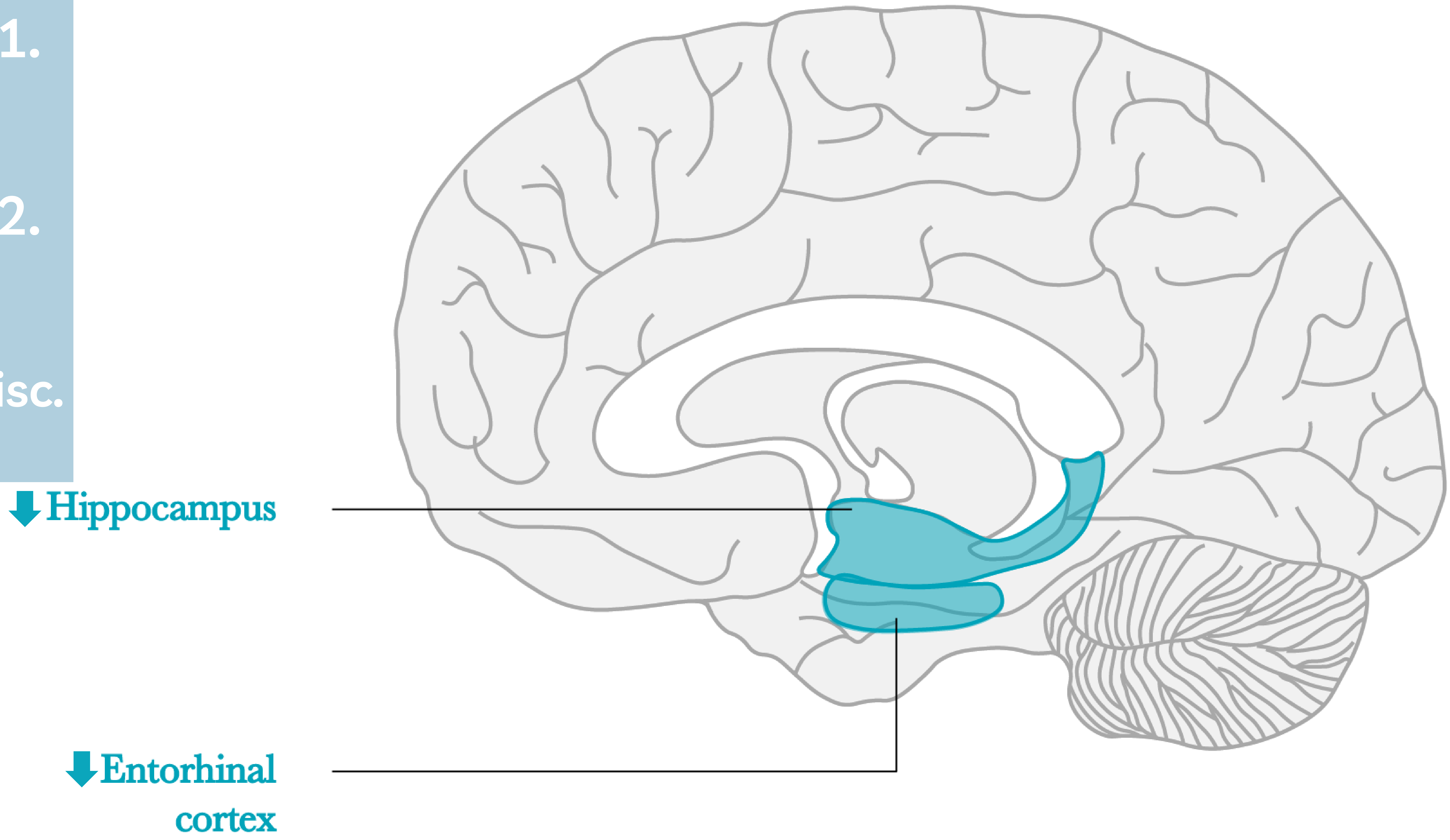

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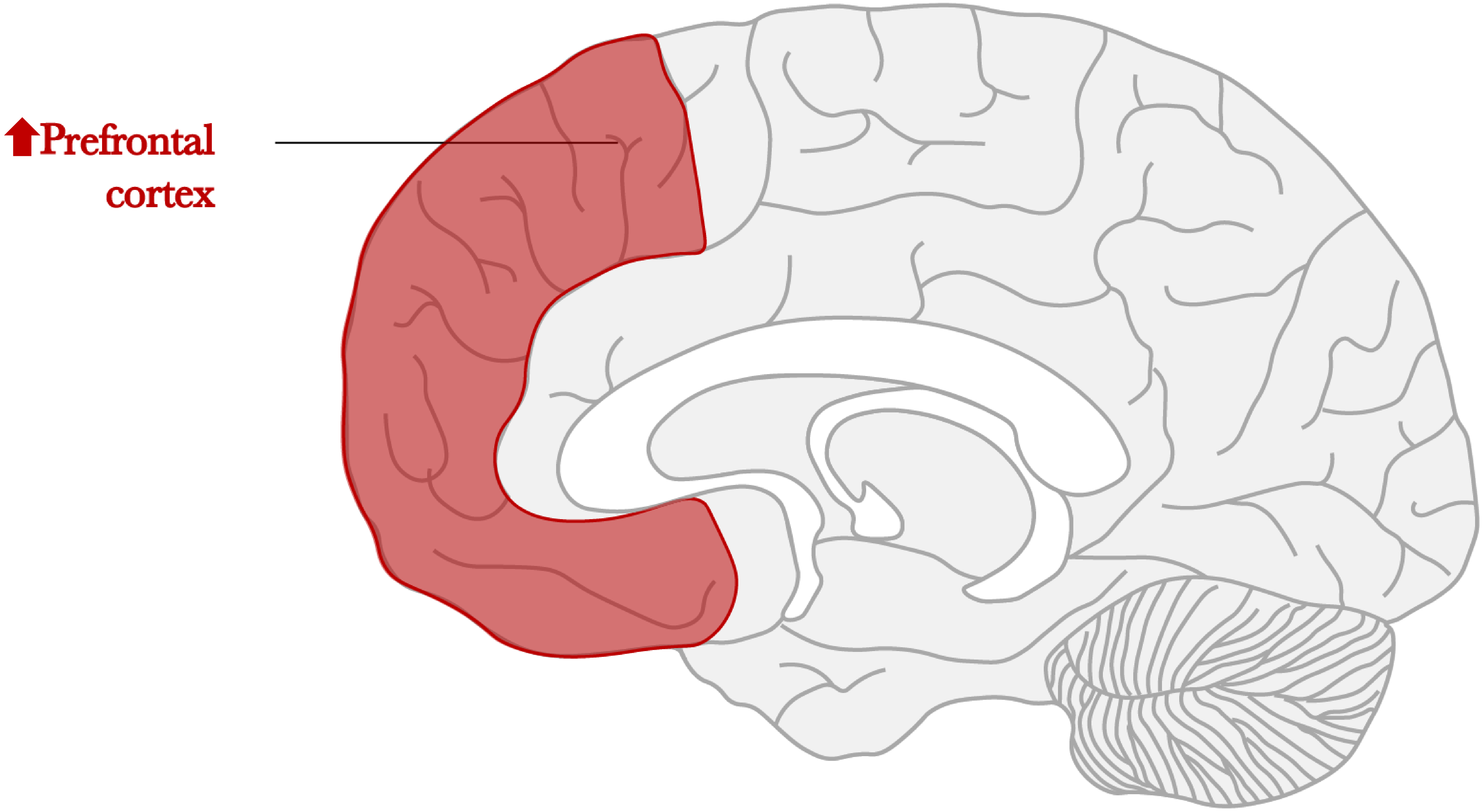

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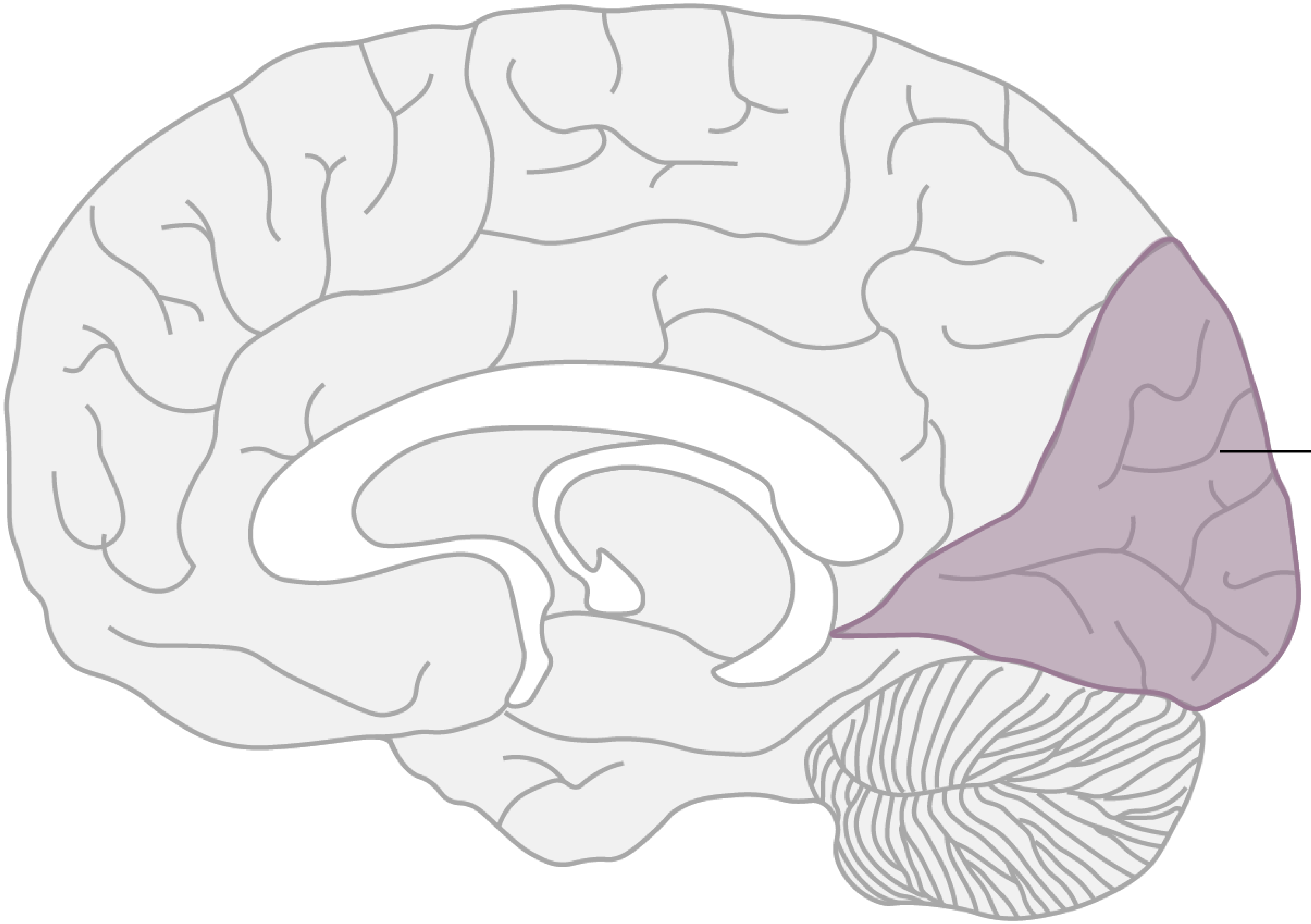

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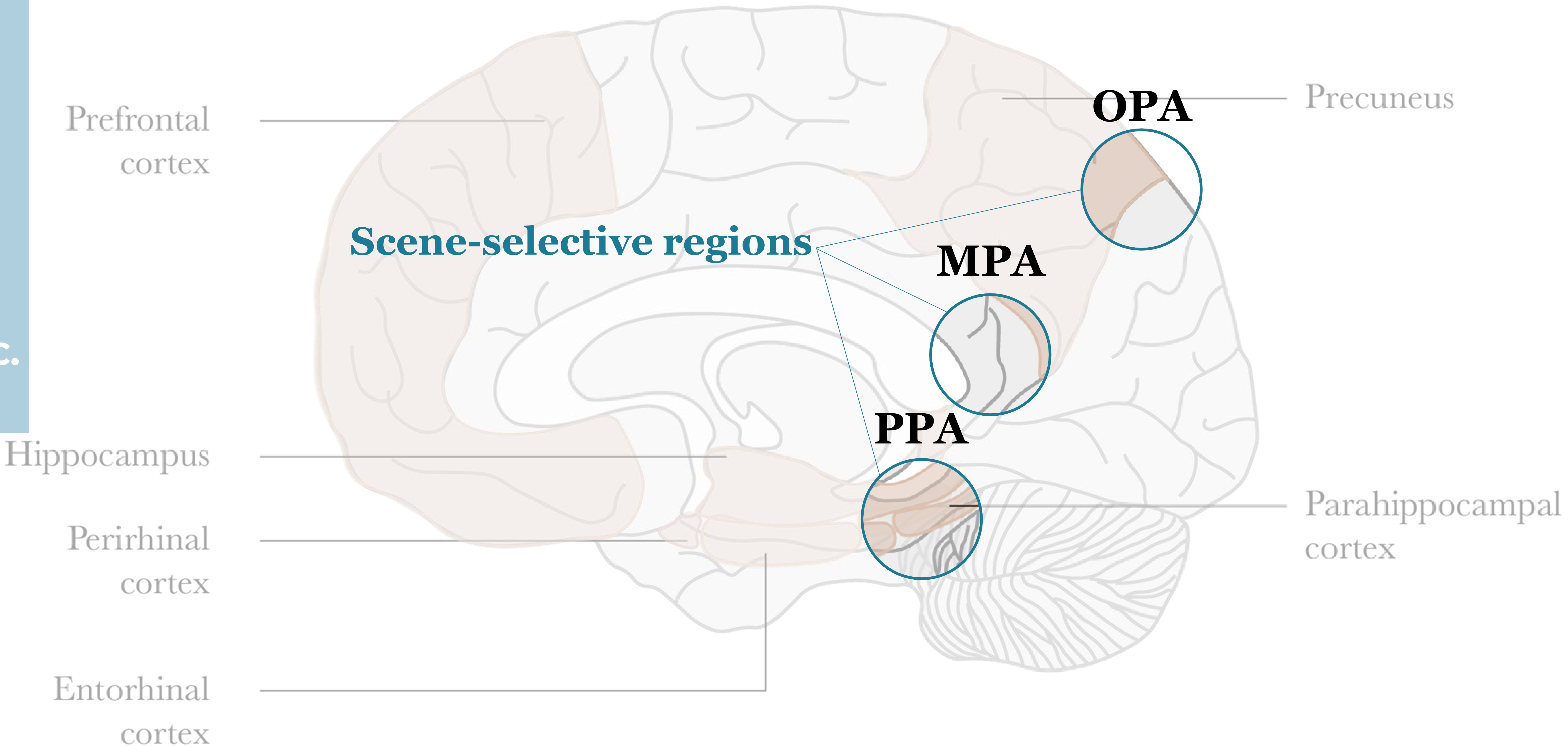

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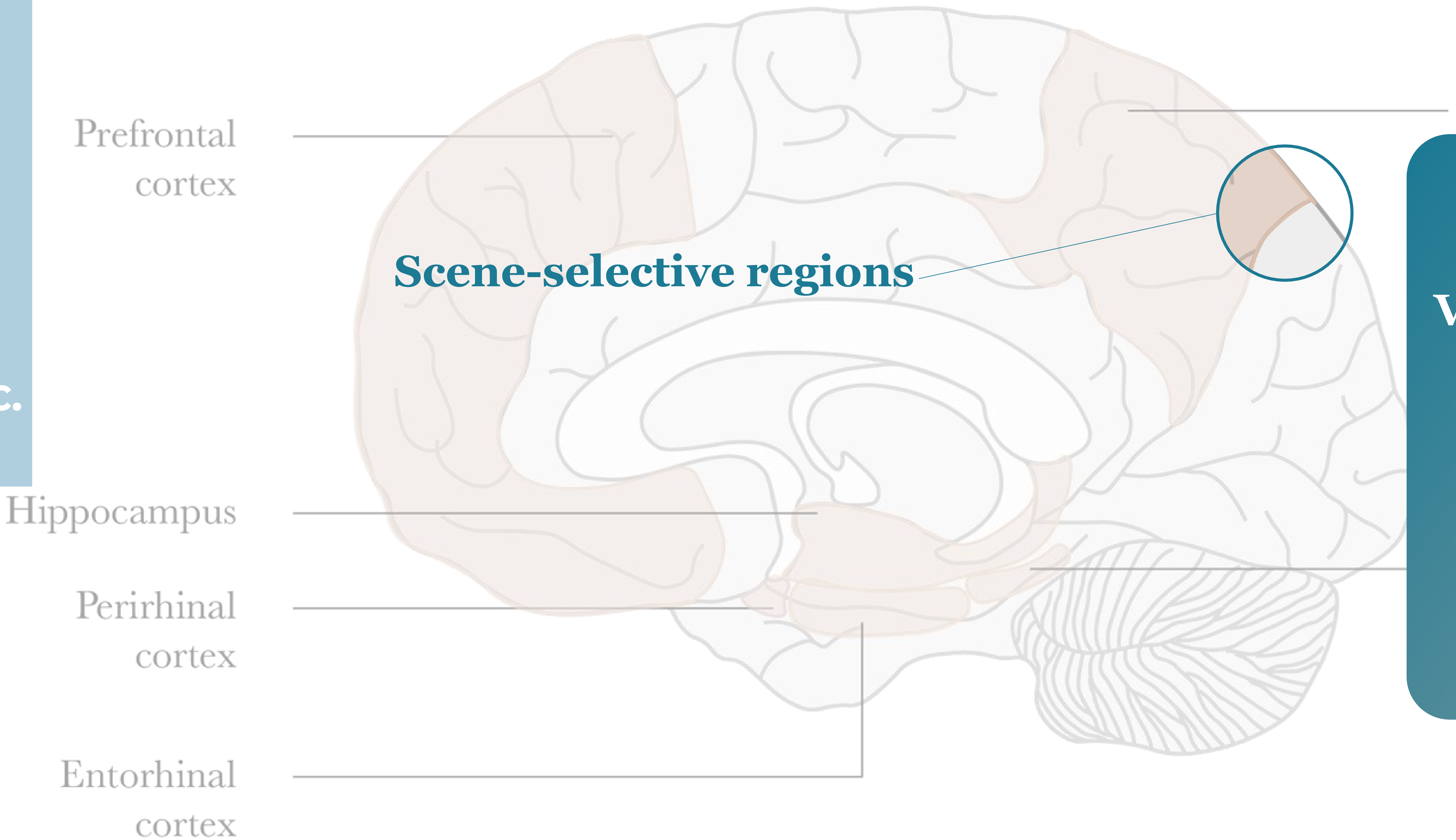

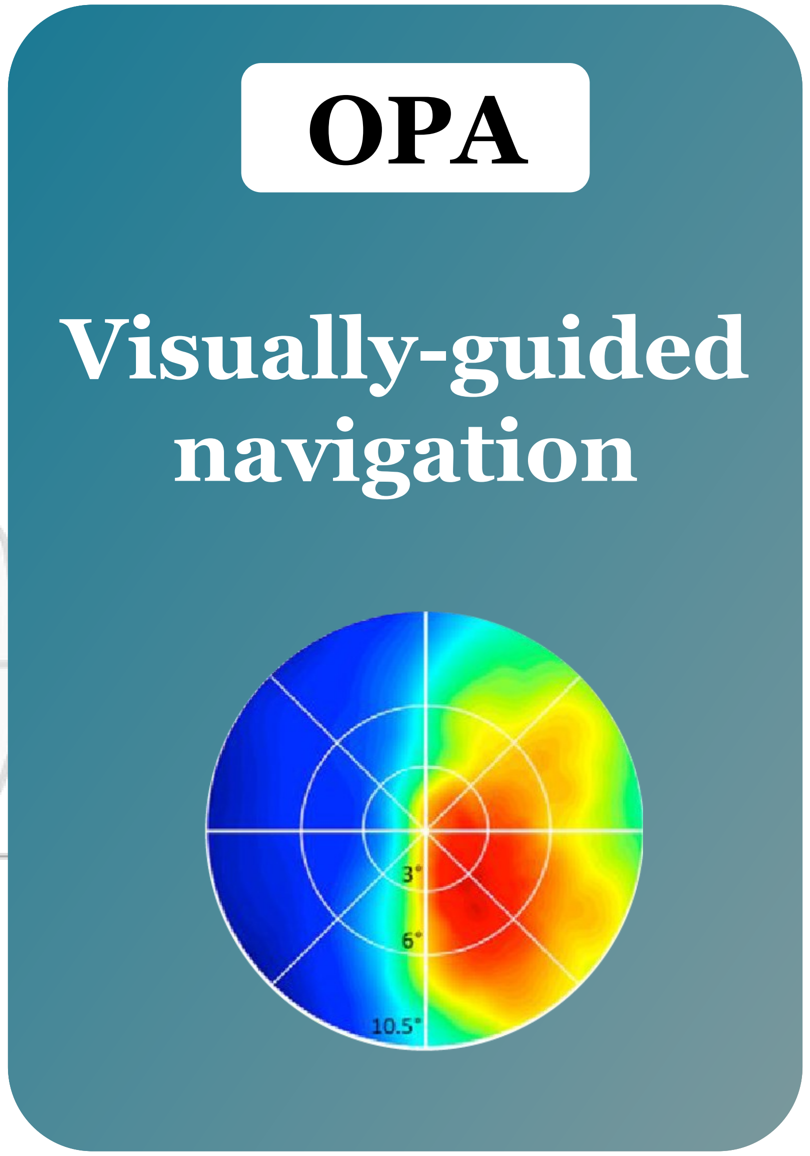

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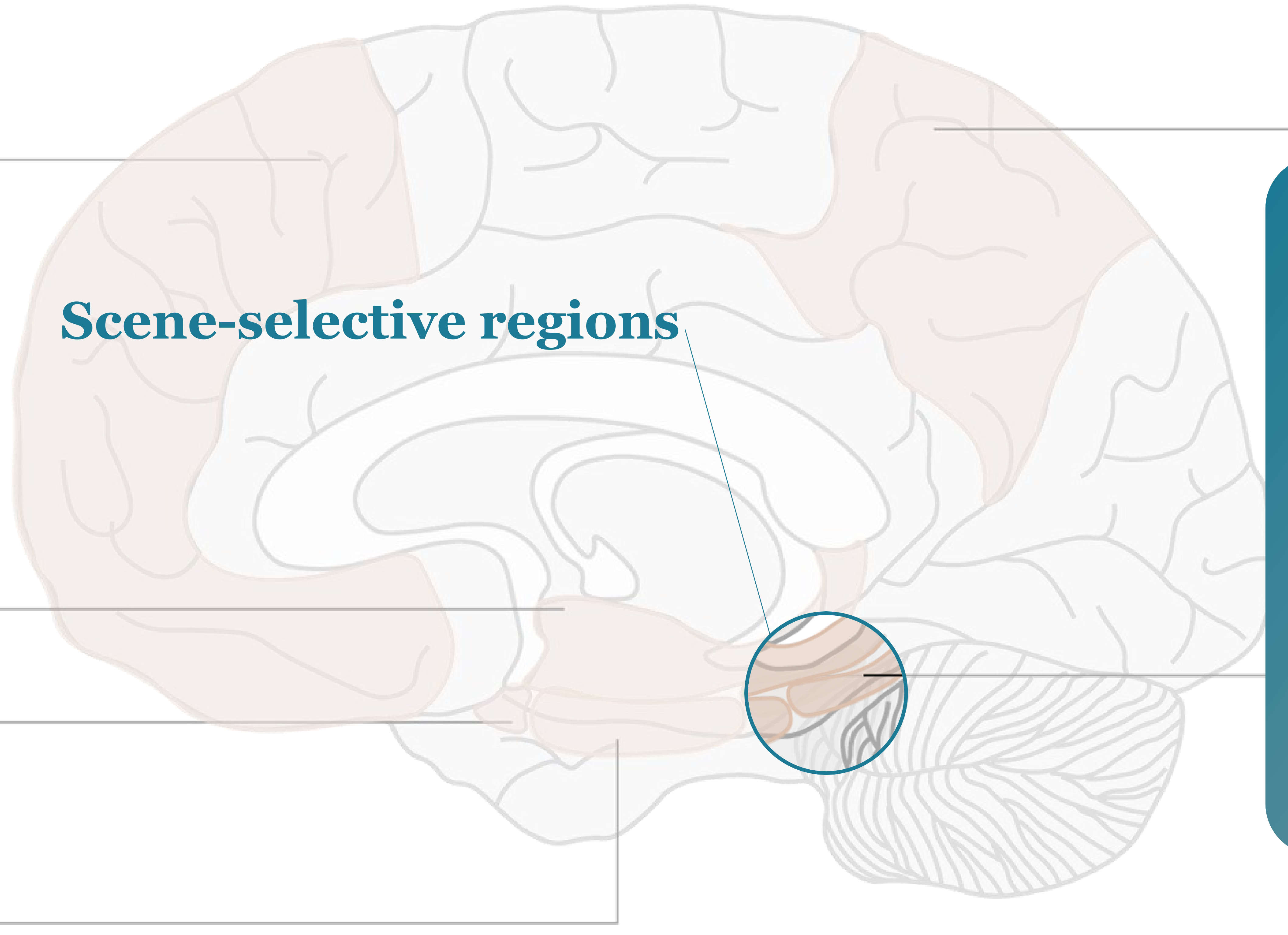
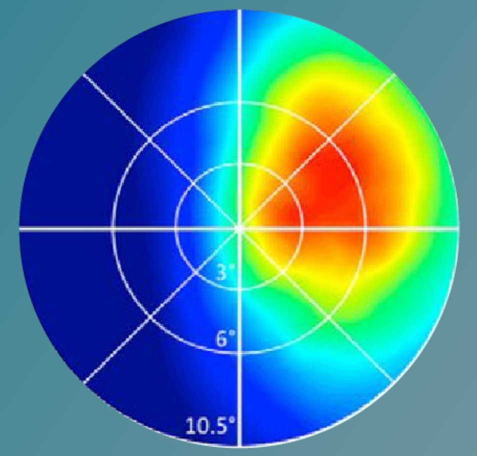


PPA

Scene categorisation



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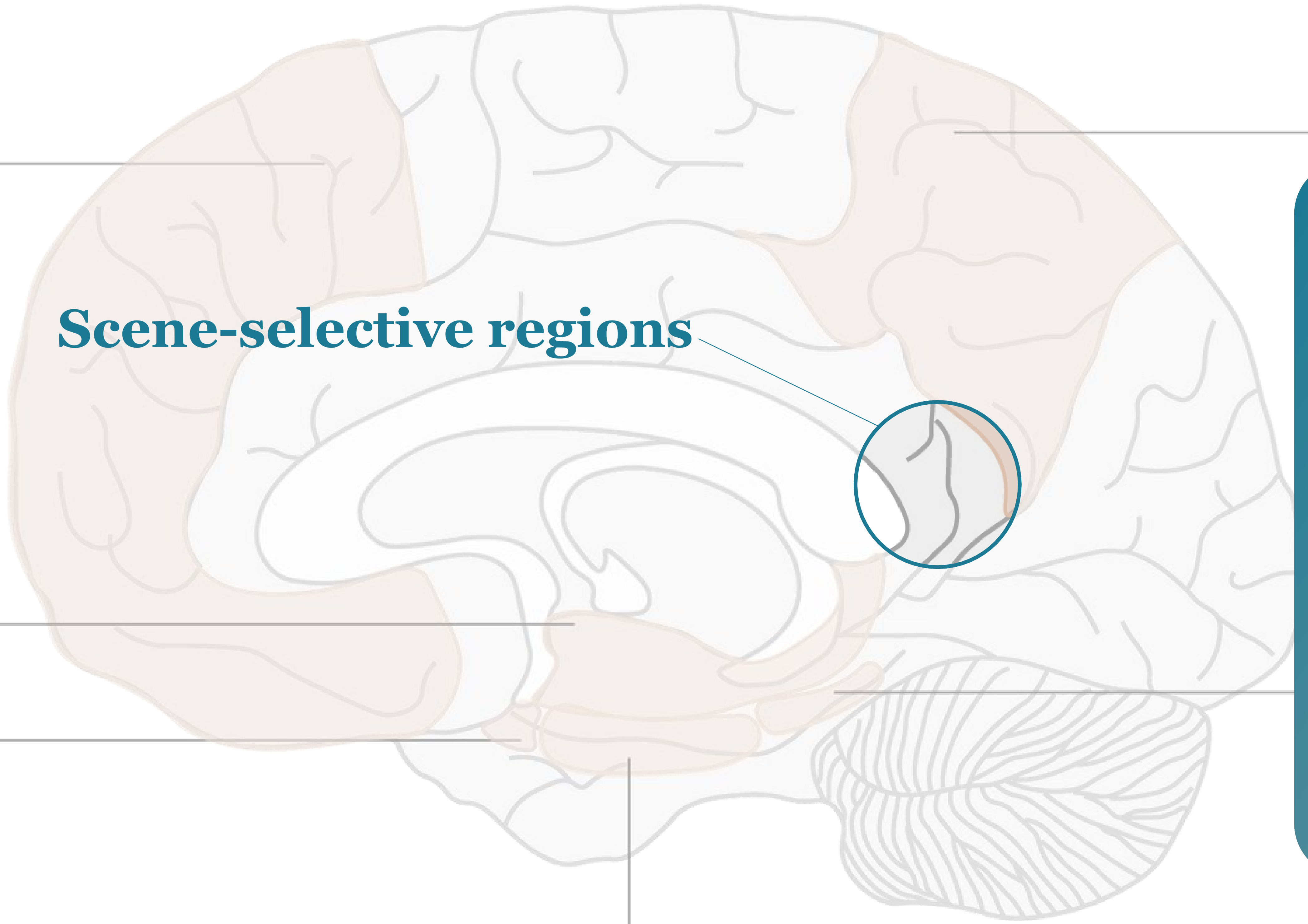
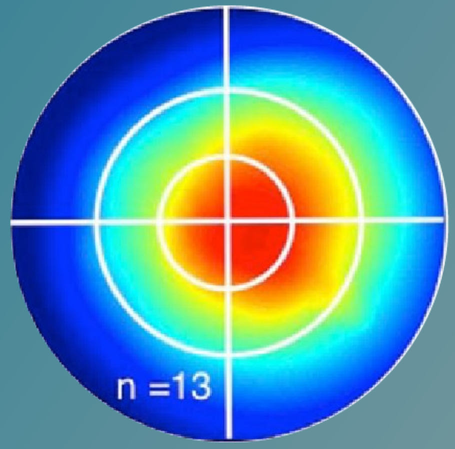
Neural correlates of navigation deficits



MPA

Map-based navigation



Dilks et al, 2022, *Trends Cog. Sci.*; Silson et al., 2015, *J. Neurosci.*; Silson et al., 2016, *Front. Hum. Neurosci.*

Aims of the present work

01.

Neural bases of visual cue-based navigation throughout adulthood

1. Do different types of visual cues elicit distinct neural patterns?
2. What are the age-related neural differences during object-based navigation?

02.

The vertical position of information for spatial memory and navigation throughout adulthood

Study 1

Methods

1

Do different types of visual cues elicit distinct neural patterns?

Modality: fMRI

Experiment: Virtual spatial navigation task

Virtual environment: Y-maze

Sample: 25 young adults (25.4 ± 2.7 y.o.)

Durteste*, Ramanoël* et al, 2022, *Hum. Brain Mapp.*

Study 1
Methods

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silversight research chair

Durteste*, Ramanoël* et al, 2022, *Hum. Brain Mapp.*

Study 1

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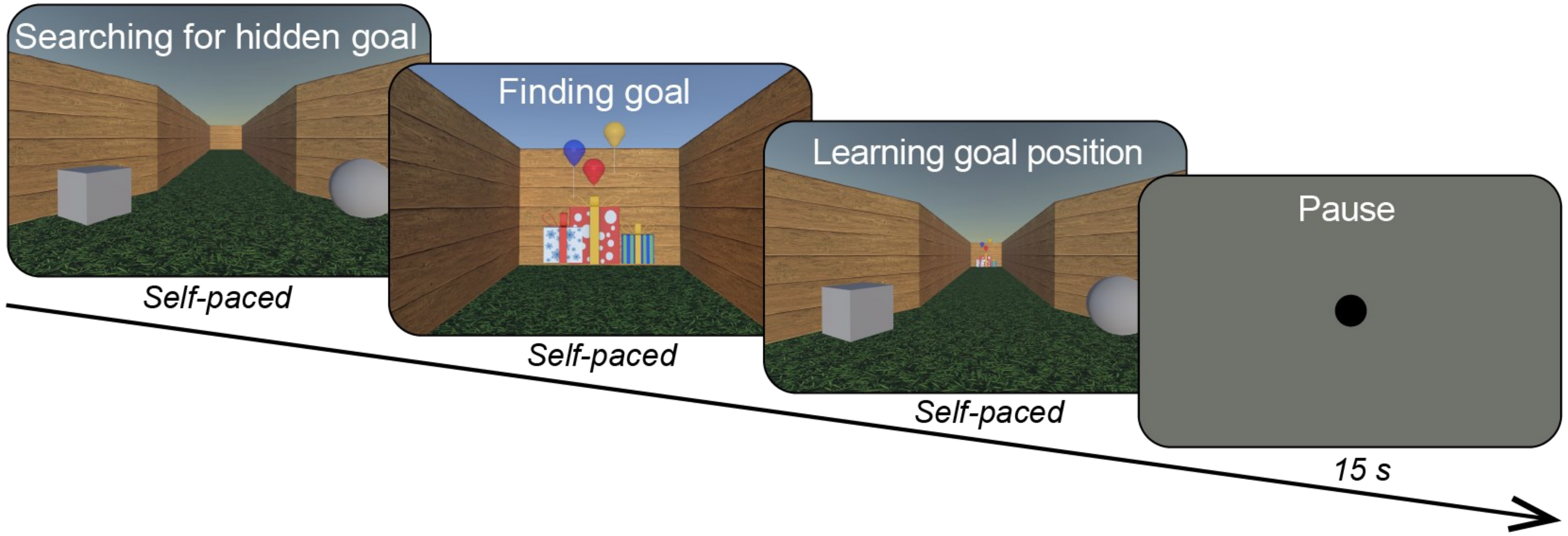

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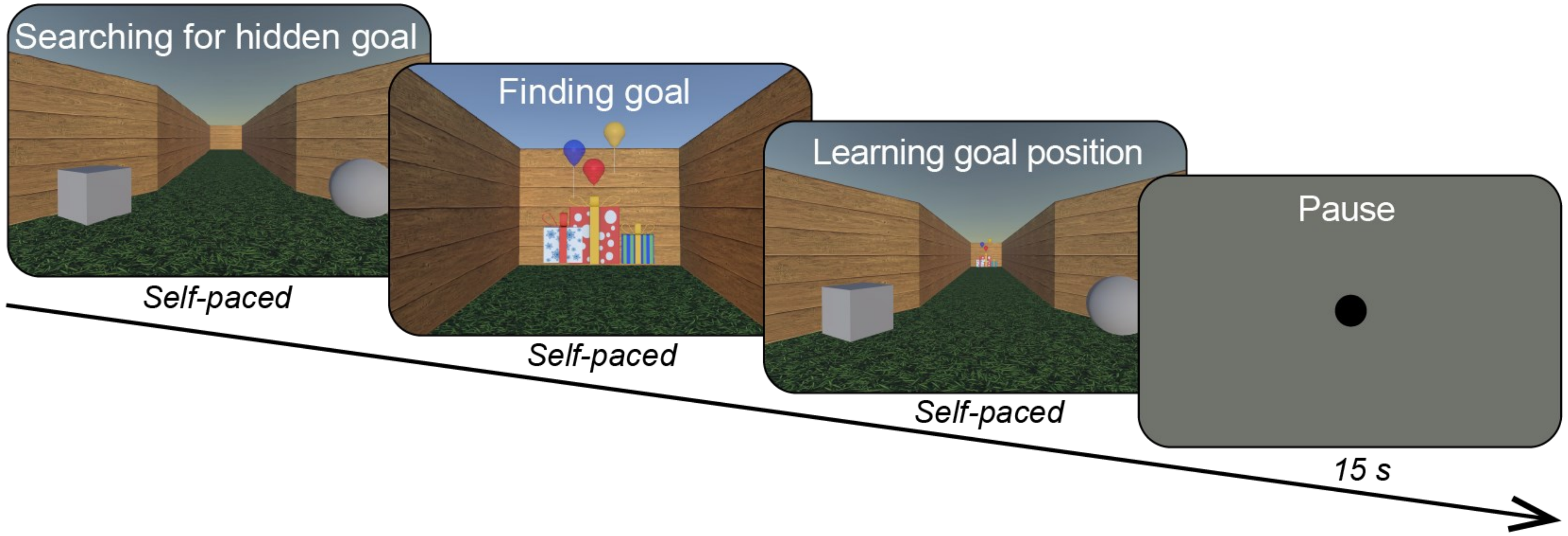

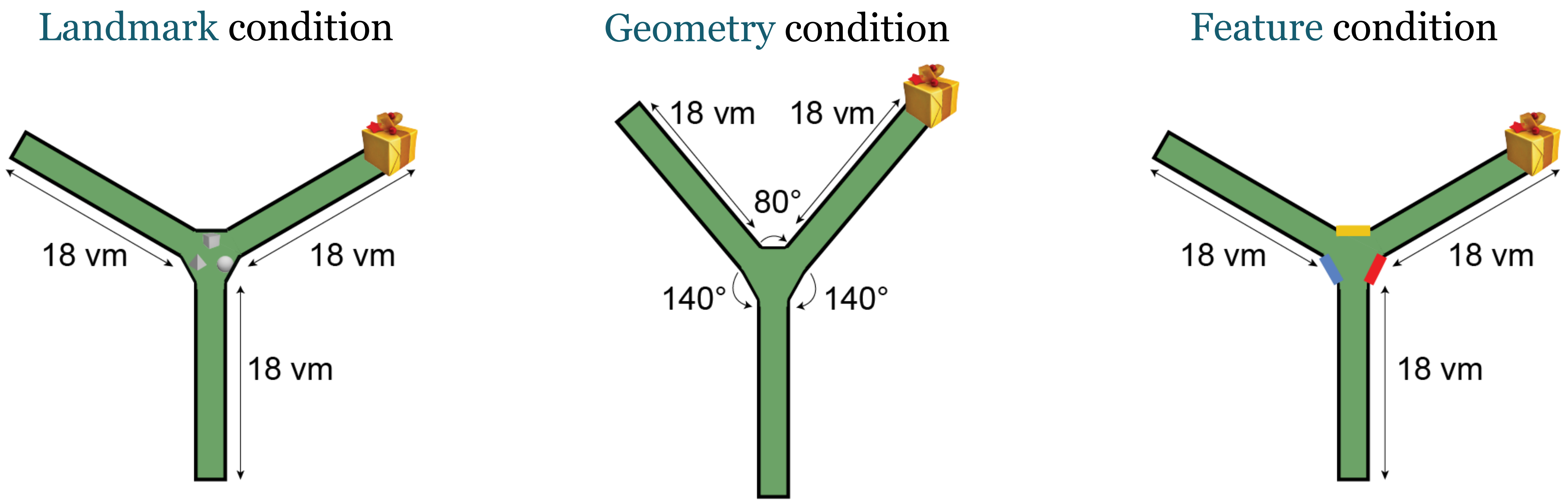

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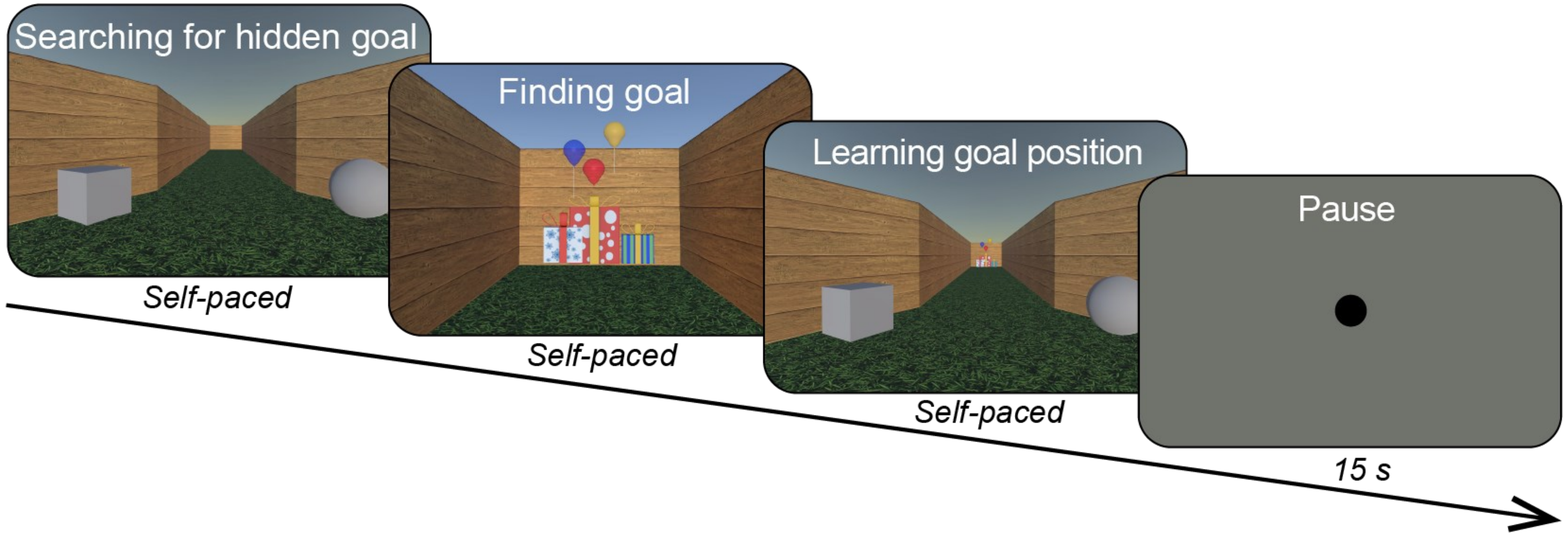
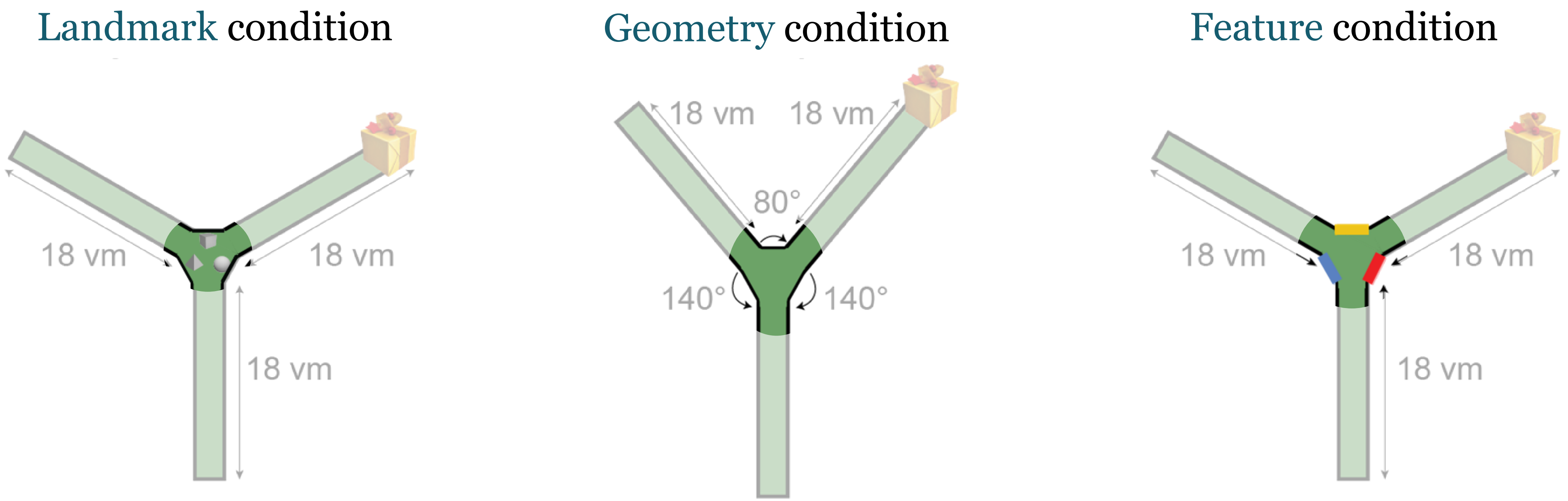
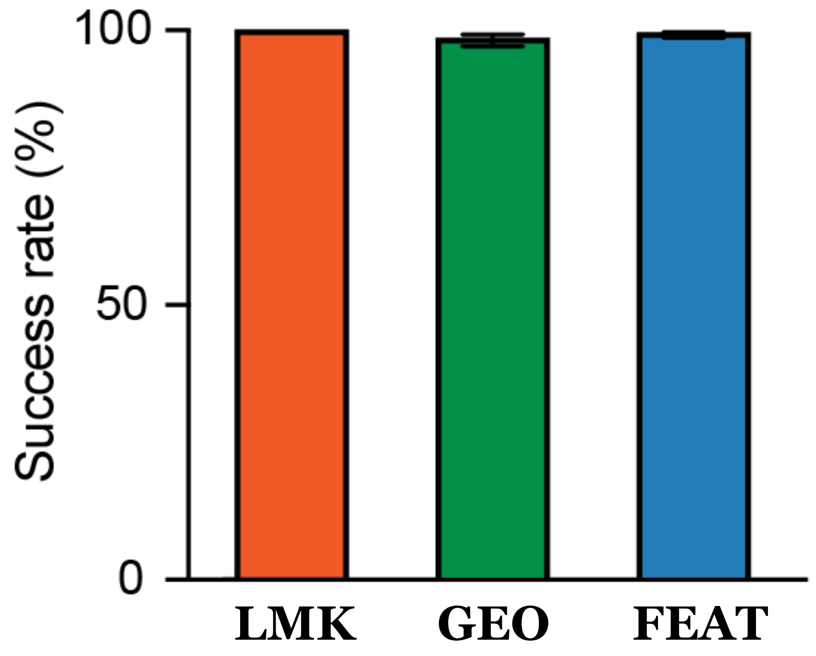




Durteste*, Ramanoël* et al, 2022, *Hum. Brain Mapp.*

Study 1

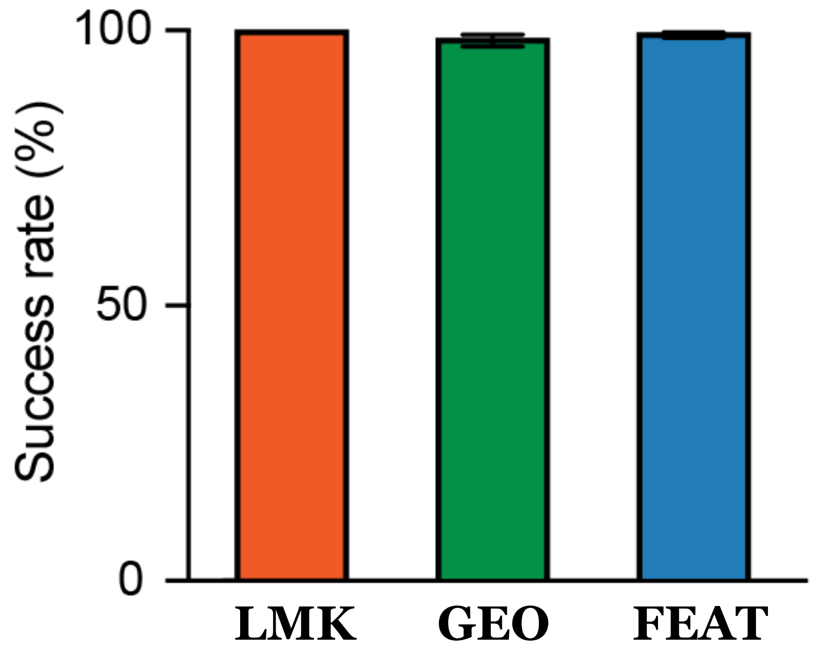
Behavioural results



Navigation performance is equivalent across conditions

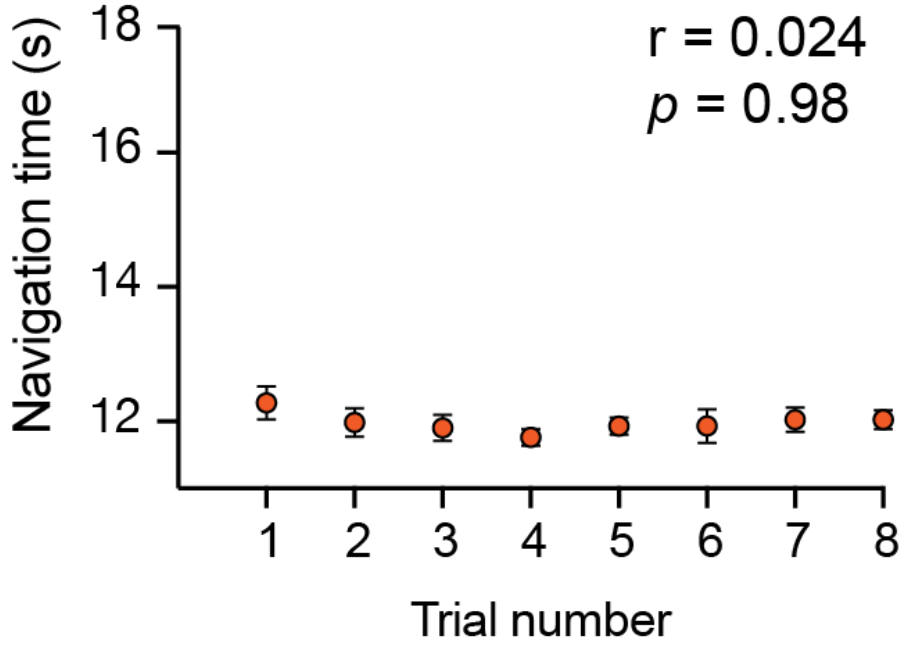
Study 1

Behavioural results

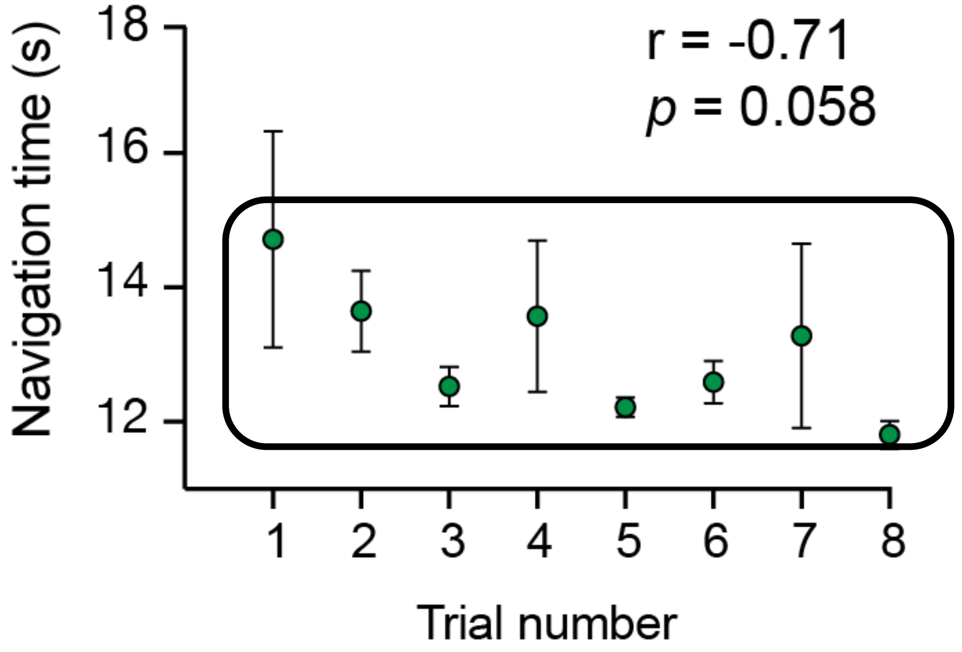


Navigation performance is equivalent across conditions

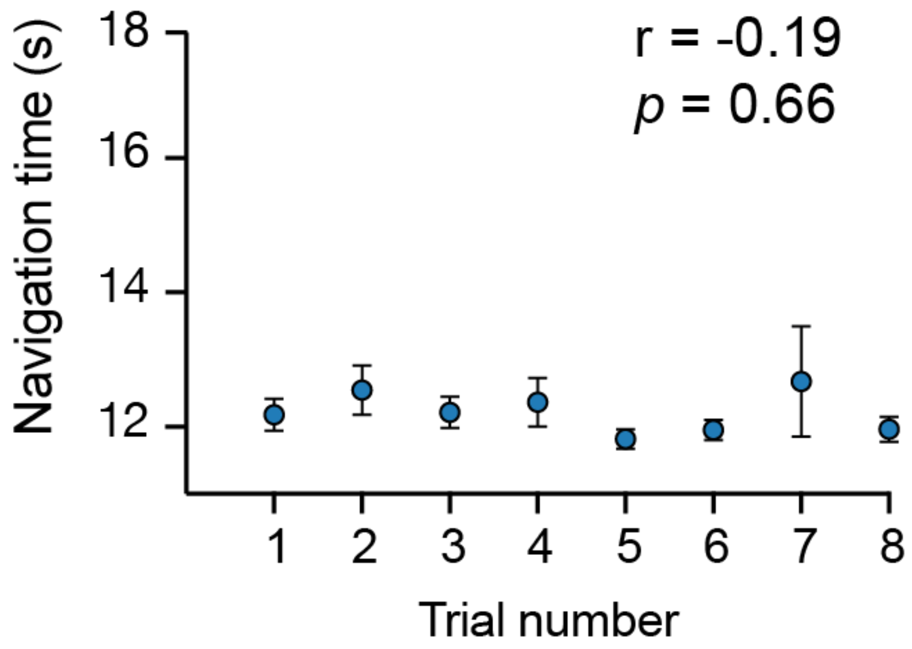
Landmark condition



Geometry condition



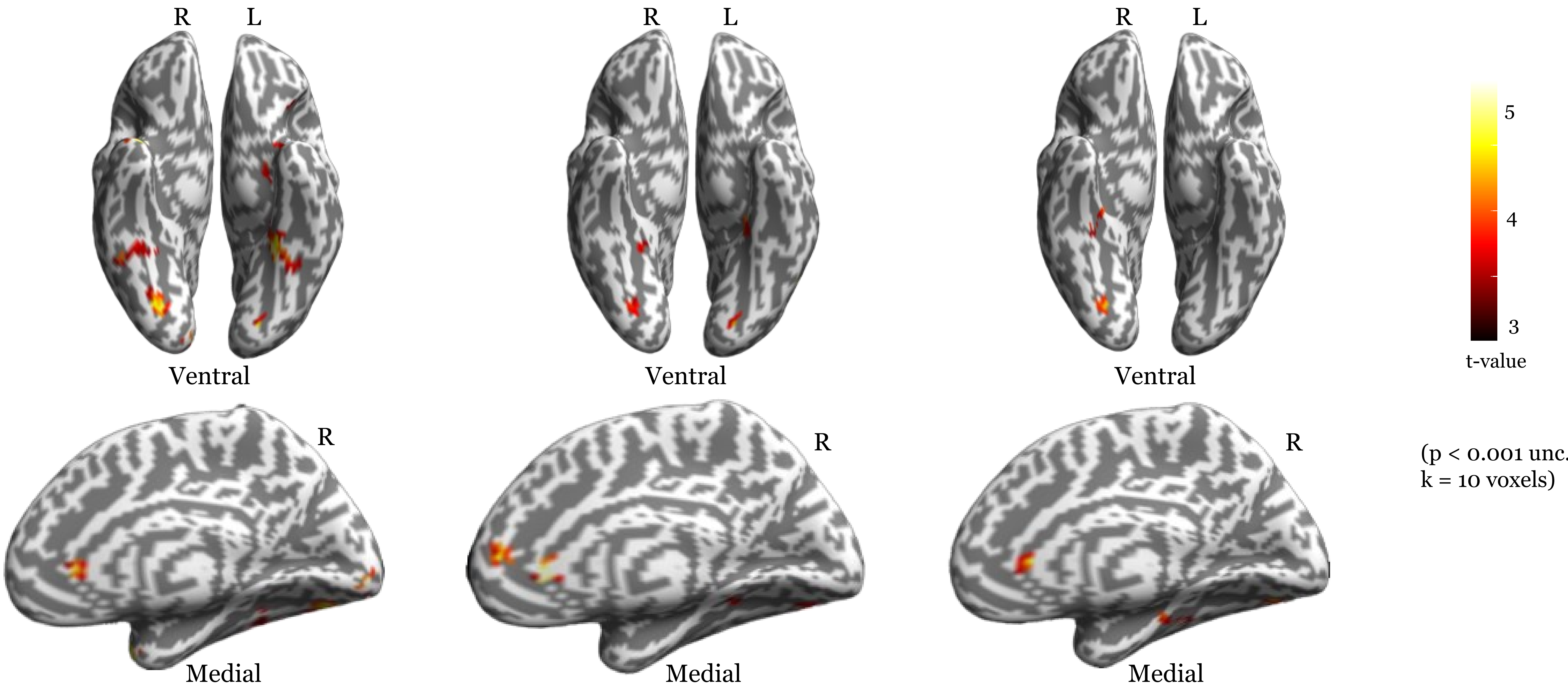
Feature condition



Study 1

Neuroimaging results

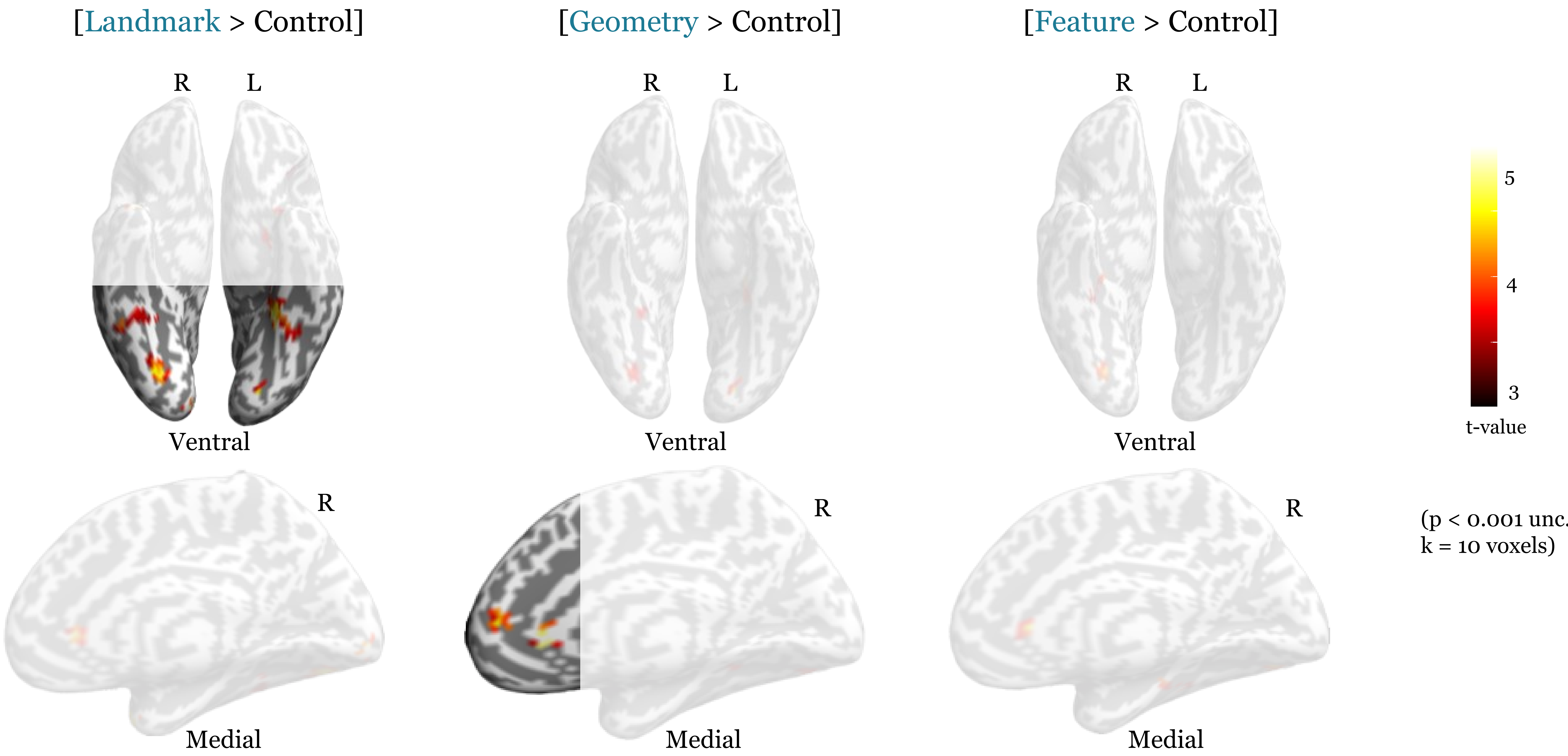
[Landmark > Control] [Geometry > Control] [Feature > Control]



(p < 0.001 unc., k = 10 voxels)

Study 1

Neuroimaging results



Study 1

Take-home message

Each type of visual cue elicits a specific pattern of neural activation

Durteste*, Ramanoël* et al, 2022, *Hum. Brain Mapp.*

Study 2
Methods

2

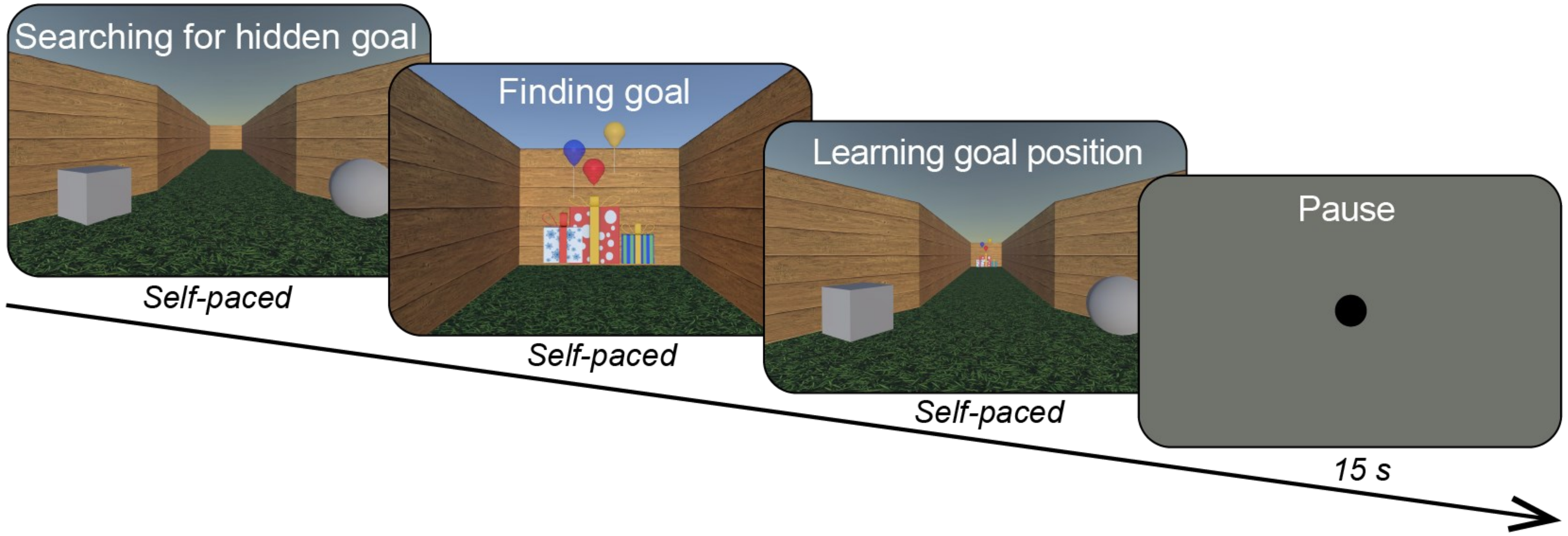
What are the age-related neural differences during landmark-based navigation?

Modality: fMRI

Experiment: Virtual spatial navigation task

Virtual environment: Y-maze

Sample: 21 older adults (73.0 ± 3.9 y.o.)
25 young adults (25.4 ± 2.7 y.o.)



Durteste*, Ramanoël* et al, 2020, *Front. Hum. Neurosci.*

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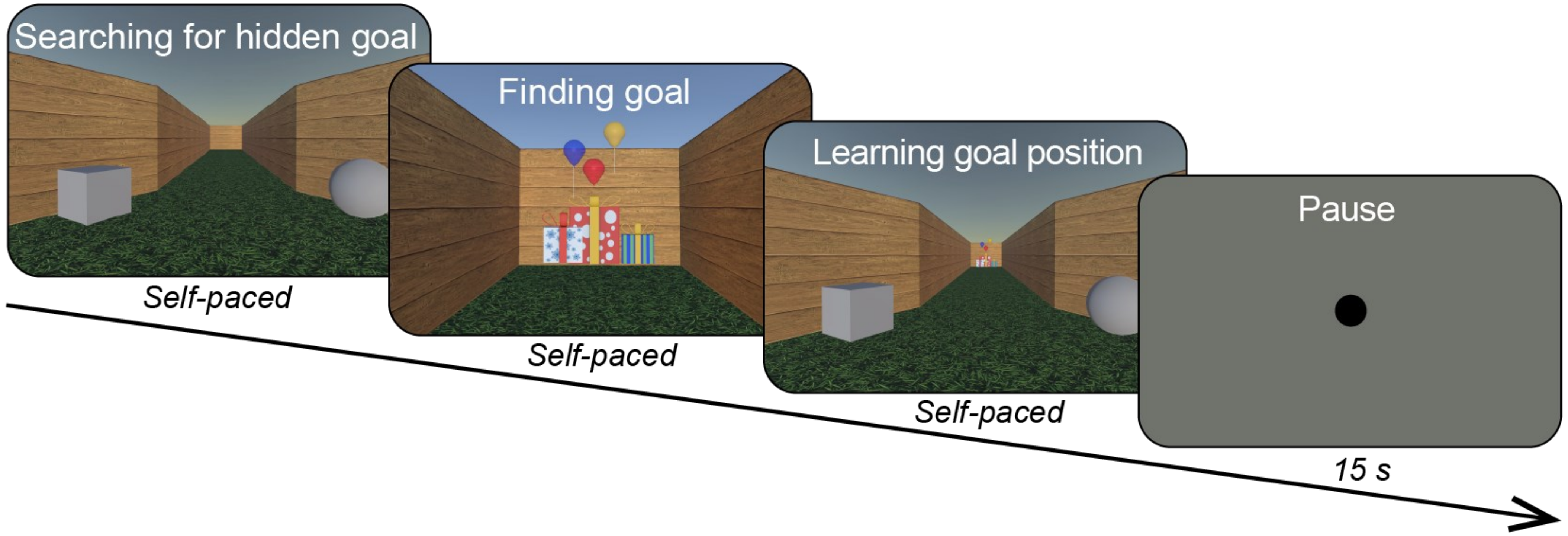
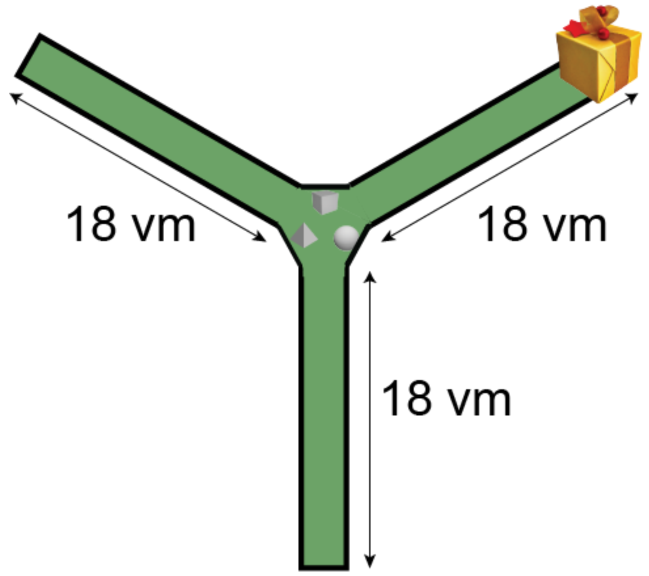


Landmark condition



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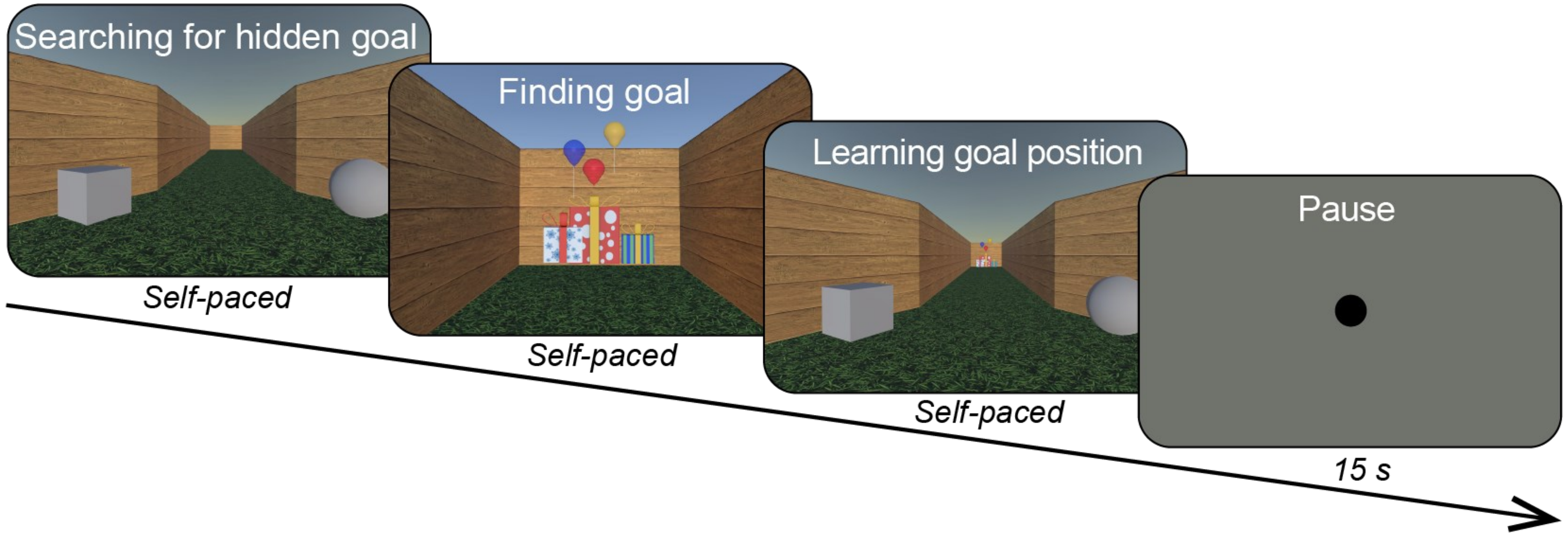

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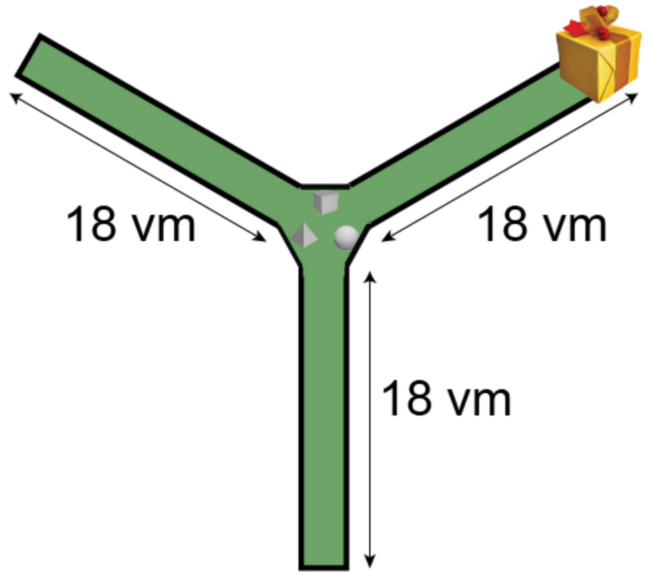


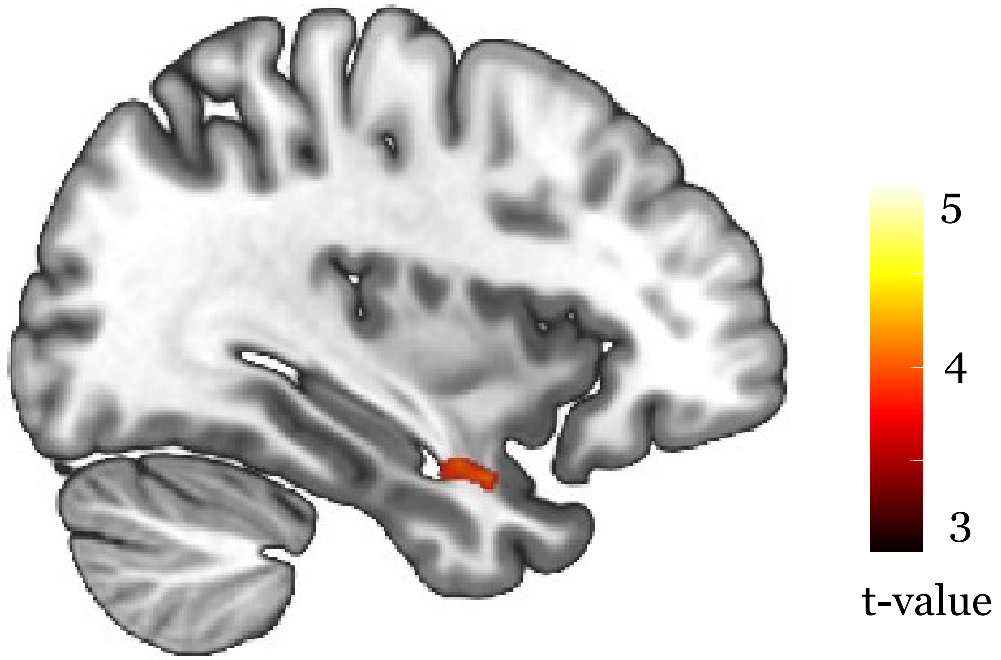
14.3% error rate in older adults vs. 0% rate in young adults ($p < 0.001$)

Durteste*, Ramanoël* et al, 2020, *Front. Hum. Neurosci.*

Study 2

Neuroimaging results

[Young > Older]



x = -33

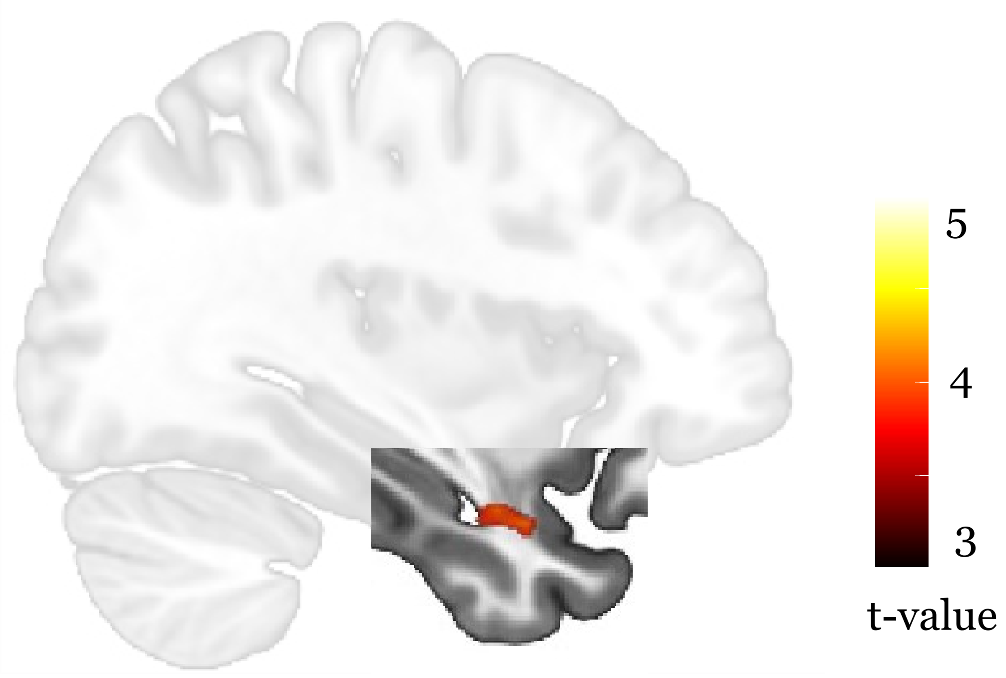
During landmark-based navigation, older adults display decreased activity in visual regions

Durteste*, Ramanoël* et al, 2020, *Front. Hum. Neurosci.*

Study 2

Neuroimaging results

[Young > Older]



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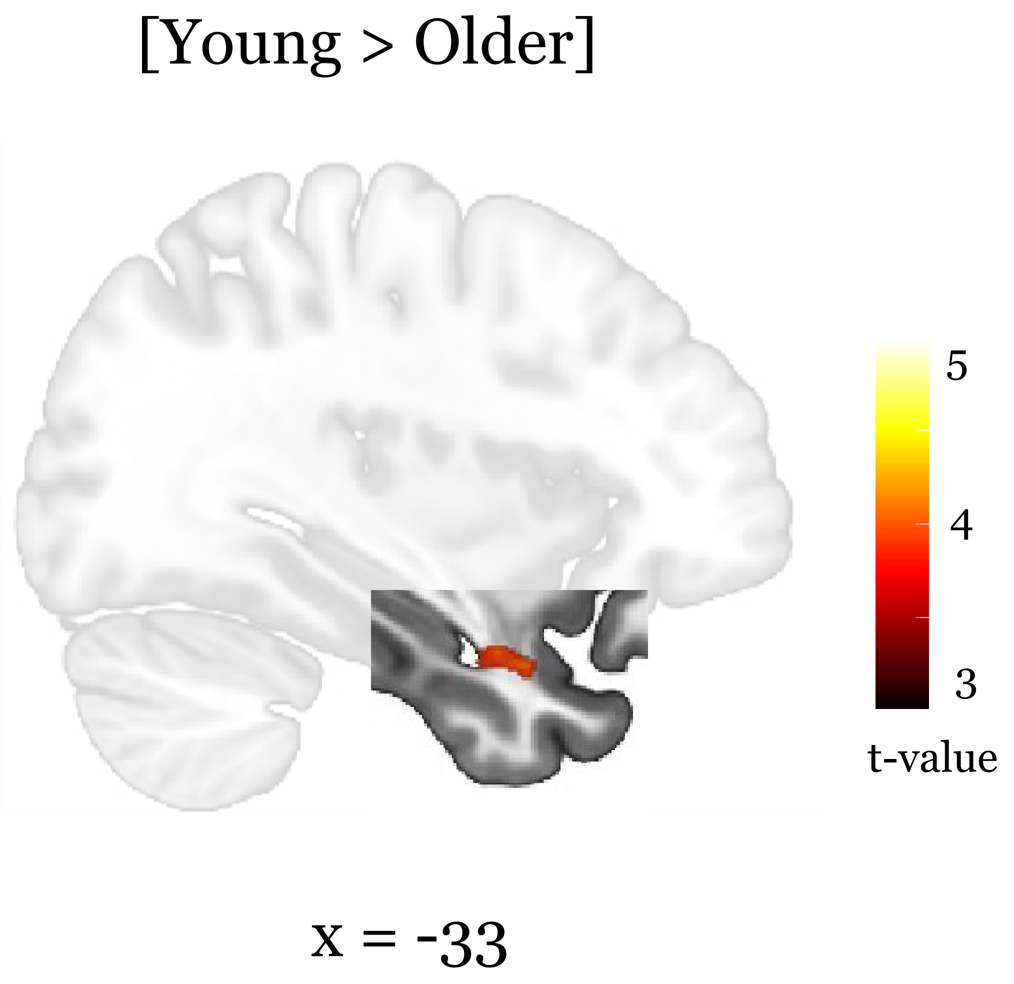
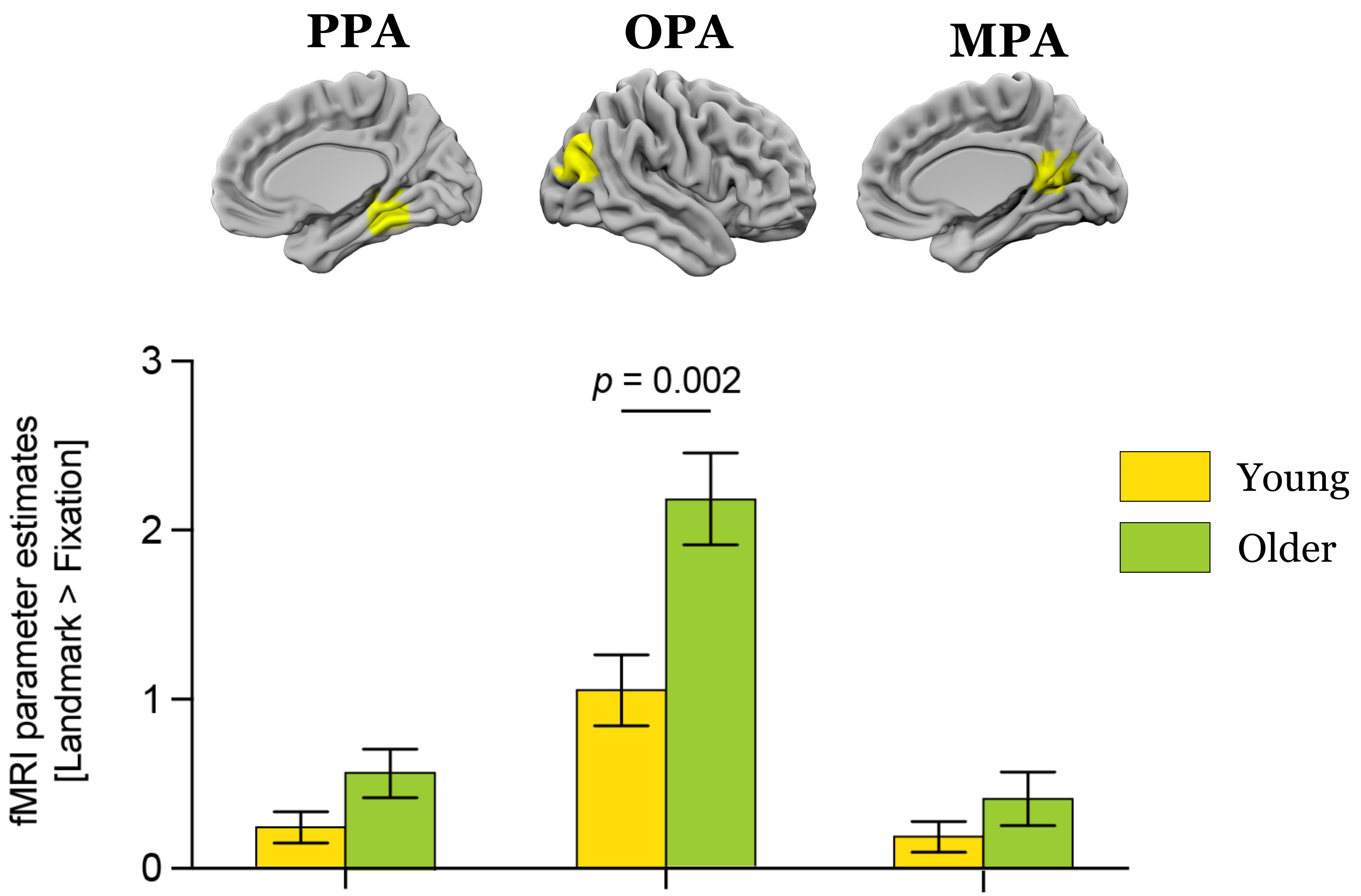




During landmark-based navigation, older adults display decreased activity in visual regions

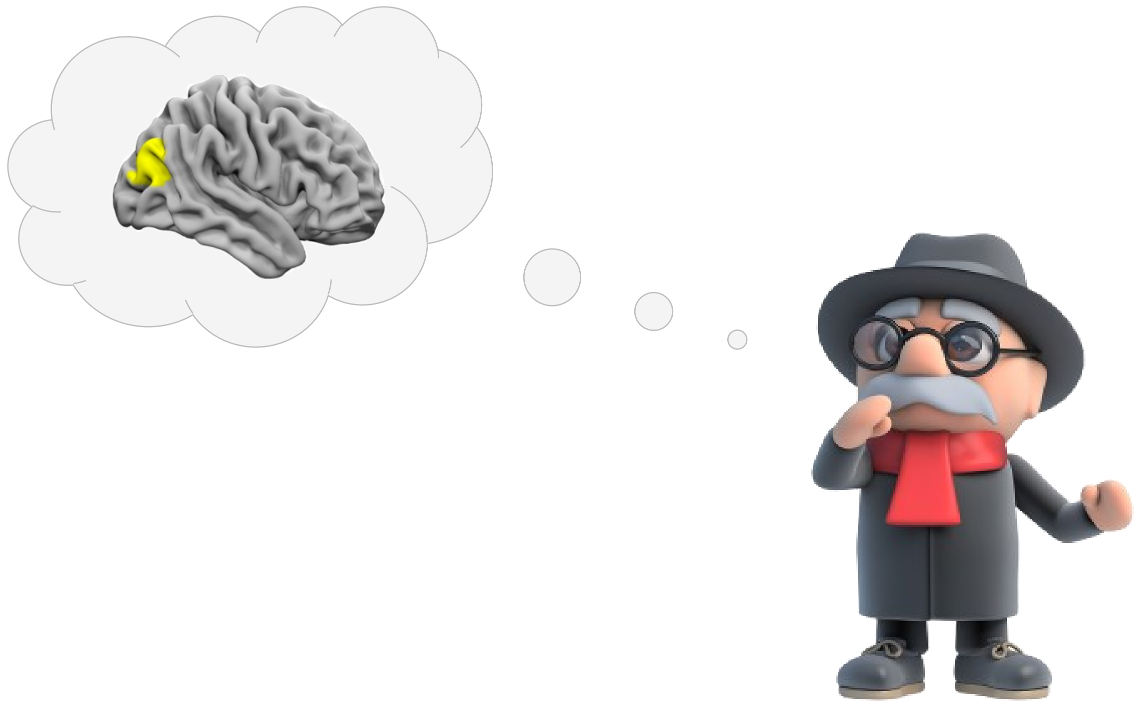
During landmark-based navigation, the OPA is more active in older adults

Durteste*, Ramanoël* et al, 2020, *Front. Hum. Neurosci.*

Study 2

Take-home message

Activity in high-level visual regions differs between young and older adults during navigation



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Aim 01

Summary

Importance of visual processing for navigation as

- visual cues influence participants' spatial behaviour
- visual cues modulate underlying neural patterns

Aim 01

Summary

- Importance of visual processing for navigation as
  - visual cues influence participants' spatial behaviour
  - visual cues modulate underlying neural patterns
- Older adults exhibit increased engagement of the OPA during landmark-based navigation

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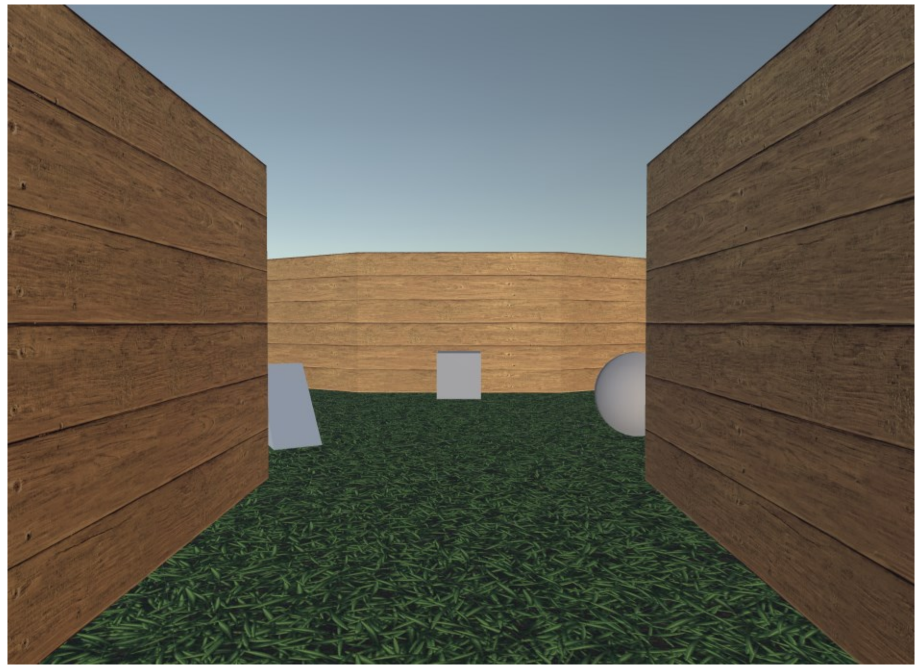

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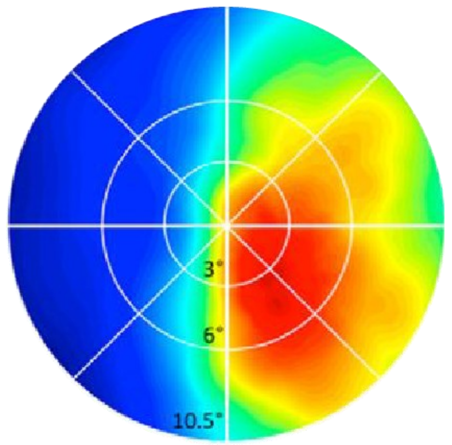
OPA



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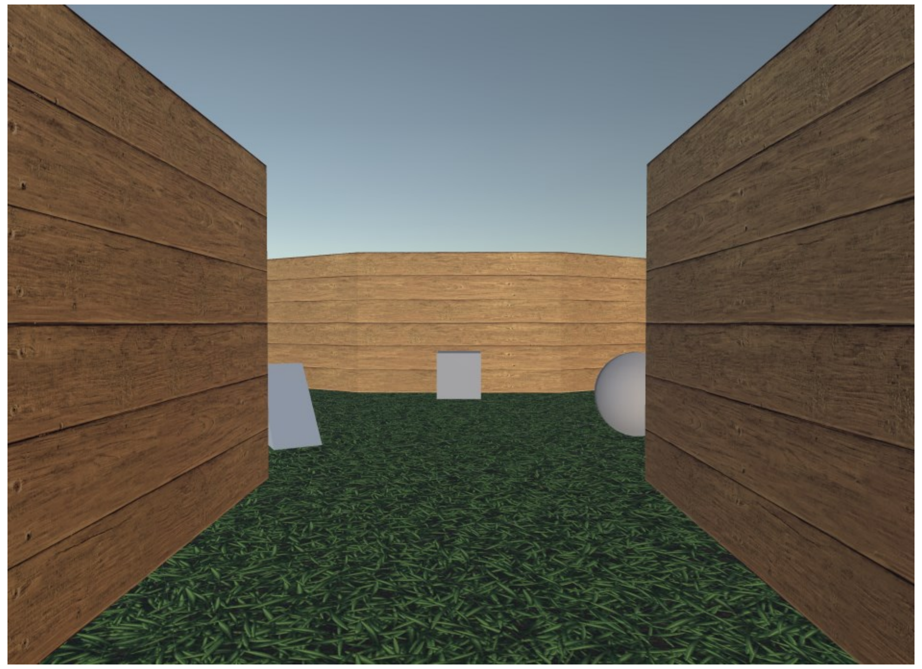

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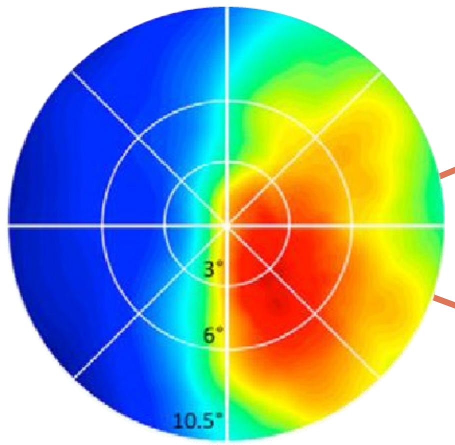

Could the vertical position of landmarks be playing a role?

Aims of the present work

01.

Neural bases of visual cue-based navigation throughout adulthood

02.

The vertical position of information for spatial memory and navigation throughout adulthood

3 Does the vertical position of objects condition mnemonic performance ?

4 How do gaze patterns adapt to the position of landmarks during spatial navigation?

5 What is the implication of scene-selective regions in encoding the vertical position of landmarks?

Study 3

Methods

3

Does the vertical position of objects condition mnemonic performance?

Modality: Desktop-based + Eye tracking

Experiment: Source monitoring task

Stimuli: Everyday objects

Sample: 21 older adults (75.3 ± 3.8 y.o.)
26 young adults (29.1 ± 4.2 y.o.)

Durteste et al., 2023, *Comm. Psychol.*

Study 3
Methods

3

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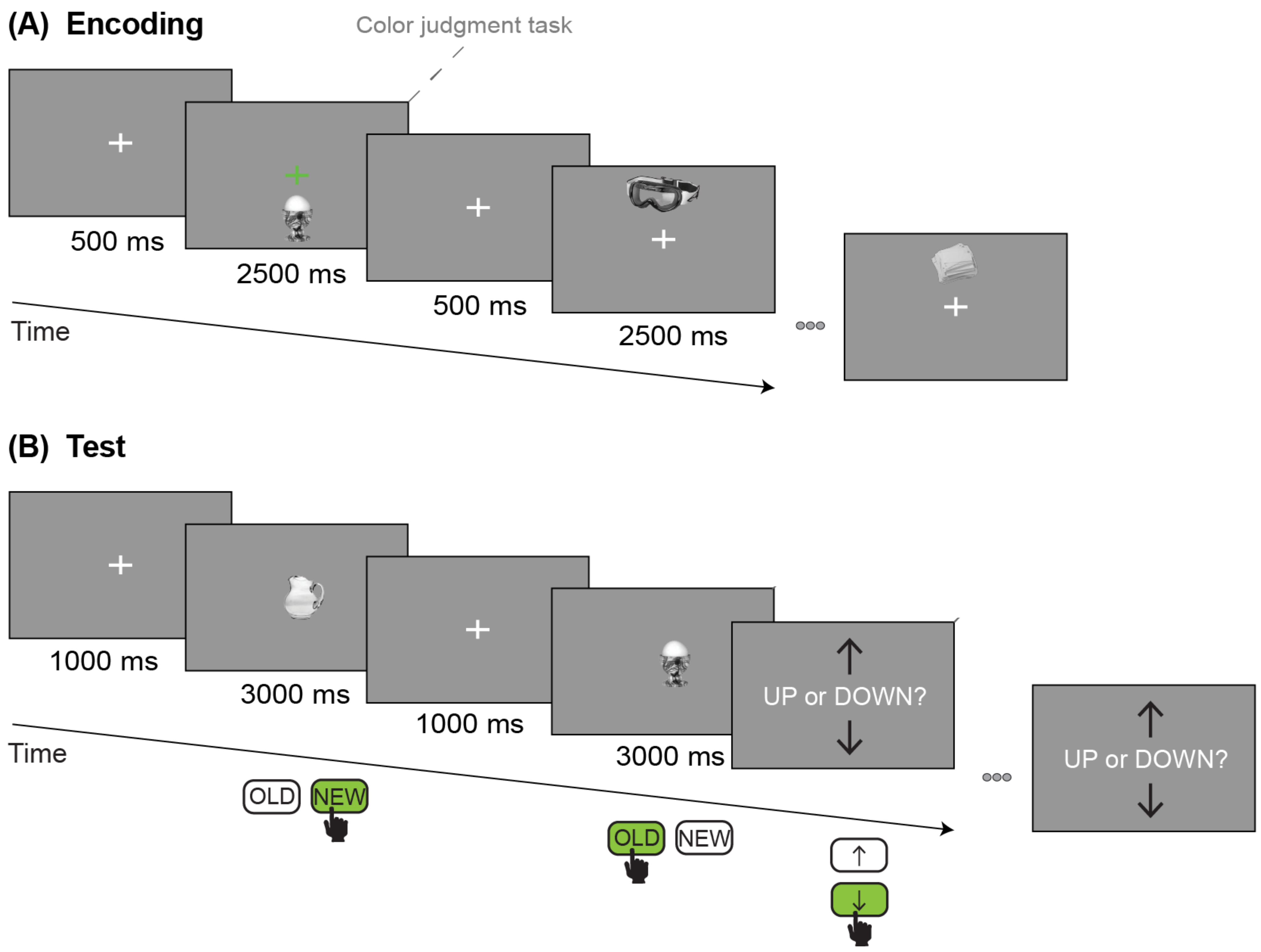
Stimuli: Everyday objects

Sample: 21 older adults (75.3 ± 3.8 y.o.)
26 young adults (29.1 ± 4.2 y.o.)



Durteste et al., 2023, *Comm. Psychol.*

Study 3

Methods

3

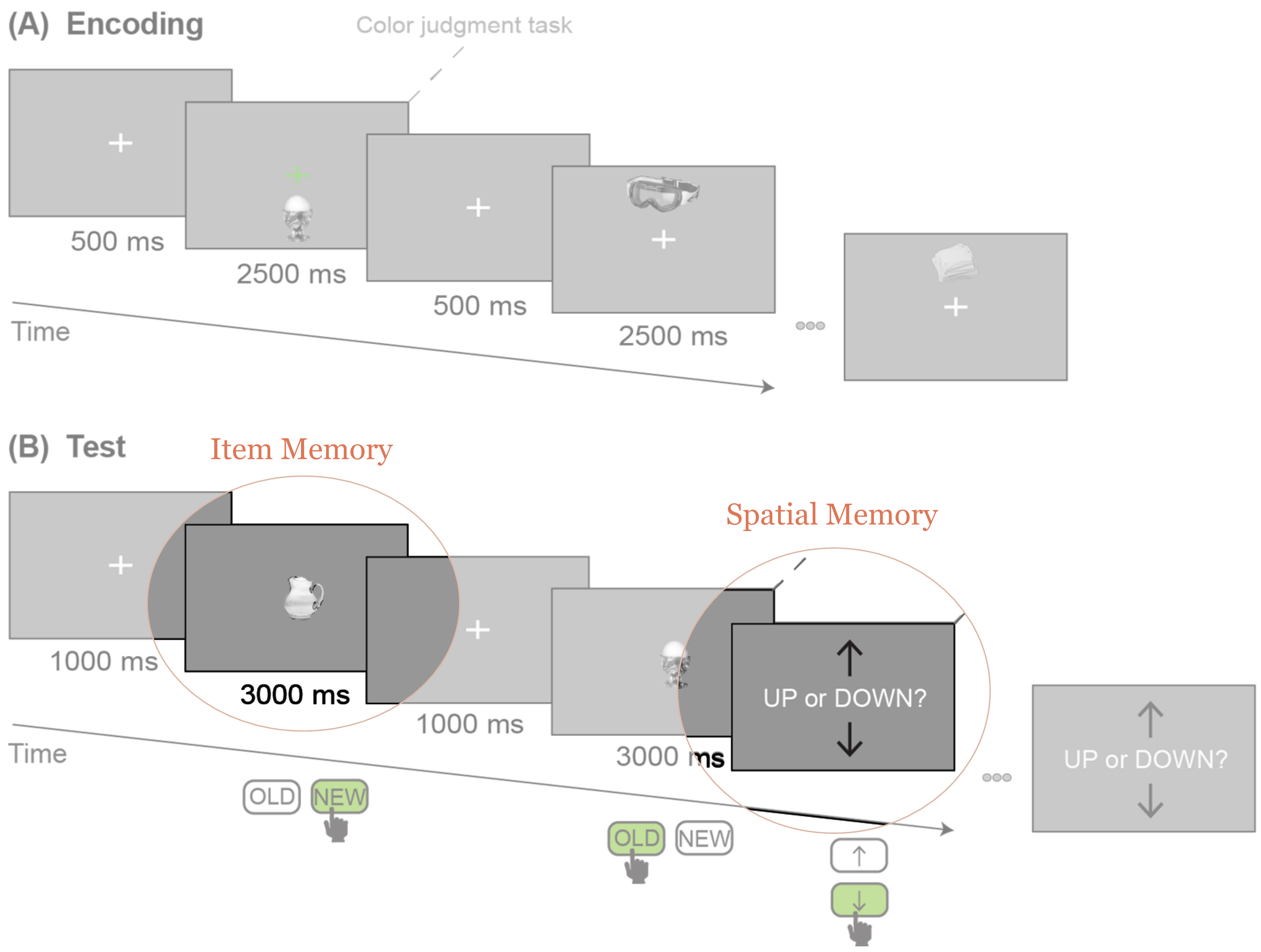
Does the vertical position of objects condition mnemonic performance?

Modality: Desktop-based + Eye tracking

Experiment: Source monitoring task

Stimuli: Everyday objects

Sample: 21 older adults (75.3 ± 3.8 y.o.)
26 young adults (29.1 ± 4.2 y.o.)

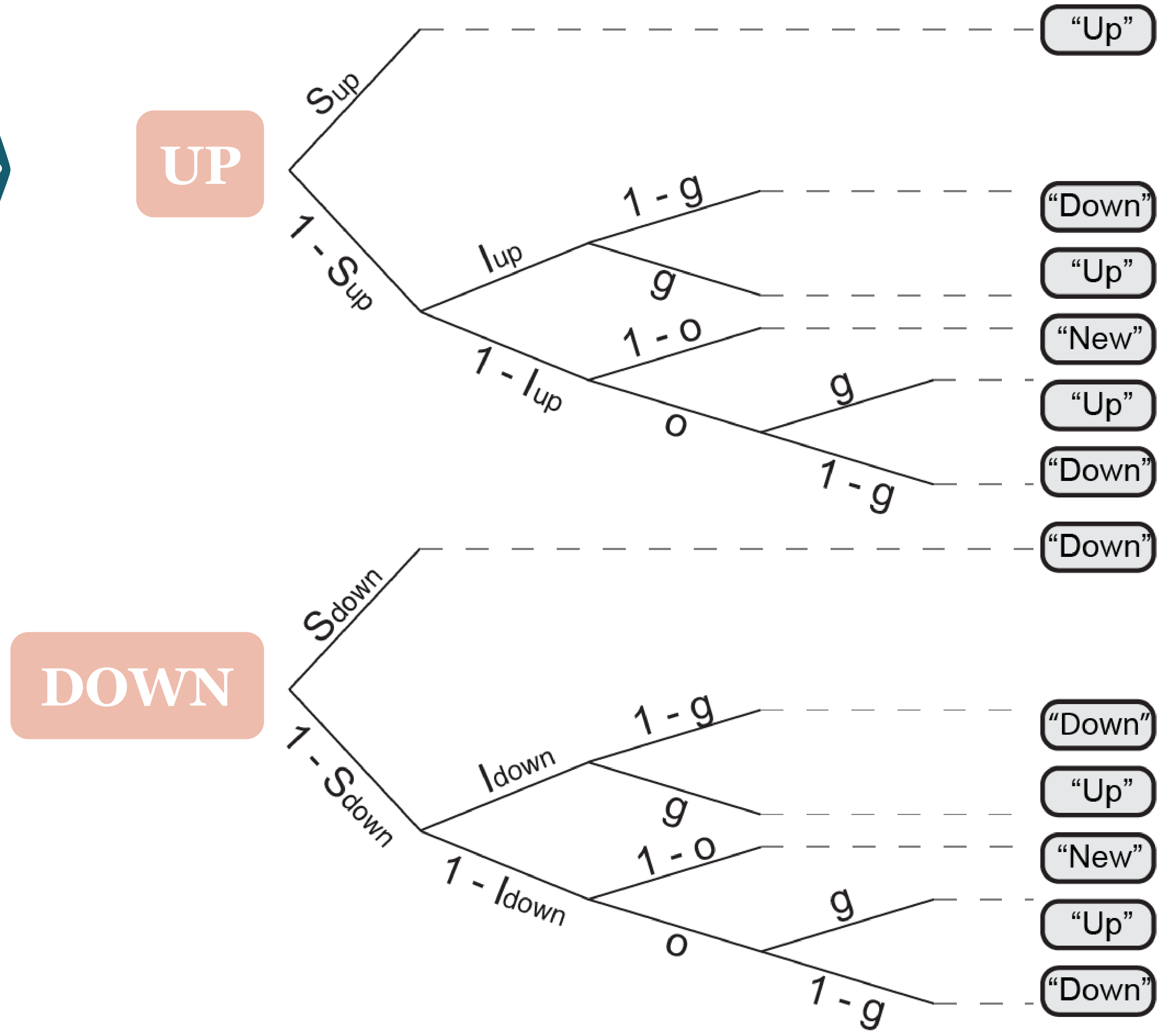


Durteste et al., 2023, *Comm. Psychol.*

Study 3

Methods

Multinomial Processing Tree Modelling

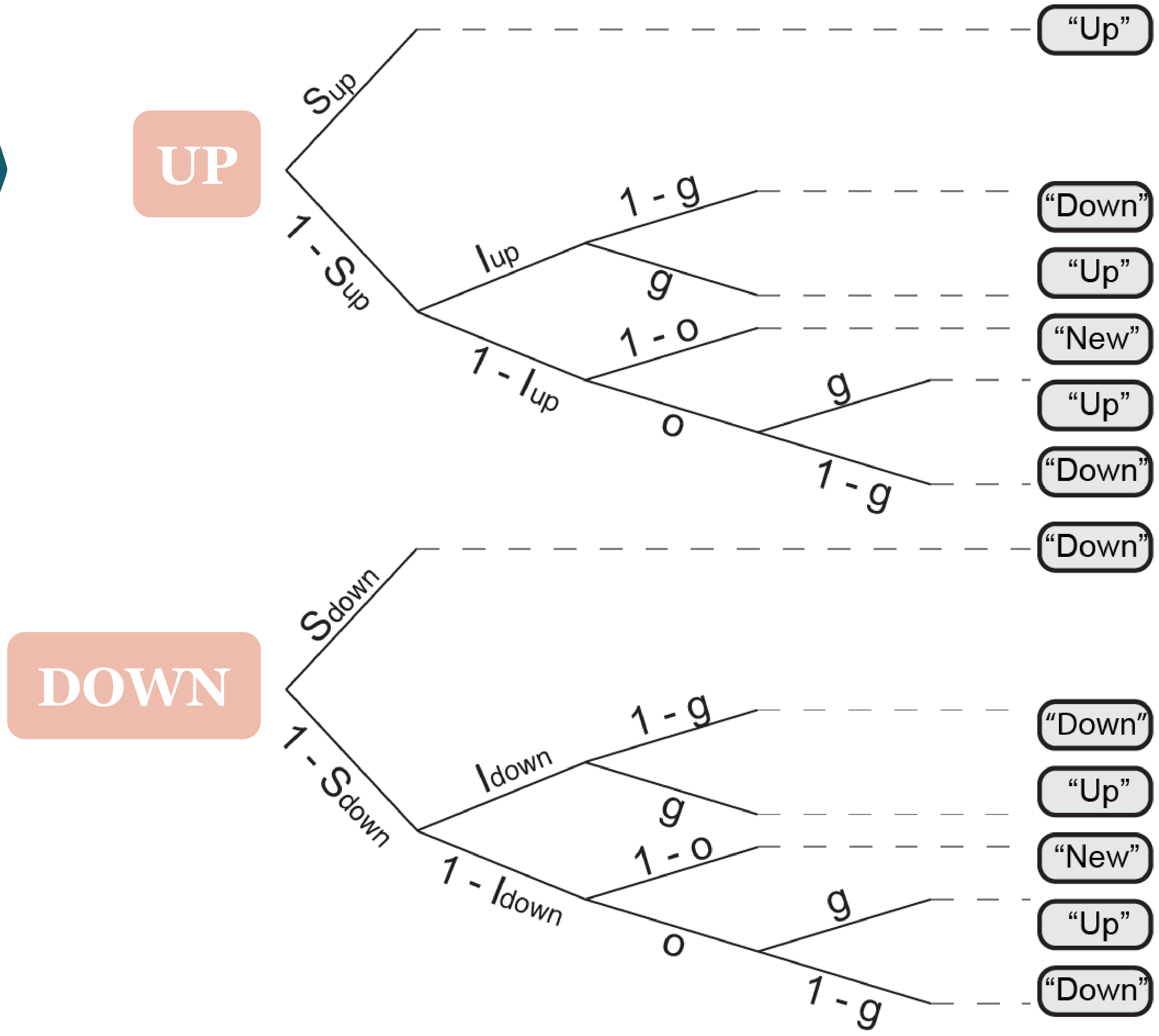


Durteste et al., 2023, *Comm. Psychol.*

Study 3

Methods

Multinomial Processing Tree Modelling



Parameters related to item memory

Item-up → Prob. of remembering UP objects

Item-down → Prob. of remembering DOWN objects

Parameters related to spatial memory

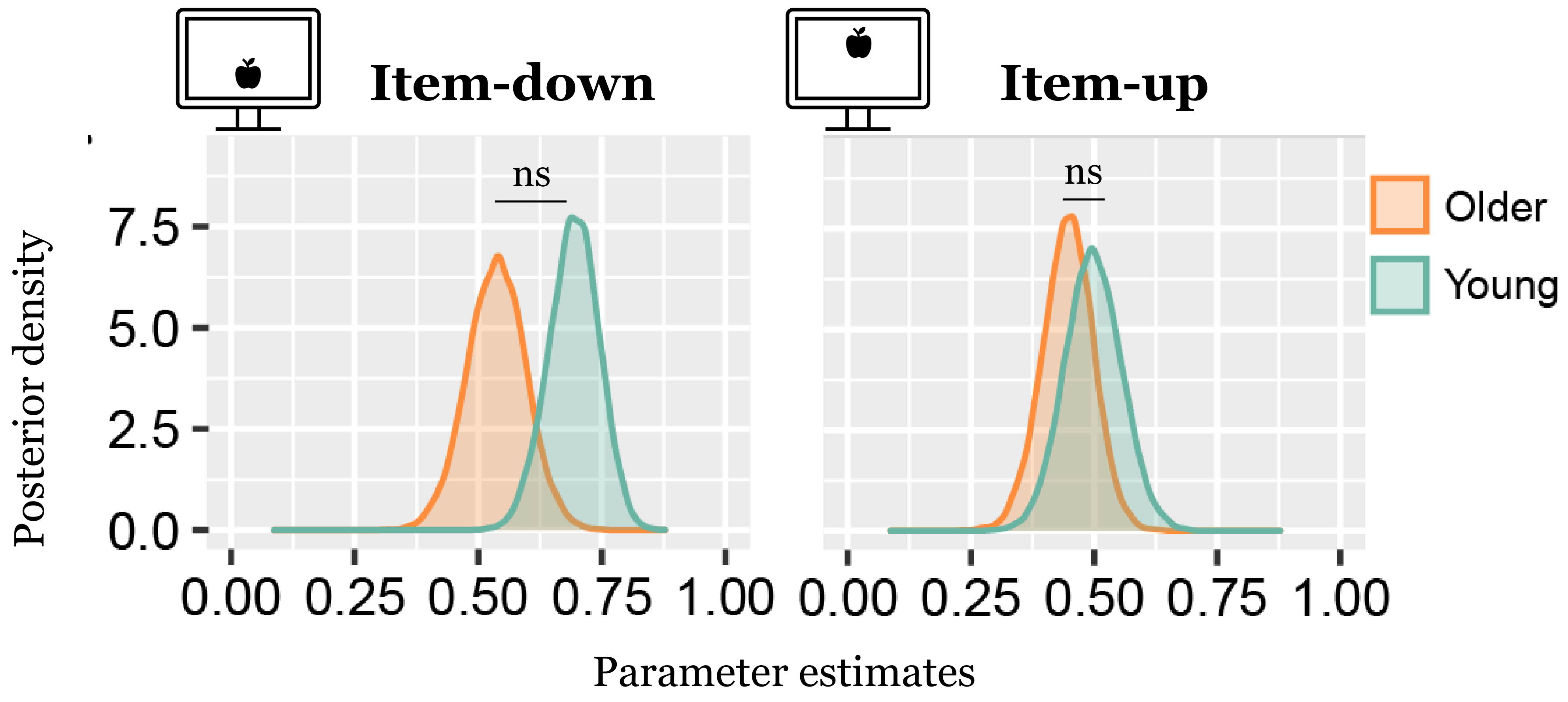
Spatial-up → Prob. of remembering the position of UP objects

Spatial-down → Prob. of remembering the position of DOWN objects

Durteste et al., 2023, *Comm. Psychol.*

Study 3

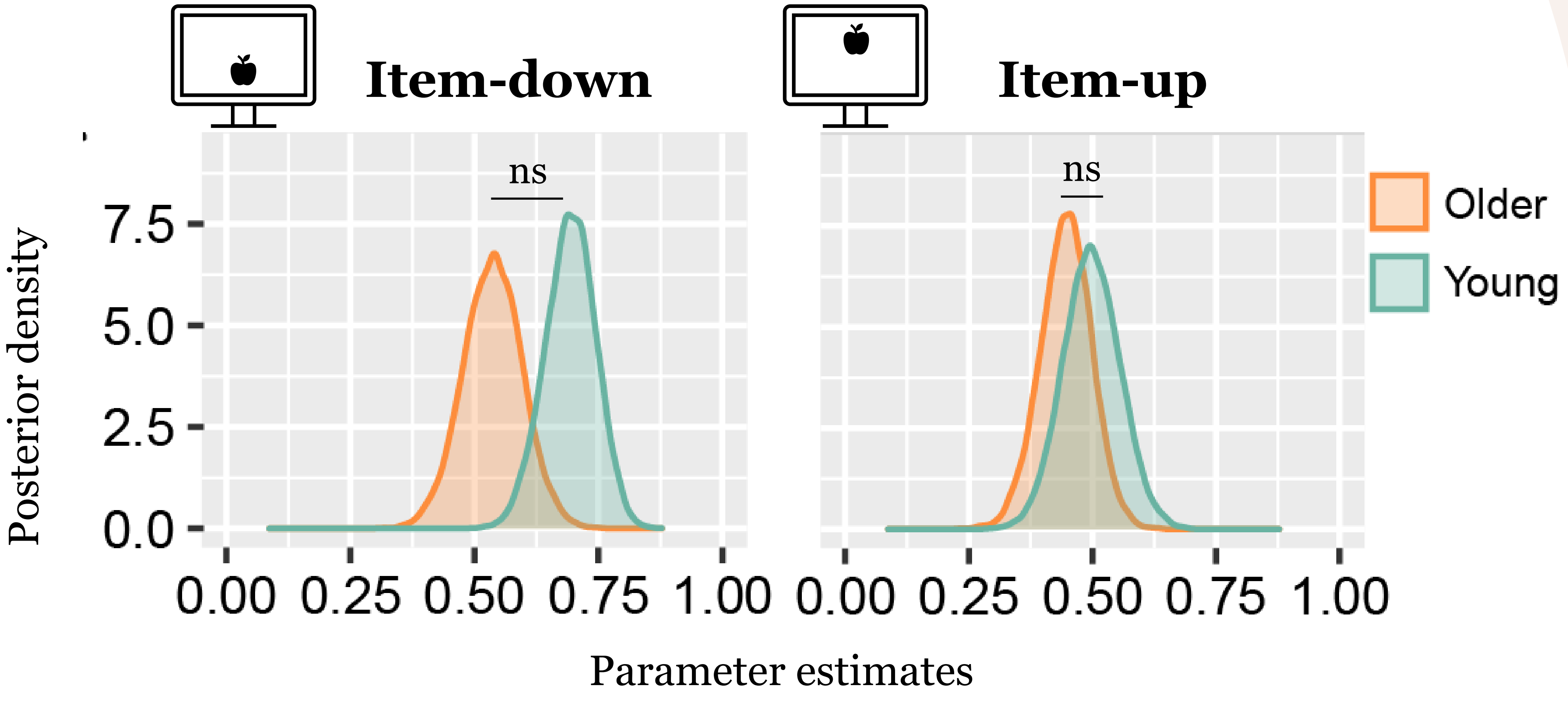
Results



Durteste et al., 2023, *Comm. Psychol.*

Study 3

Results

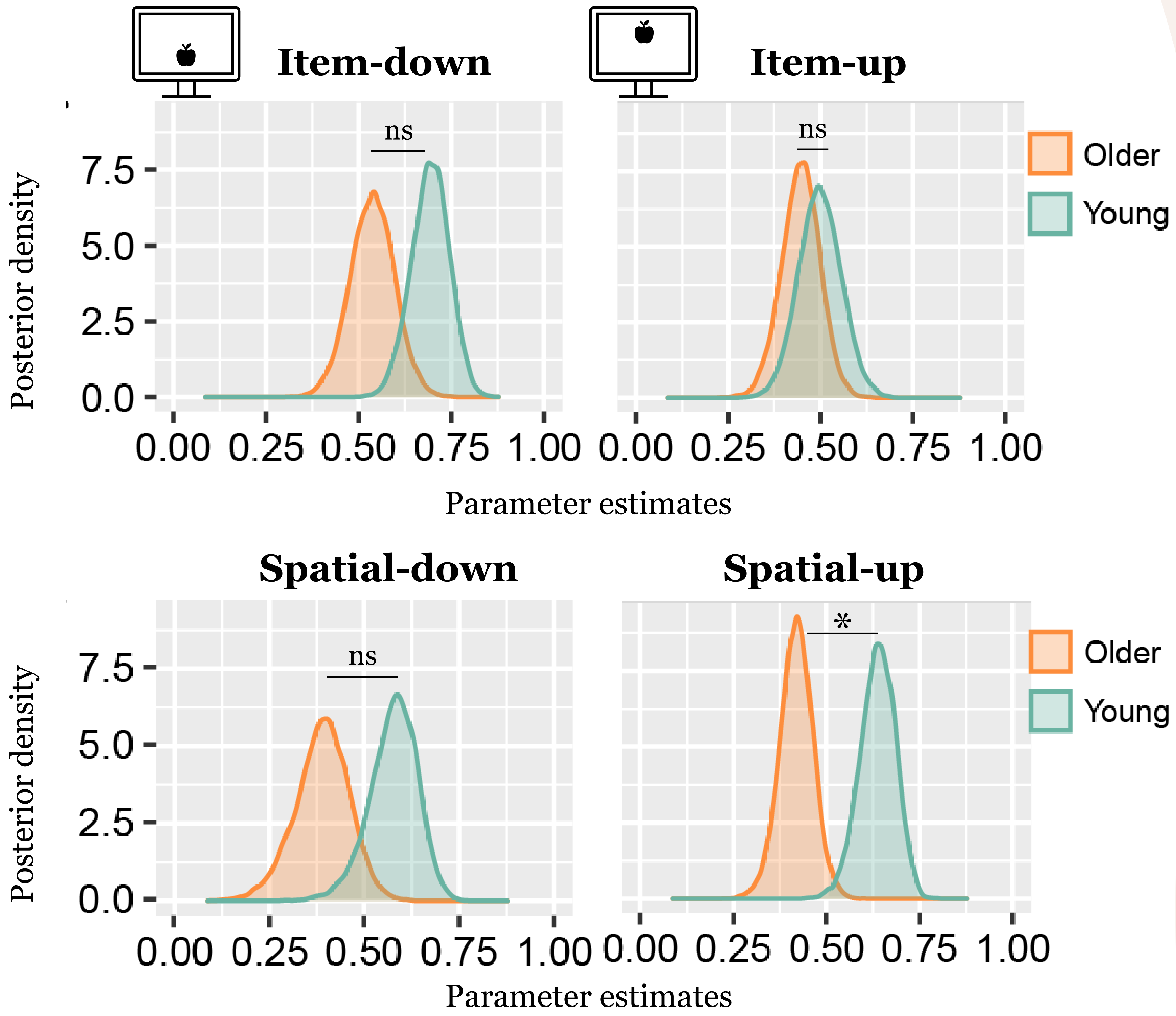


Item Memory

Durteste et al., 2023, *Comm. Psychol.*

Study 3

Results

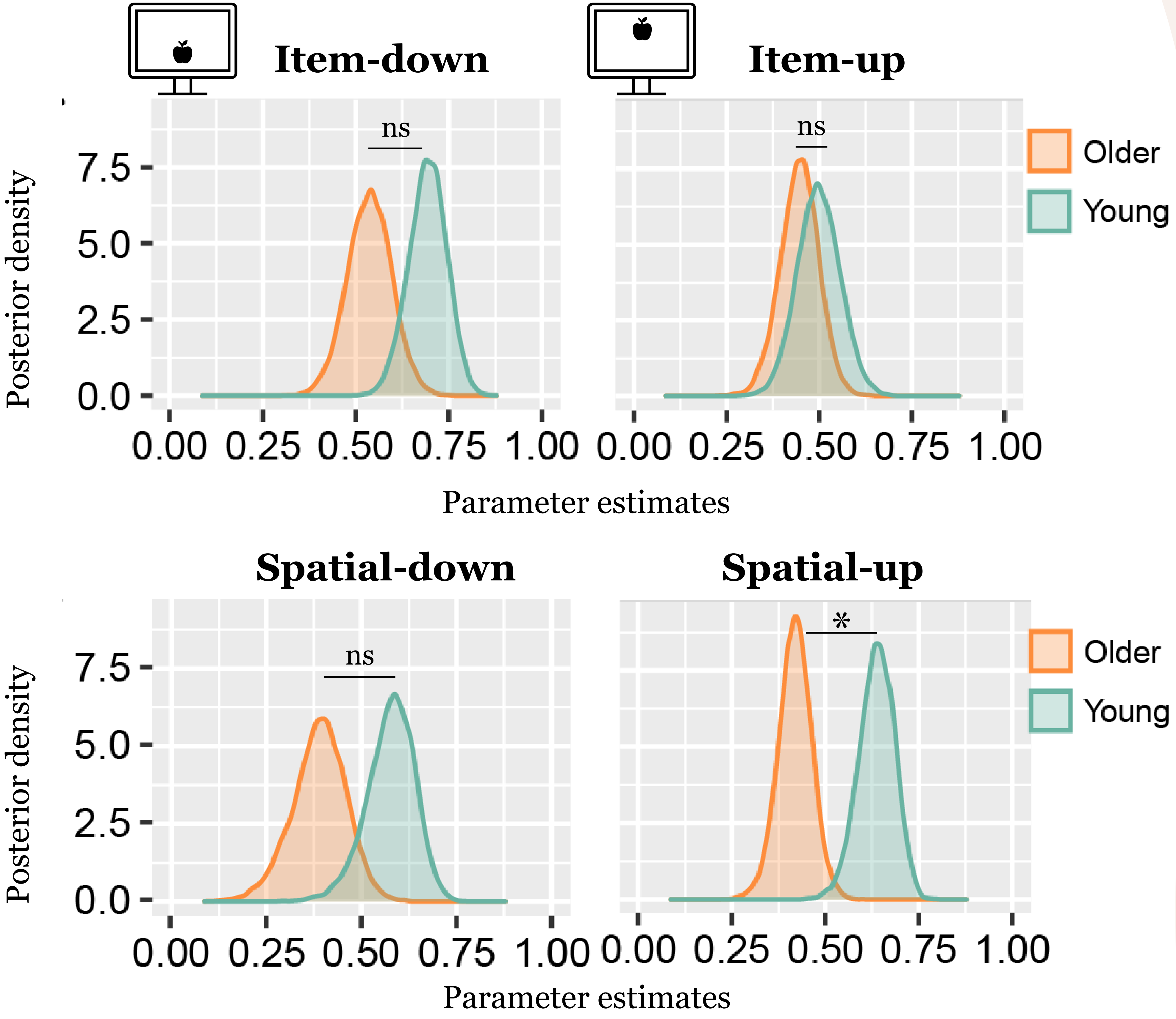


Item Memory

Durteste et al., 2023, *Comm. Psychol.*

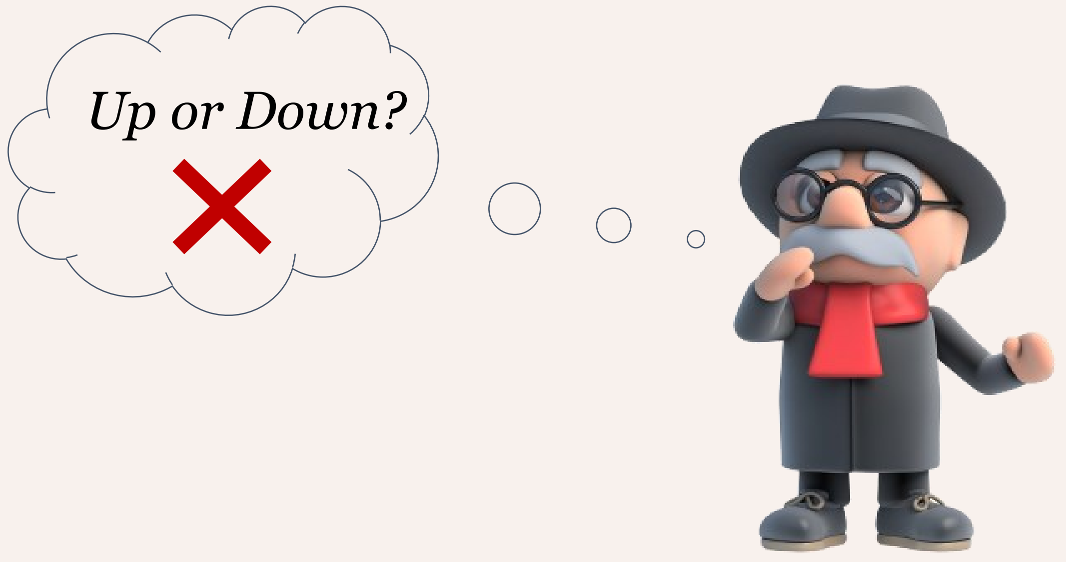
Study 3

Results



Item Memory

Spatial Memory

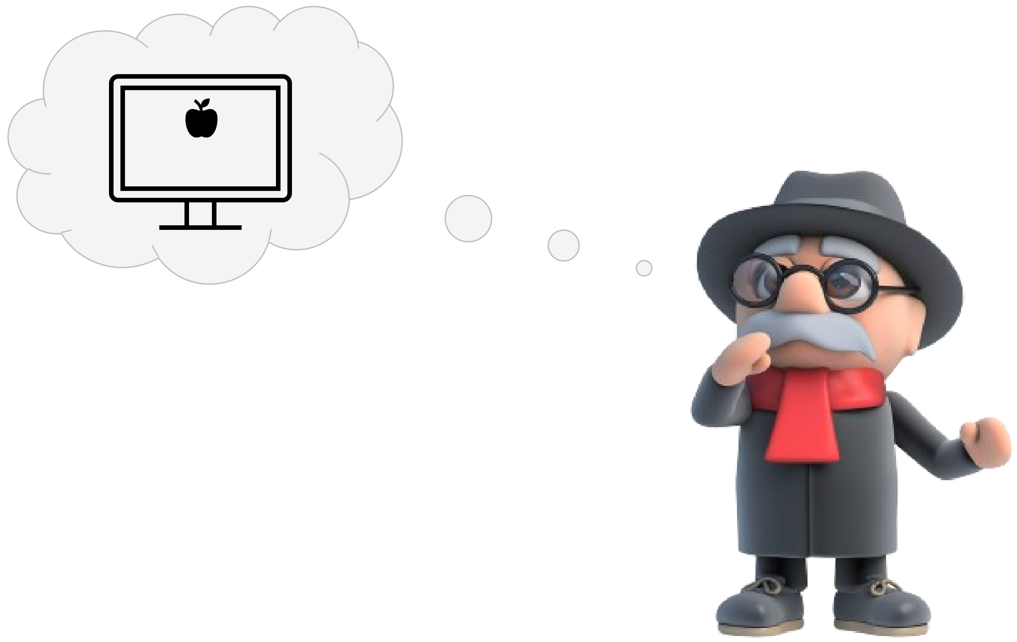


Durteste et al., 2023, *Comm. Psychol.*

Study 3

Take-home message

The vertical position of objects conditions spatial memory performance in older adults



Durteste et al., 2023, *Comm. Psychol.*

Study 4

Methods

4

How do gaze patterns adapt to the position of landmarks during spatial navigation?

Modality: Desktop + Eye tracking + EEG

Experiment: Virtual spatial navigation task

Virtual environment: City-like (4 streets)

Sample: 21 older adults (75.8 ± 3.8 y.o.)
21 young adults (29.0 ± 4.3 y.o.)

Durteste*, Delaux* et al., 2023, BioRxiv

Study 4

Methods

4

How do gaze patterns adapt to the position of landmarks during spatial navigation?

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Experiment: Virtual spatial navigation task

Virtual environment: City-like (4 streets)

Sample: 21 older adults (75.8 ± 3.8 y.o.)
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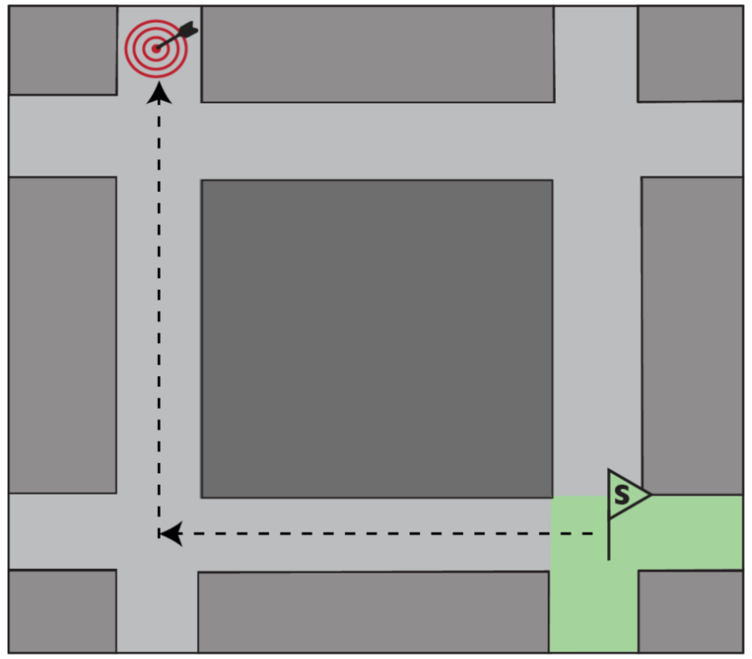

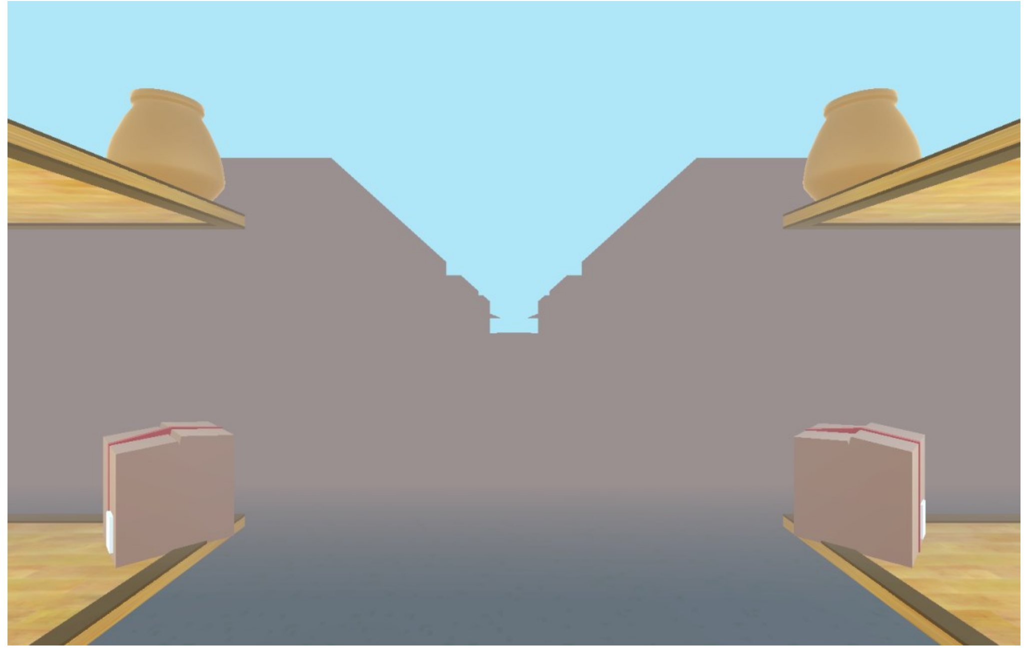

Durteste*, Delaux* et al., 2023, BioRxiv

Study 4

Methods

4

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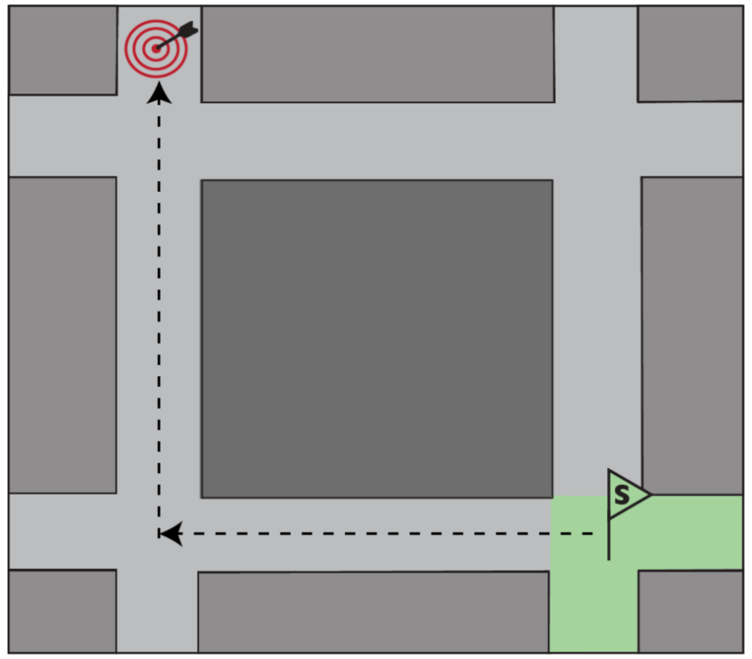
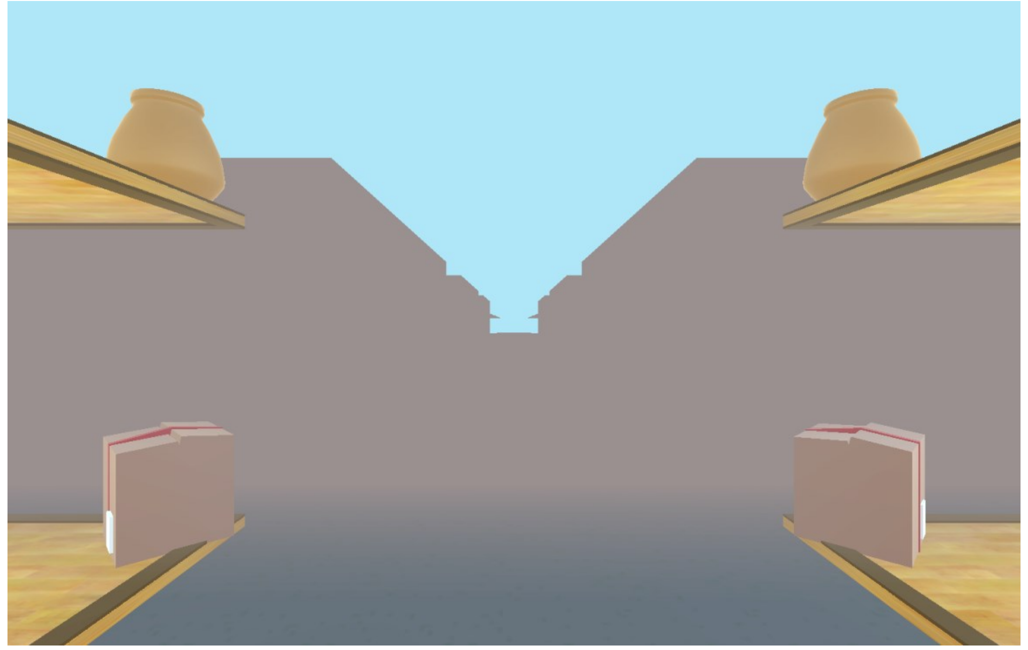




Encoding

Participants learn the position of the goal during passive navigation

Test

Participants retrieve the goal from various starting positions

Durteste*, Delaux* et al., 2023, BioRxiv

Study 4

Methods

UP condition | DOWN condition | MIX condition

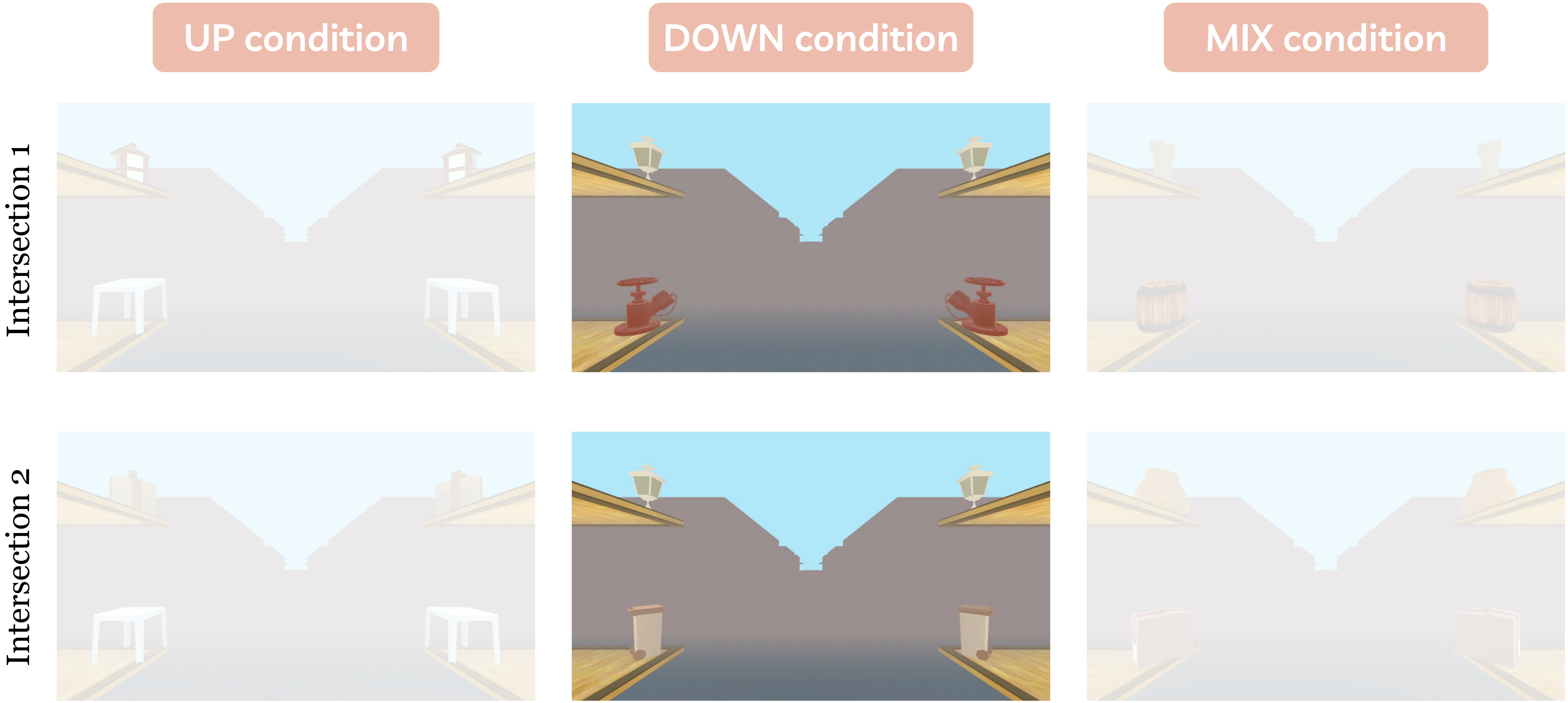
Intersection 1

Intersection 2

Durteste*, Delaux* et al., 2023, BioRxiv

Study 4

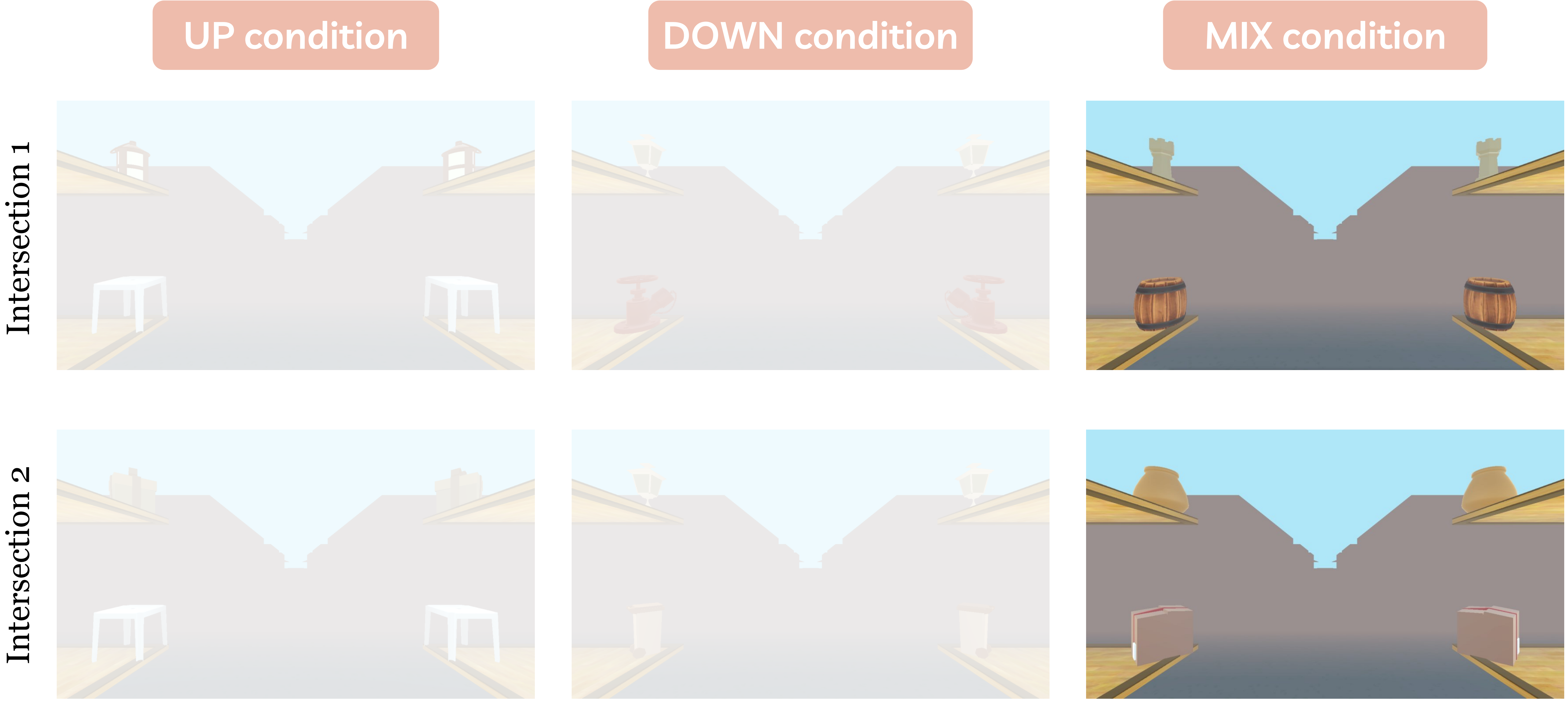
Methods



Durteste*, Delaux* et al., 2023, BioRxiv

Study 4

Methods

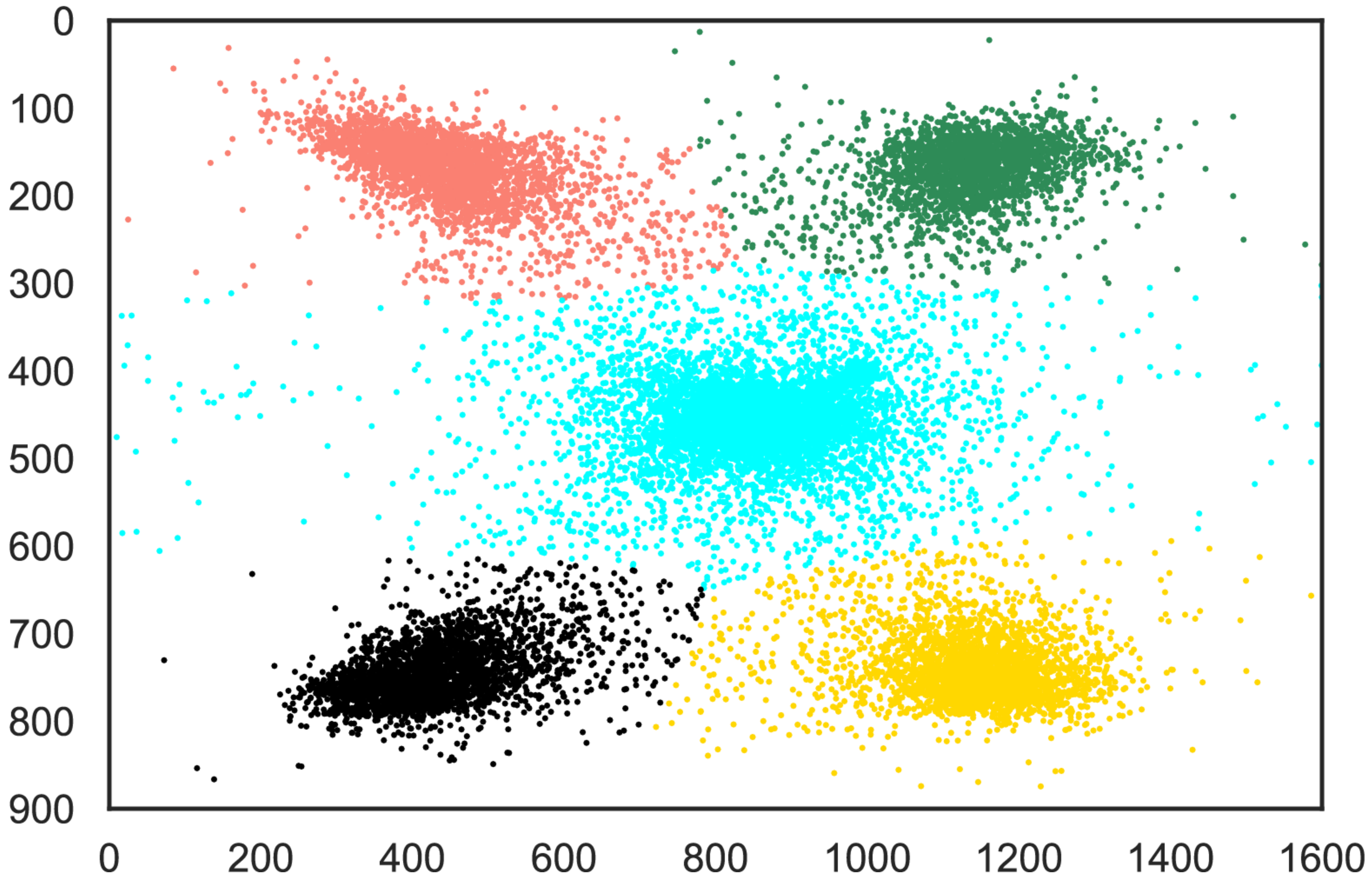


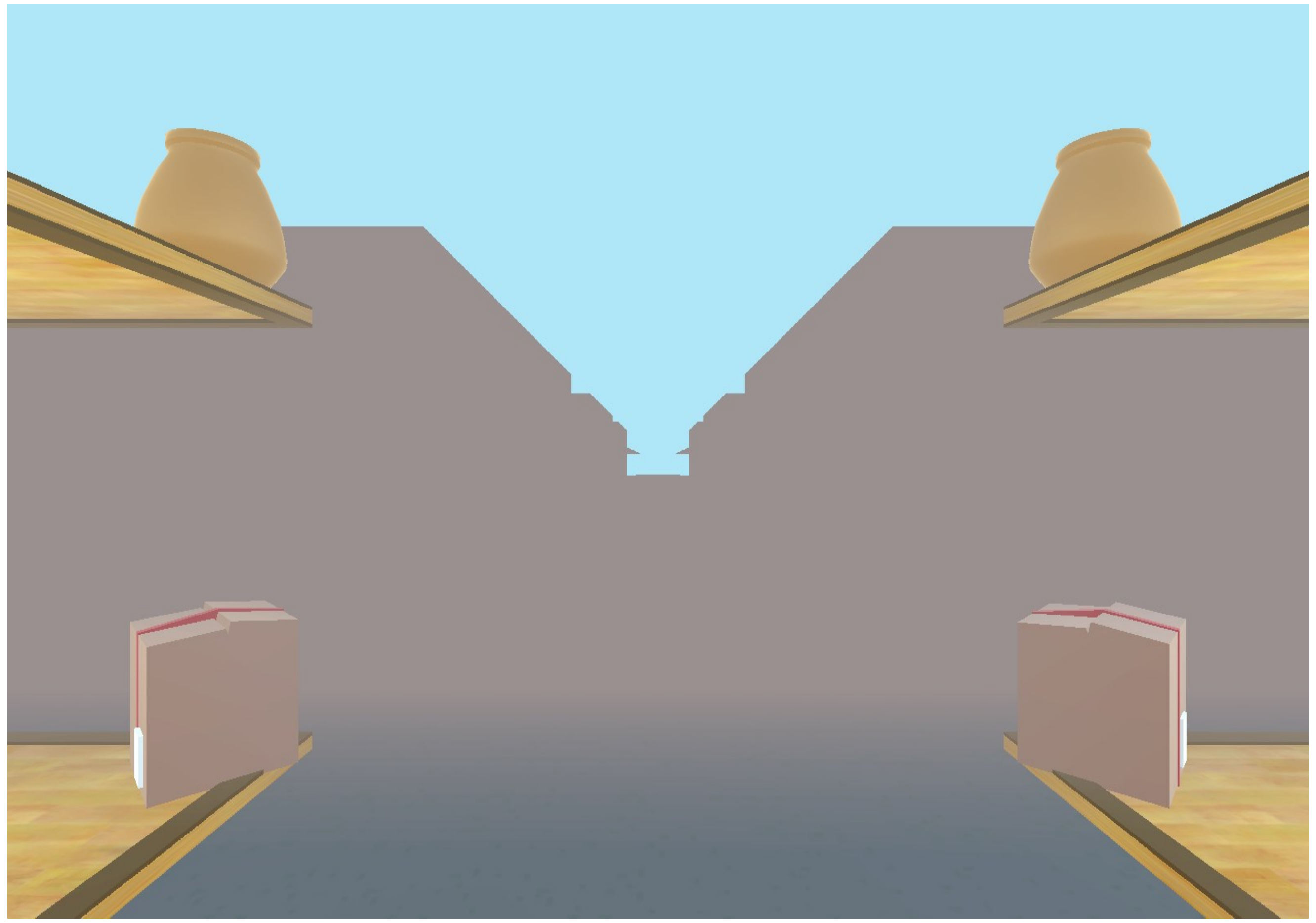
Durteste*, Delaux* et al., 2023, BioRxiv

Study 4

Methods

Gaussian mixture modelling



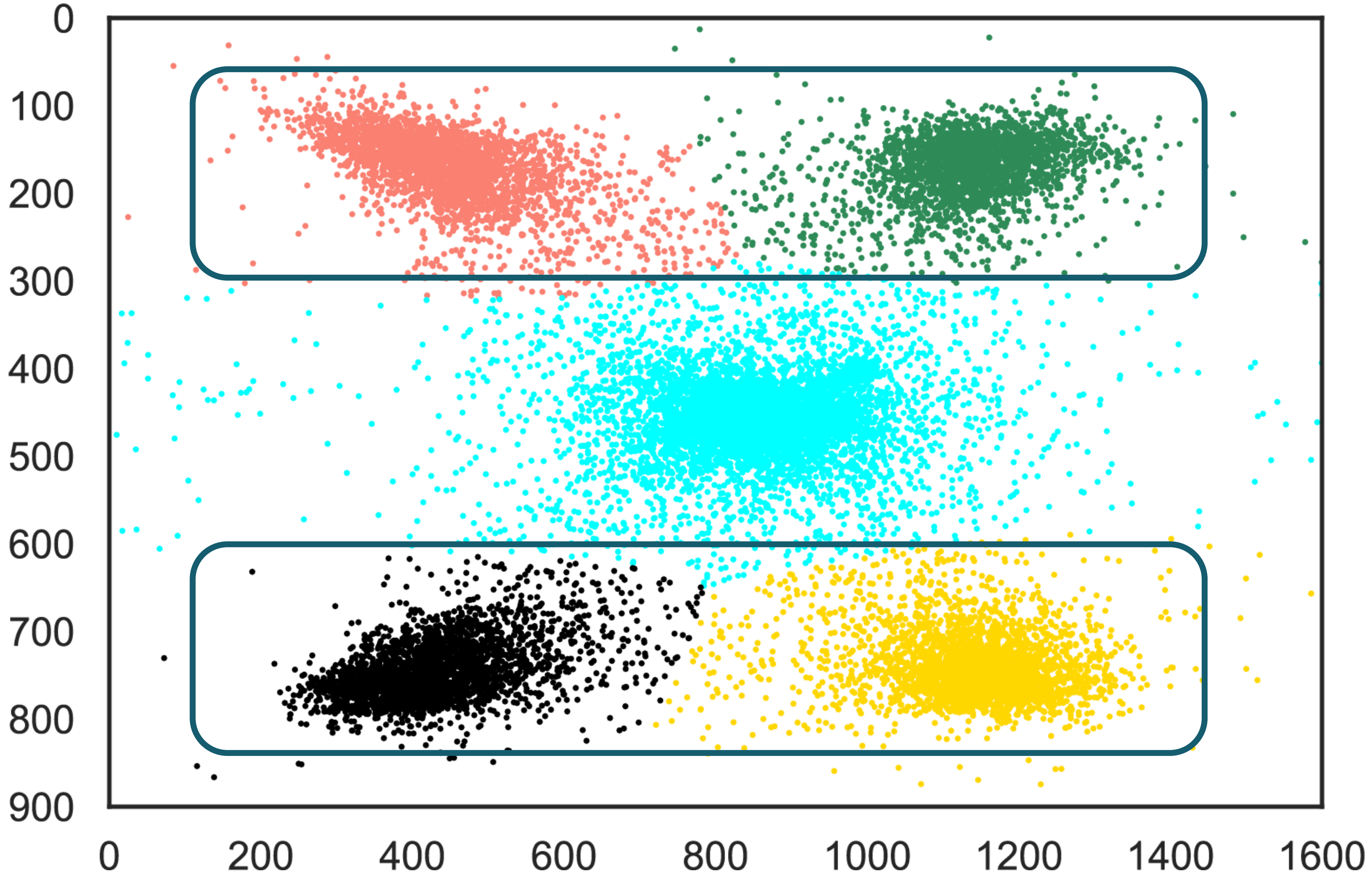


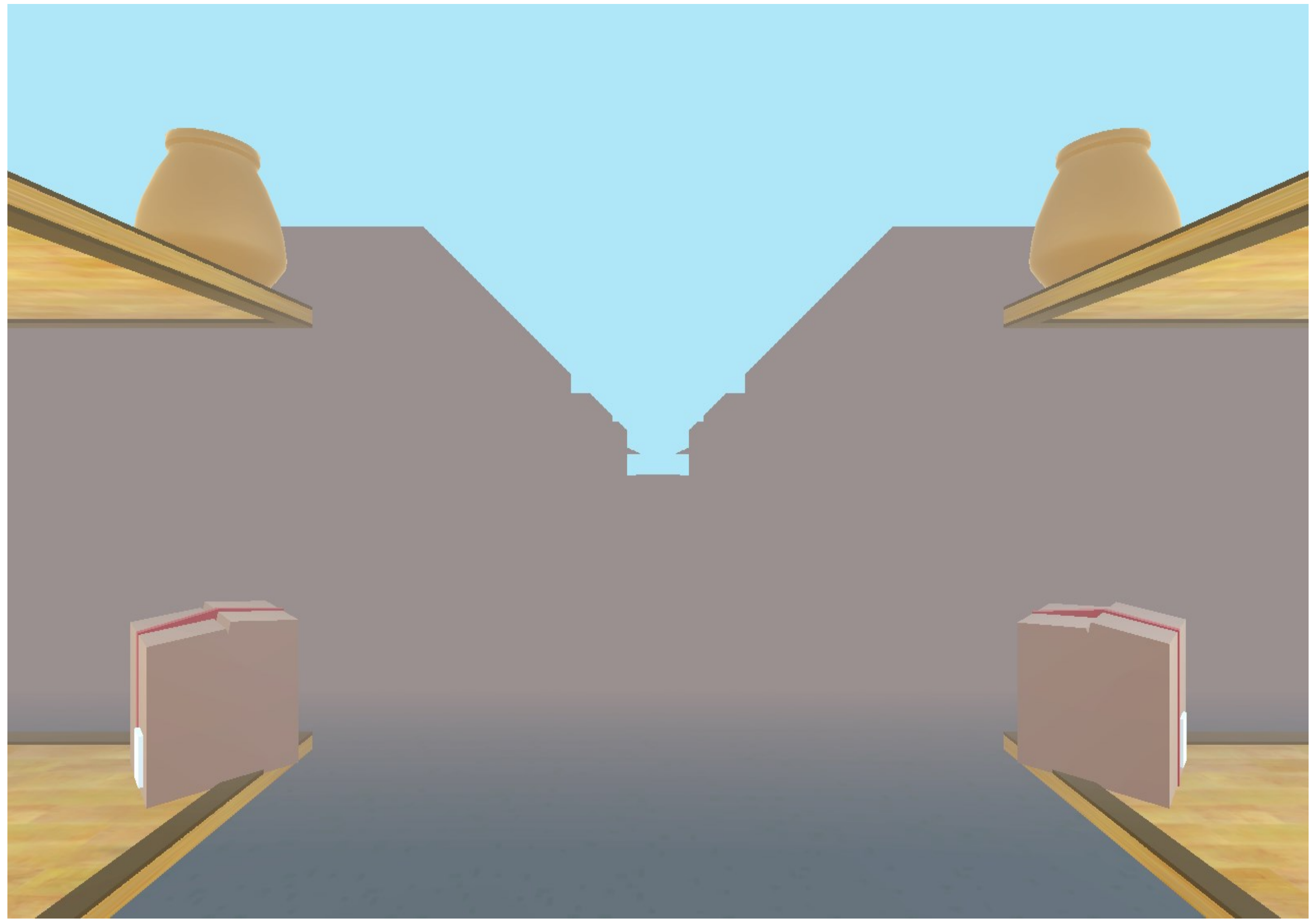
Durteste*, Delaux* et al., 2023, BioRxiv

Study 4

Methods

Gaussian mixture modelling



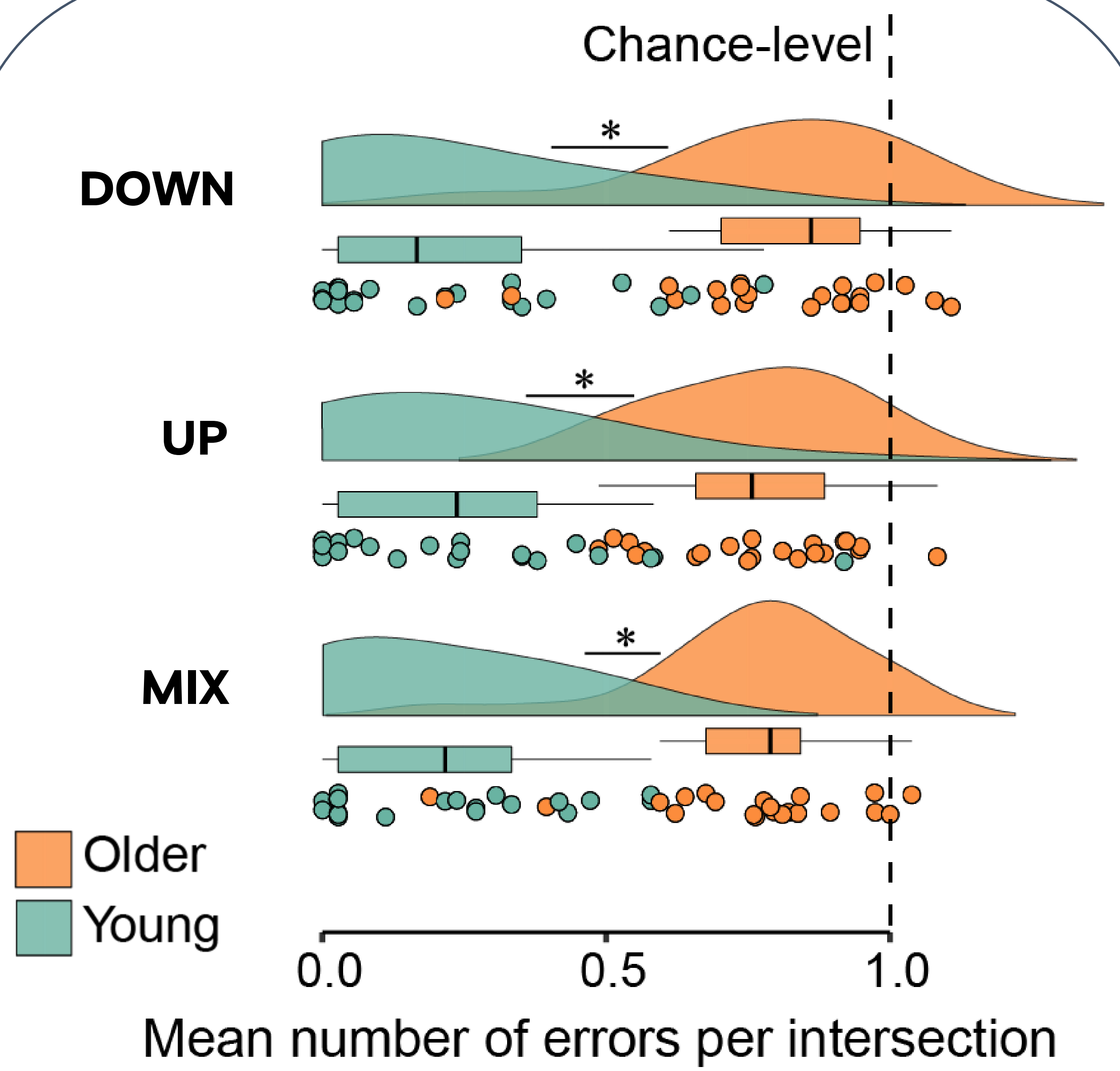


Definitions of three areas of interest: upper, lower and central AOIs

Durteste*, Delaux* et al., 2023, BioRxiv

Study 4

Eye tracking results

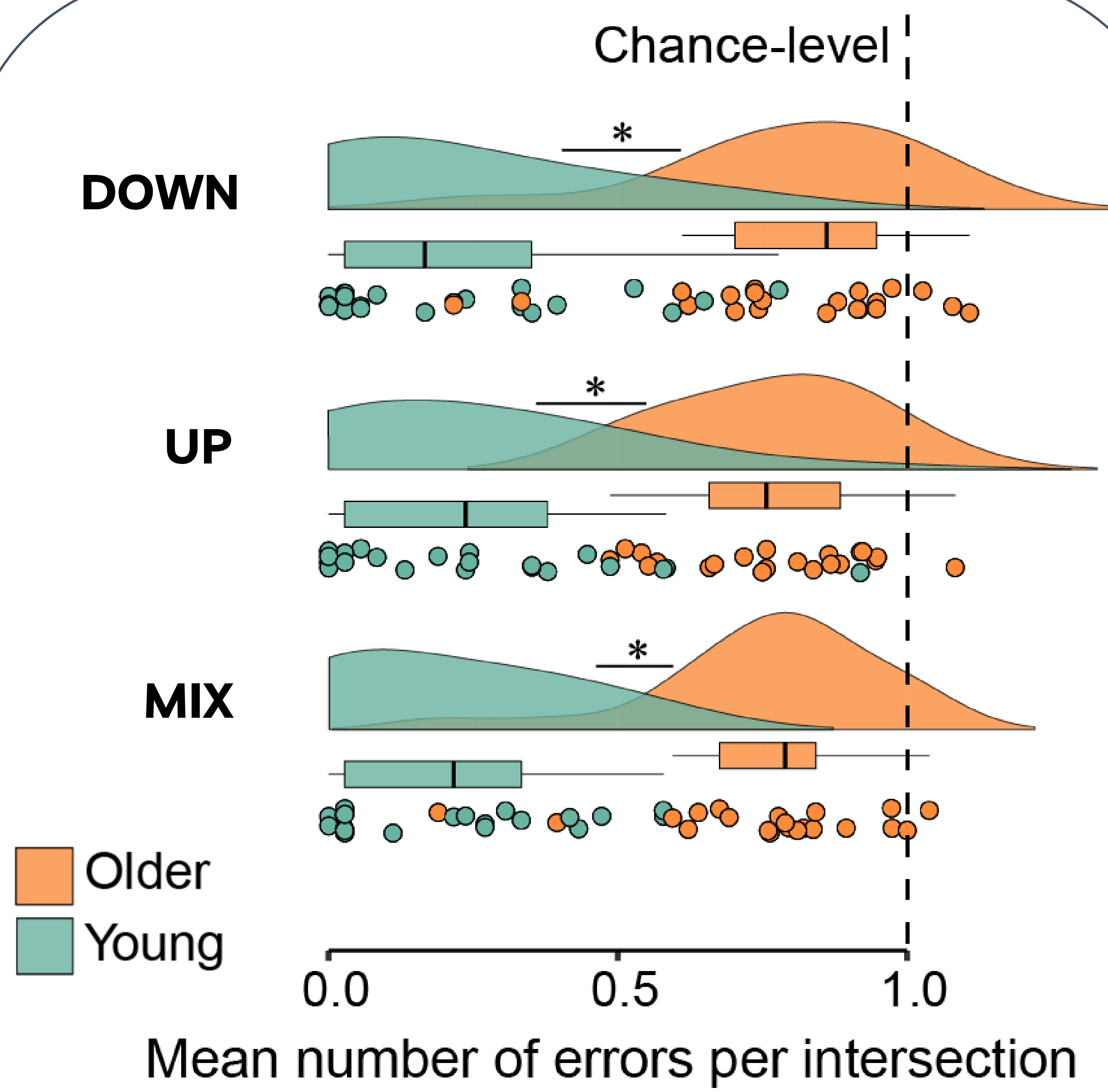


Navigation performance was sig. lower in older adults

Durteste*, Delaux* et al., 2023, BioRxiv

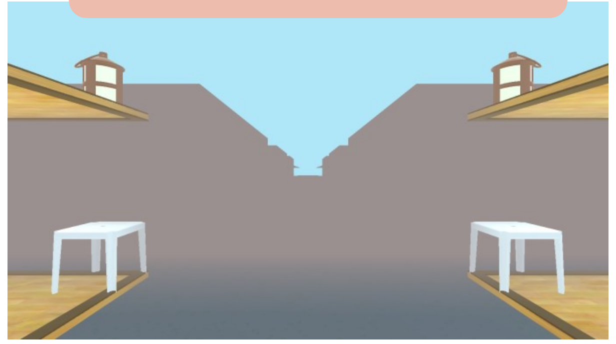
Study 4

Eye tracking results



Navigation performance was sig. lower in older adults

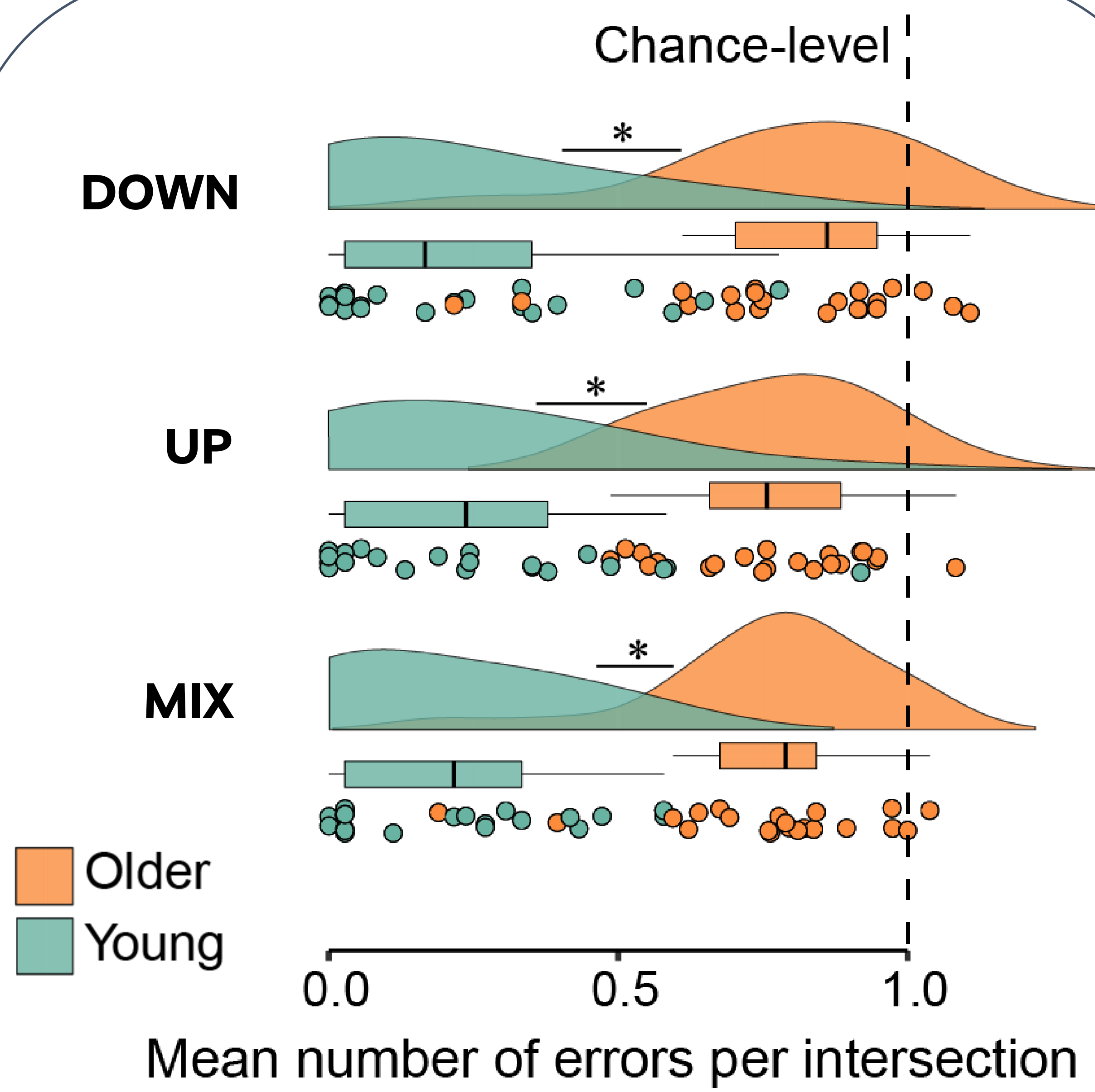
First fixations



Durteste*, Delaux* et al., 2023, BioRxiv

Study 4

Eye tracking results



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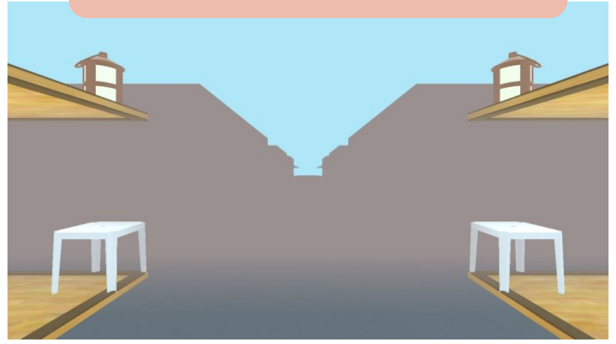

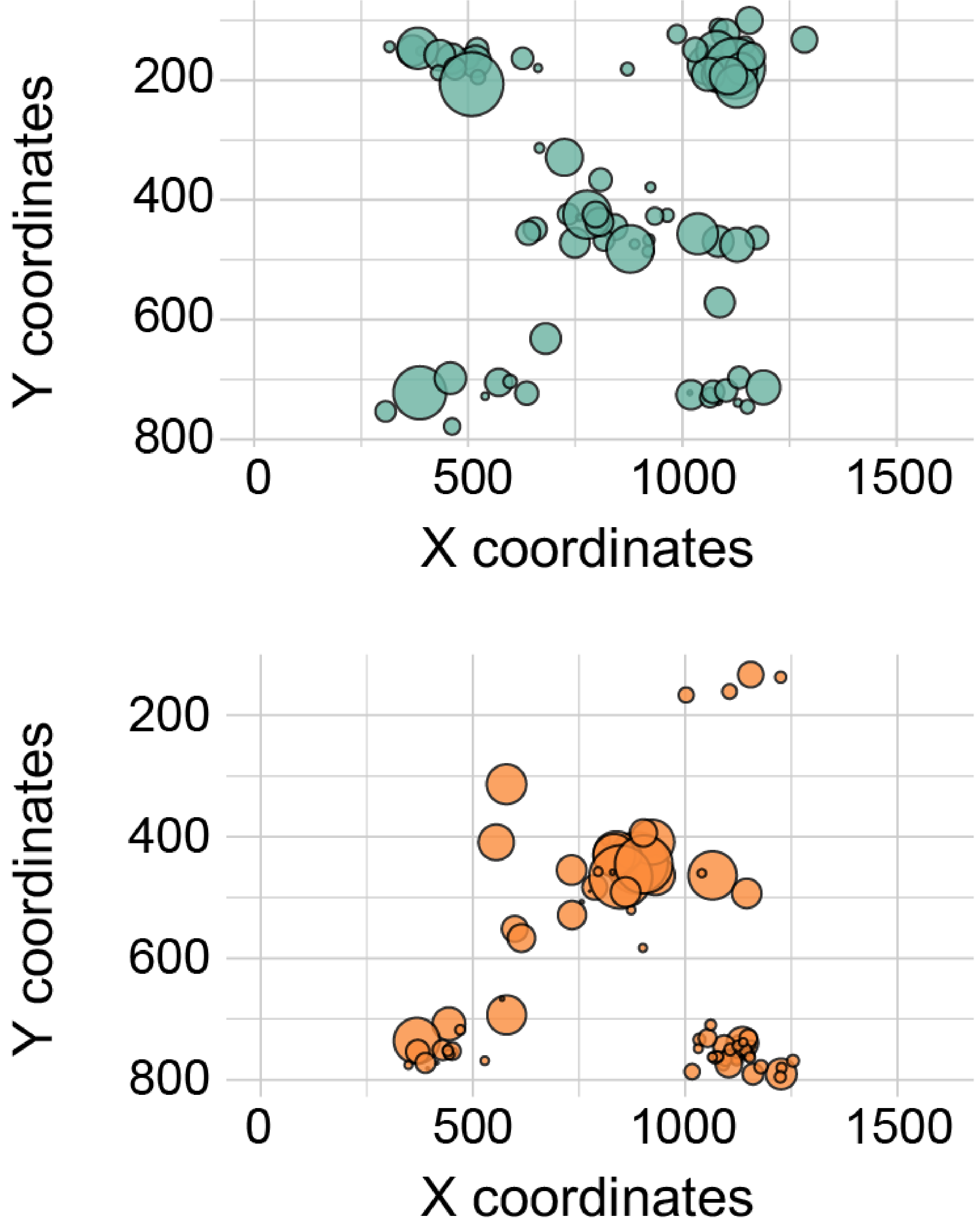

Durteste*, Delaux* et al., 2023, BioRxiv

Intro

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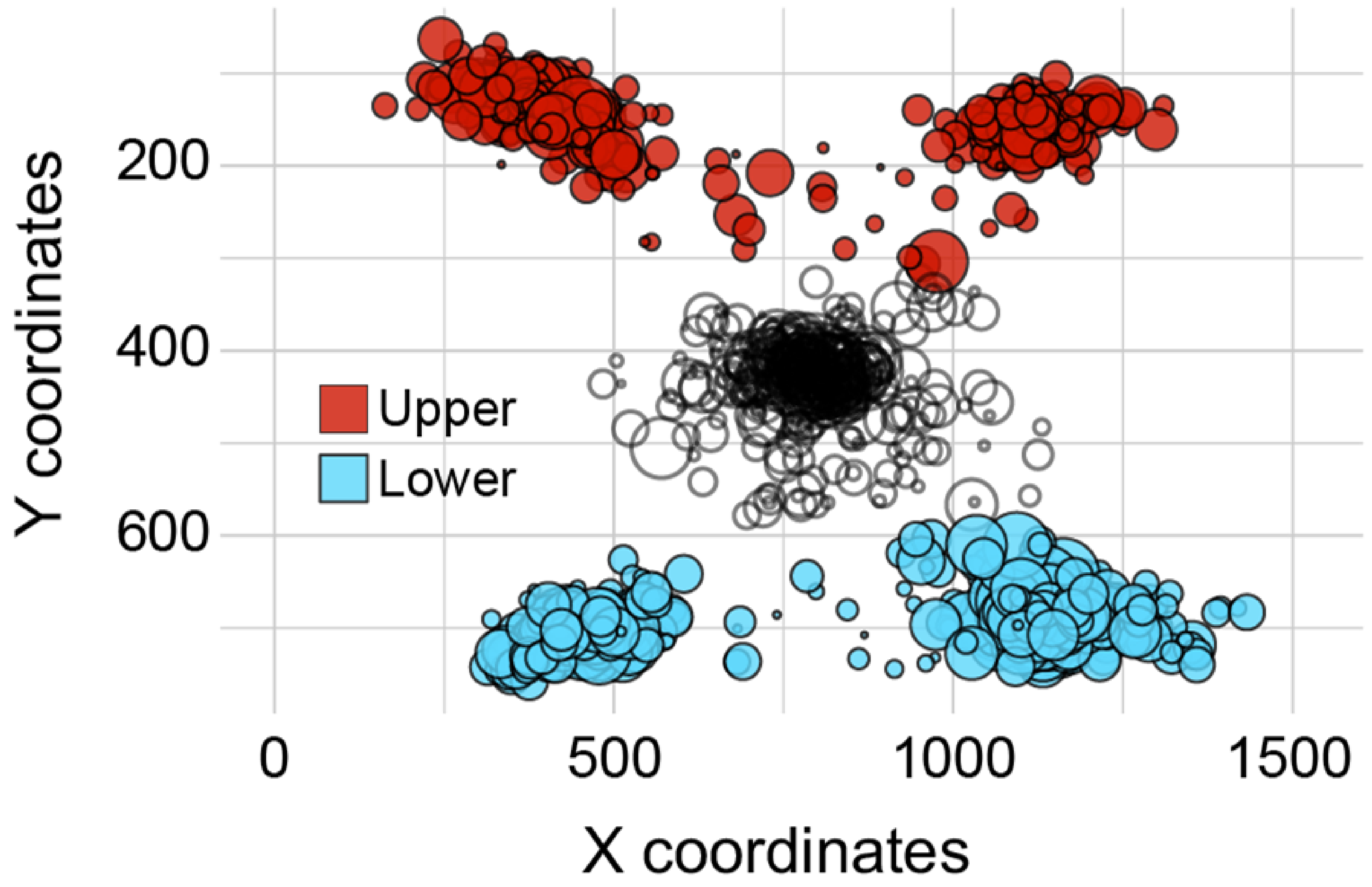
Study 4

Eye tracking results

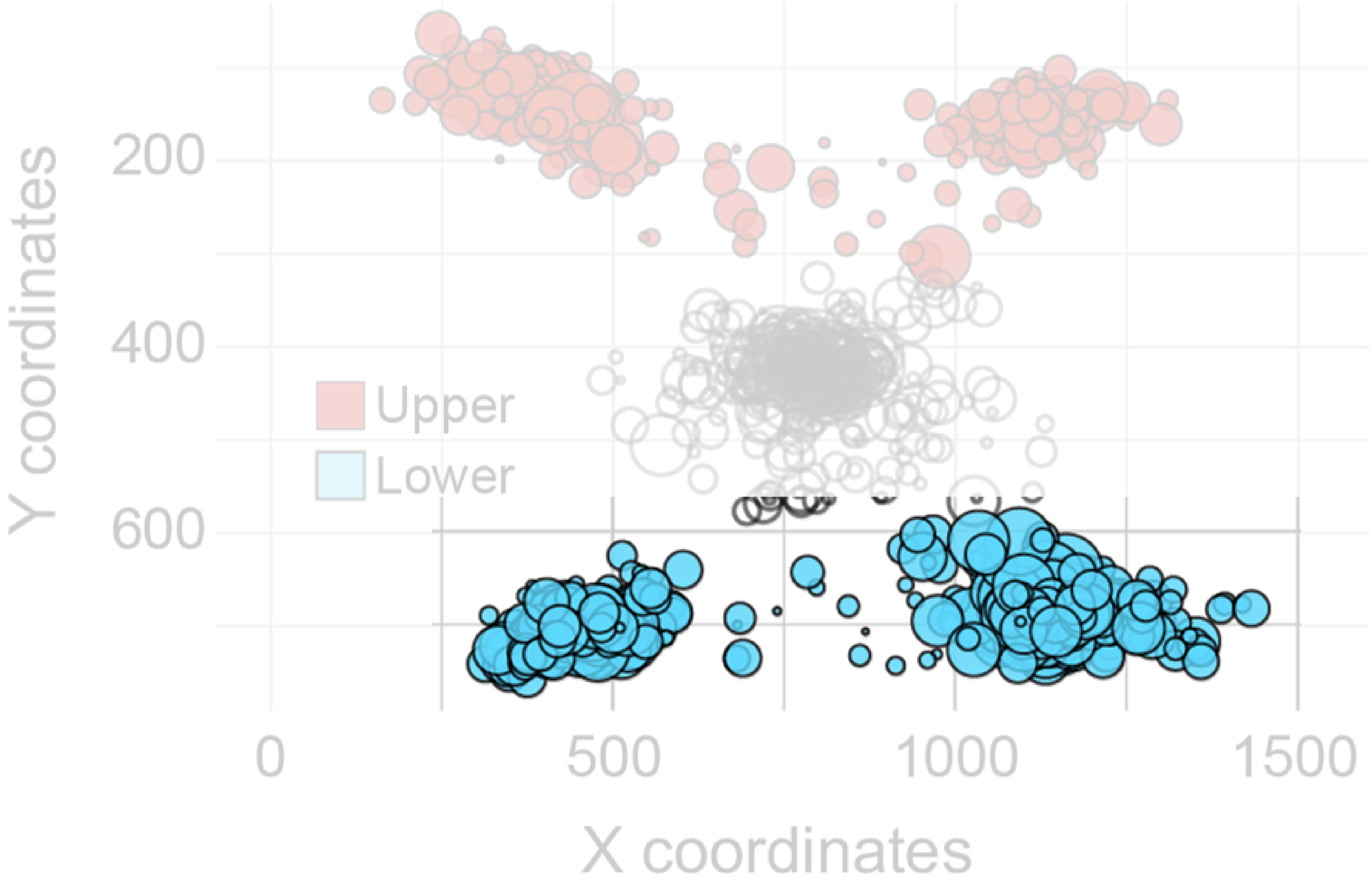


$$\text{VMA} = \frac{\text{dwell time lower} - \text{dwell time upper}}{\text{average dwell time}} \times 100$$

Durteste*, Delaux* et al., 2023, BioRxiv

Study 4

Eye tracking results



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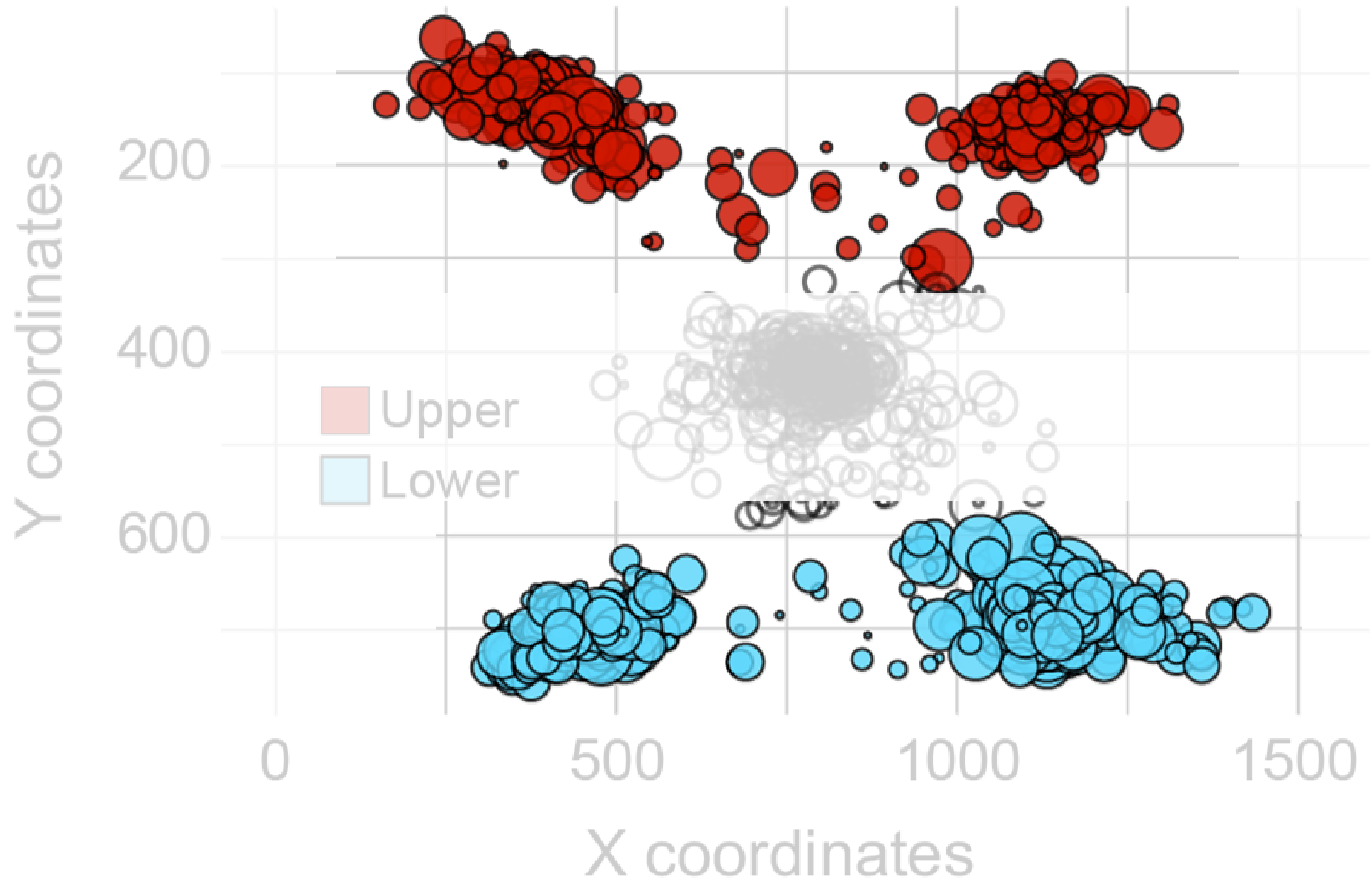
Durteste*, Delaux* et al., 2023, BioRxiv

Study 4

Eye tracking results



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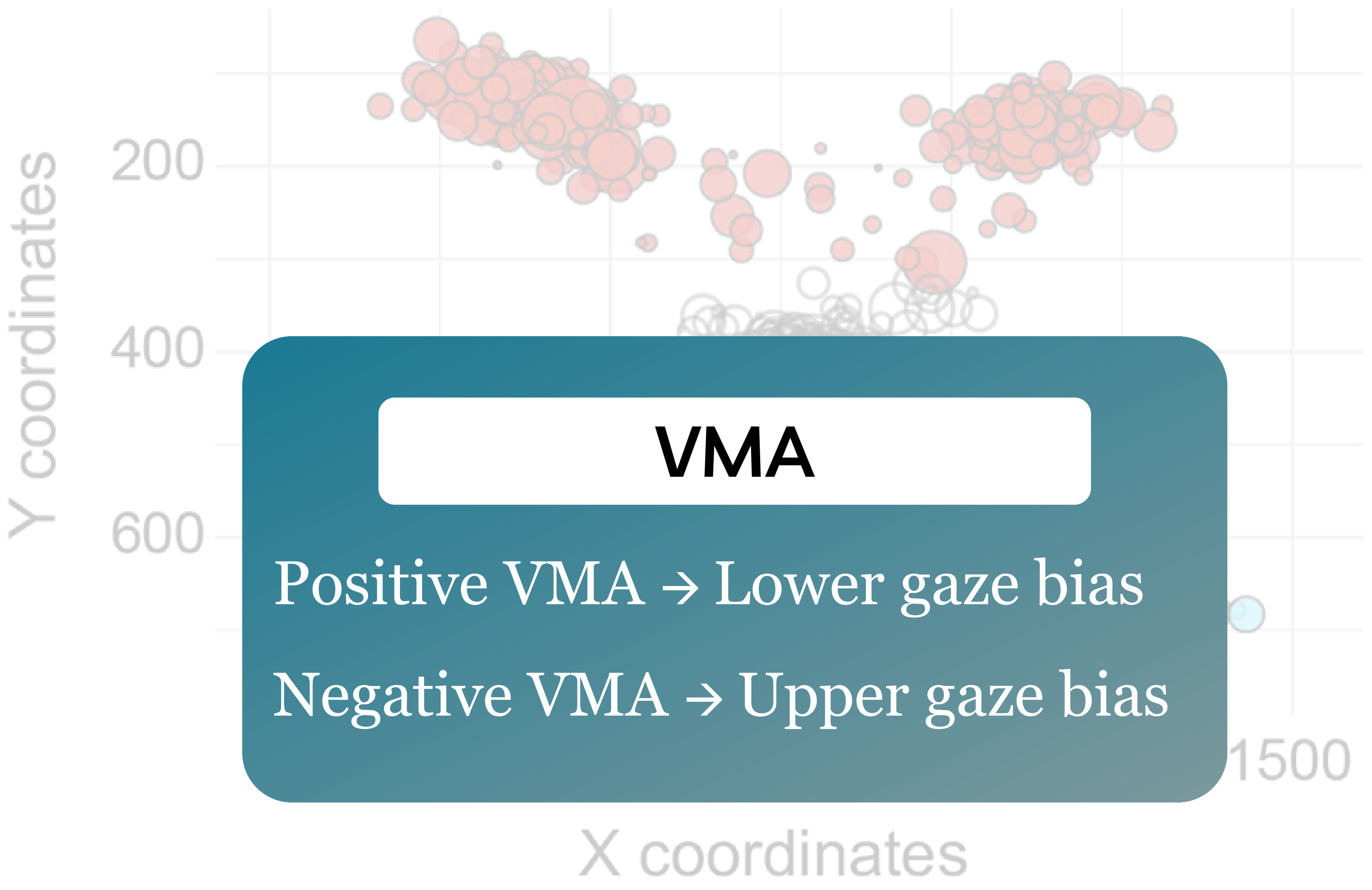
Study 4

Eye tracking results

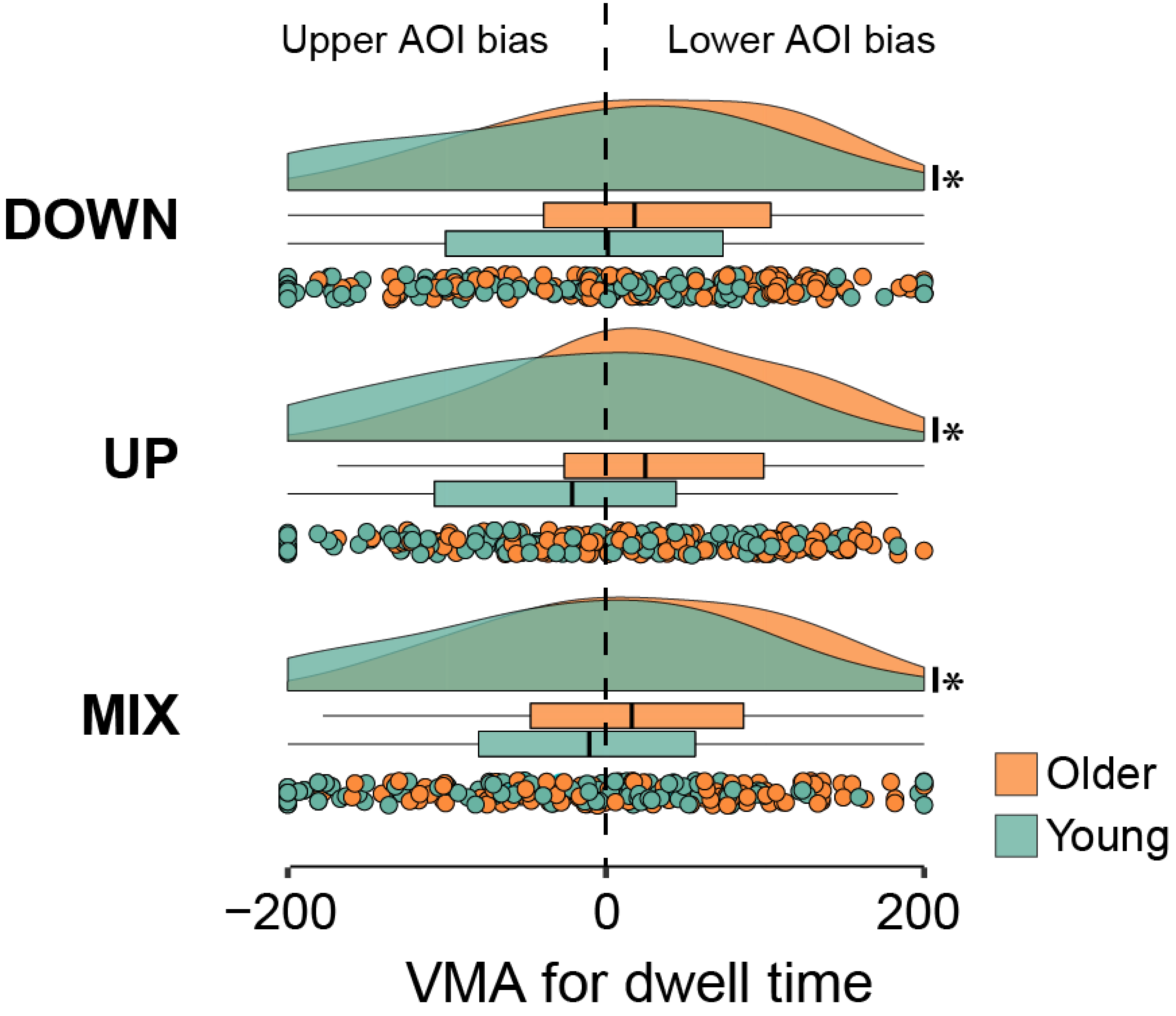


VMA

Positive VMA → Lower gaze bias

Negative VMA → Upper gaze bias

$$\text{VMA} = \frac{\text{dwell time lower} - \text{dwell time upper}}{\text{average dwell time}} \times 100$$

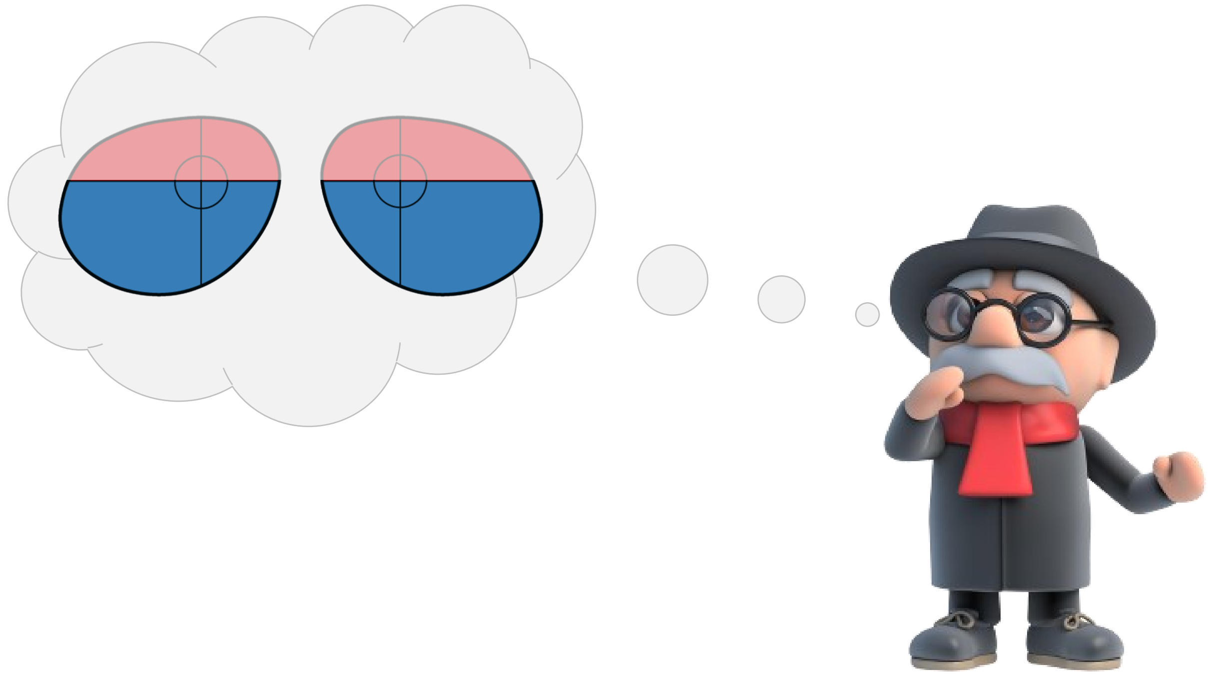


Durteste*, Delaux* et al., 2023, BioRxiv

Study 4

Take-home message

Older adults exhibit a systematic downward gaze bias, irrespective of landmark position



Durteste*, Delaux* et al., 2023, BioRxiv

Study 5
Methods

5

What is the implication of scene-selective regions in encoding the vertical position of landmarks?

Modality: fMRI

Experiment: Virtual spatial navigation task

Virtual environment: City-like (1 int.)

Sample: 20 older adults (74.0 ± 5.1 y.o.)
24 young adults (28.1 ± 4.0 y.o.)

Durteste et al., 2023, BioRxiv

Study 5

Methods

5

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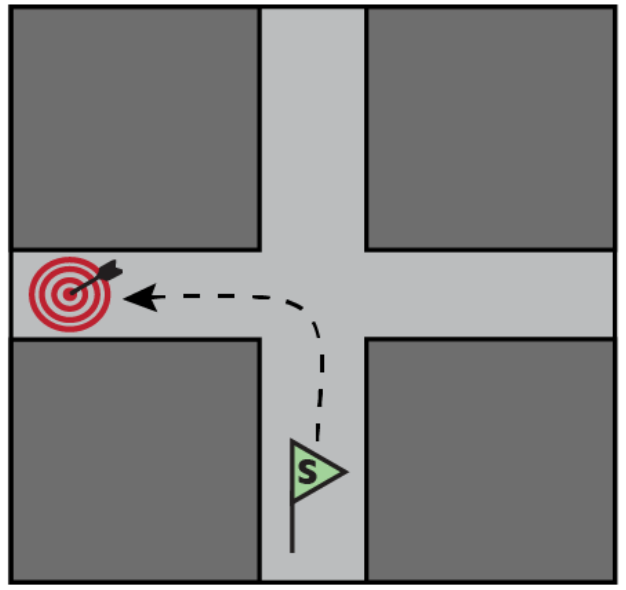

Durteste et al., 2023, BioRxiv

Study 5

Methods

5

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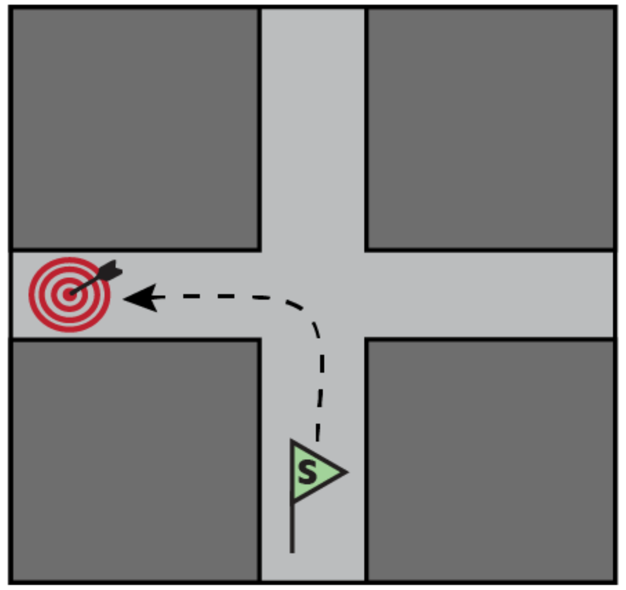
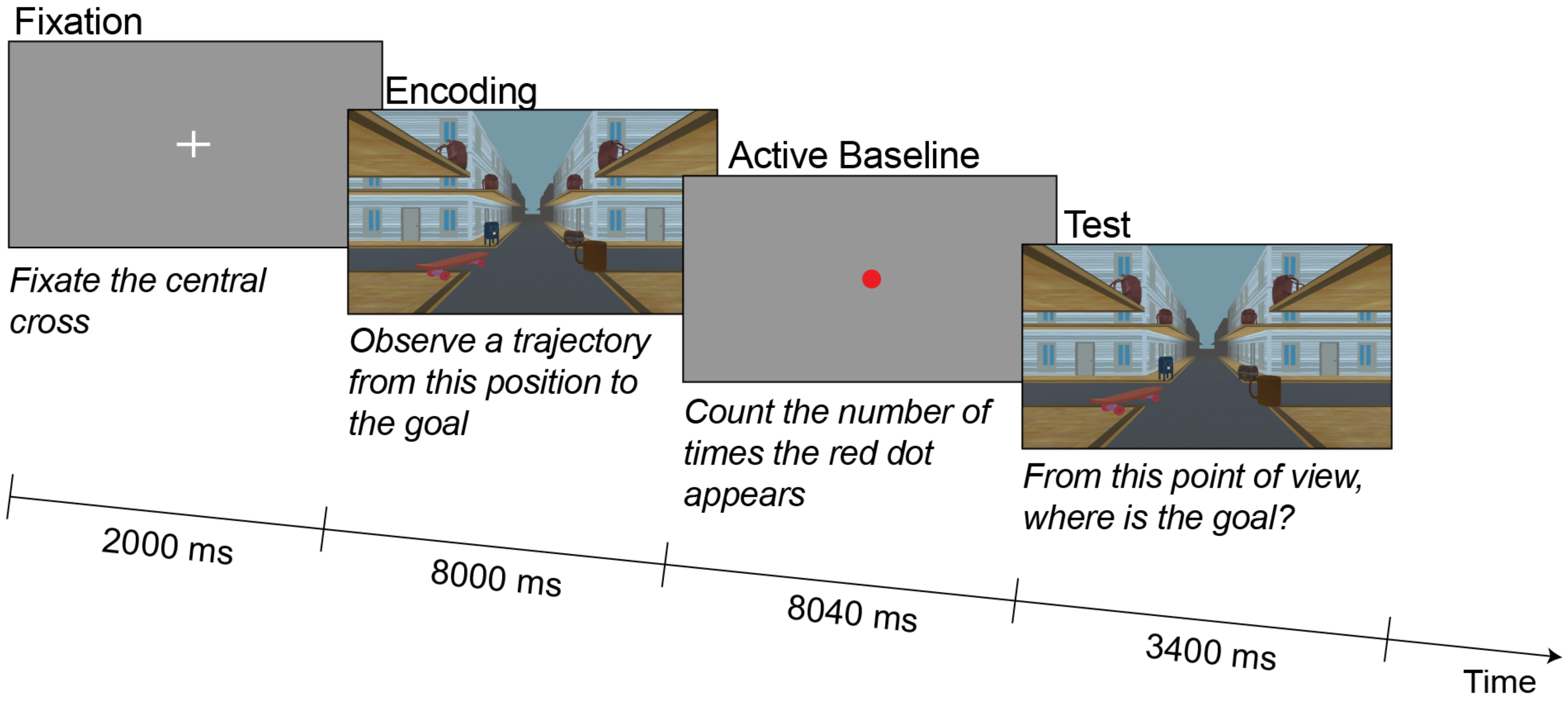




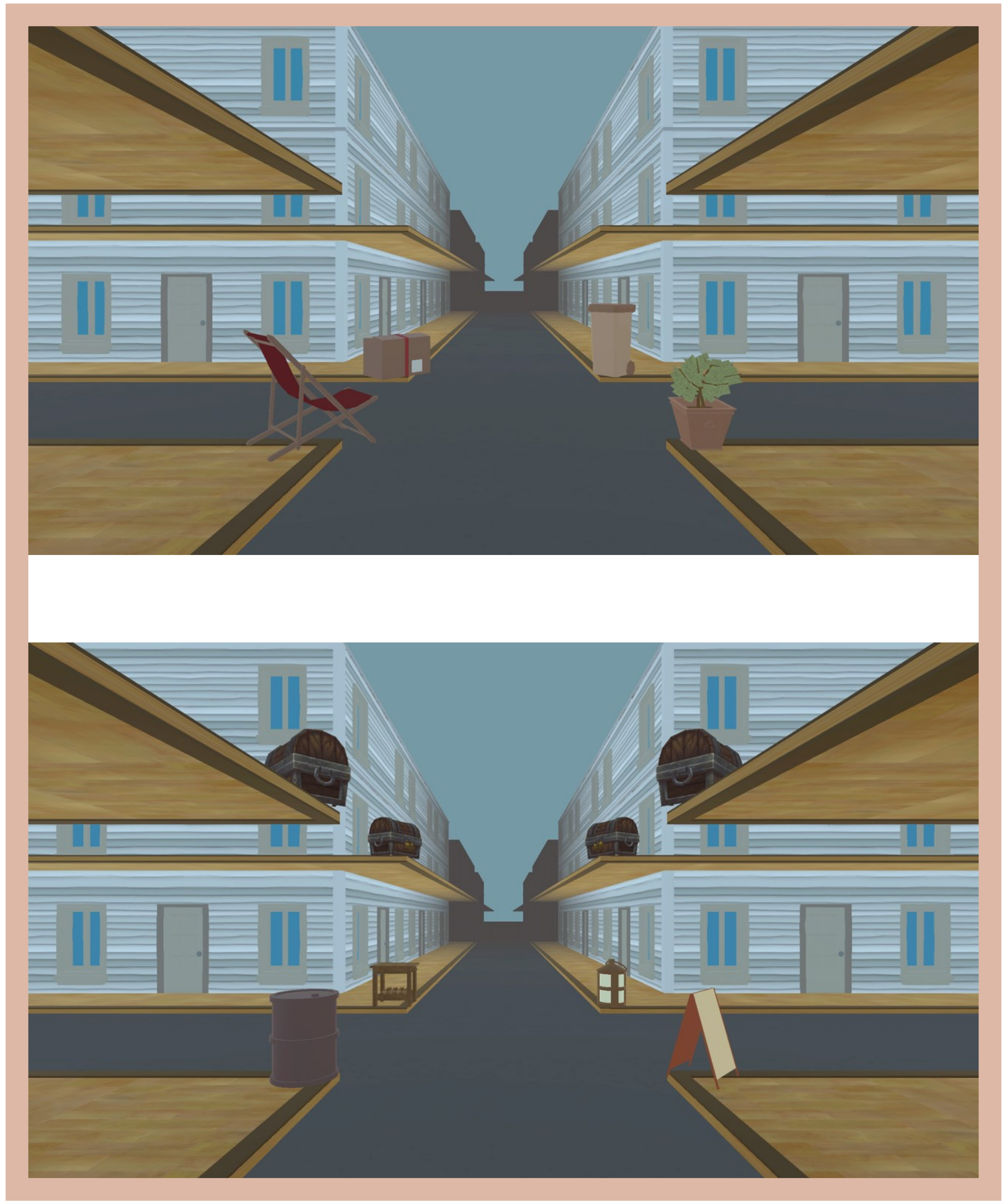
Durteste et al., 2023, BioRxiv

Study 5

Methods

Half

Full



Durteste et al., 2023, BioRxiv

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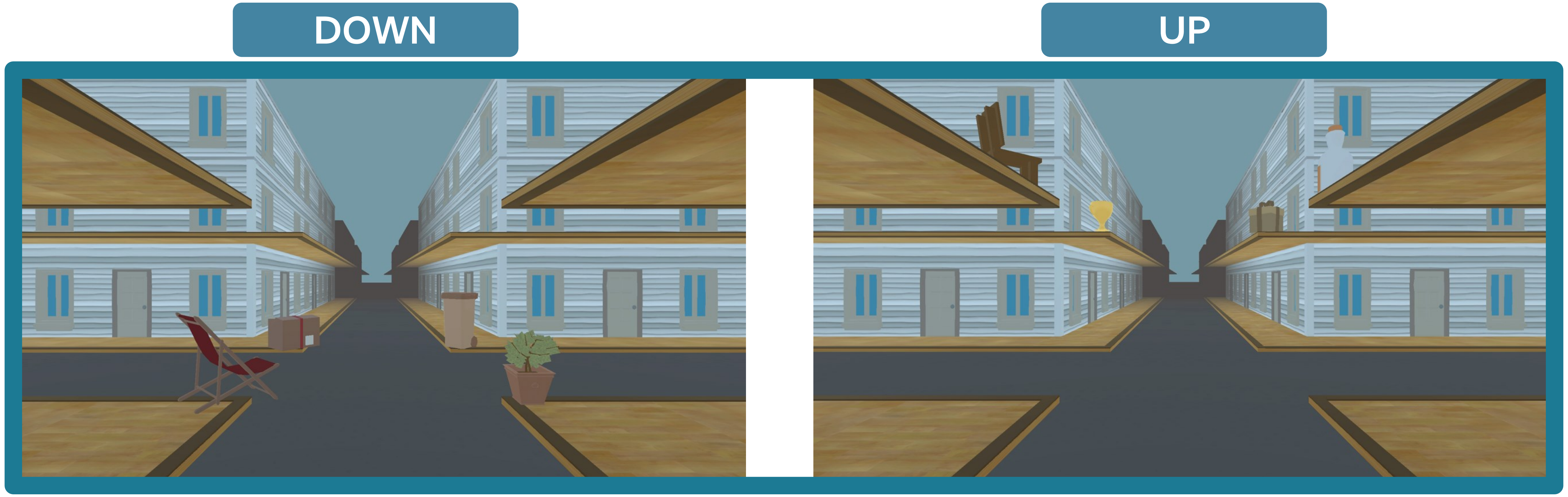
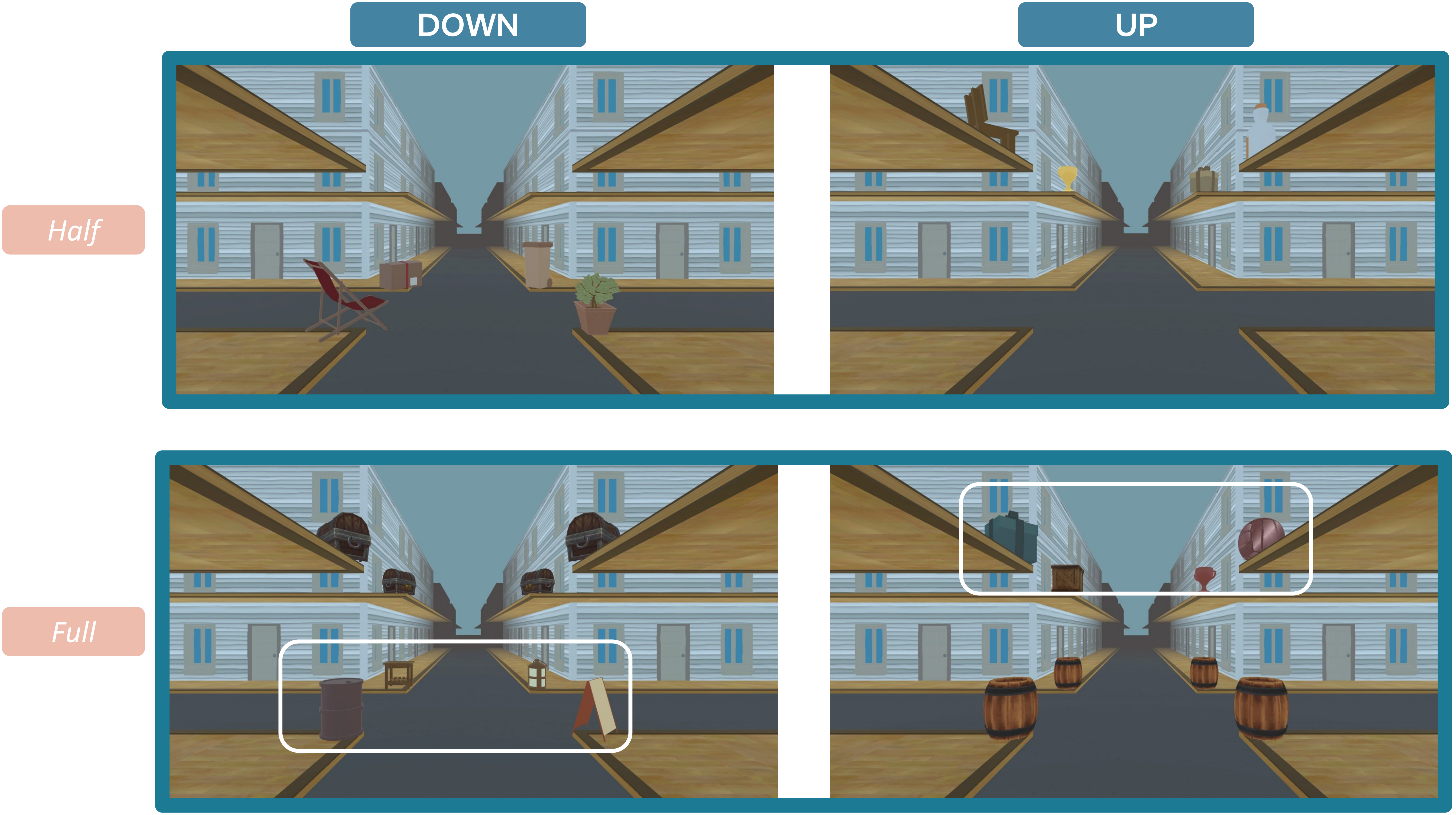
Half



Durteste et al., 2023, BioRxiv

Study 5

Methods



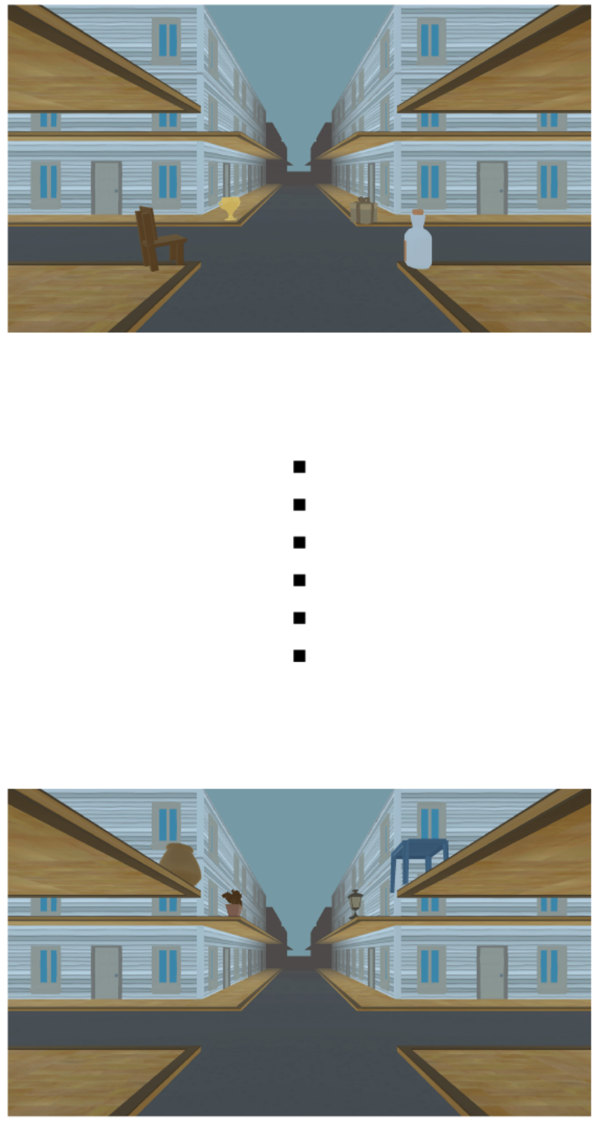
Durteste et al., 2023, BioRxiv

Study 5

Methods

Univariate and representational similarity analyses

Experimental stimuli

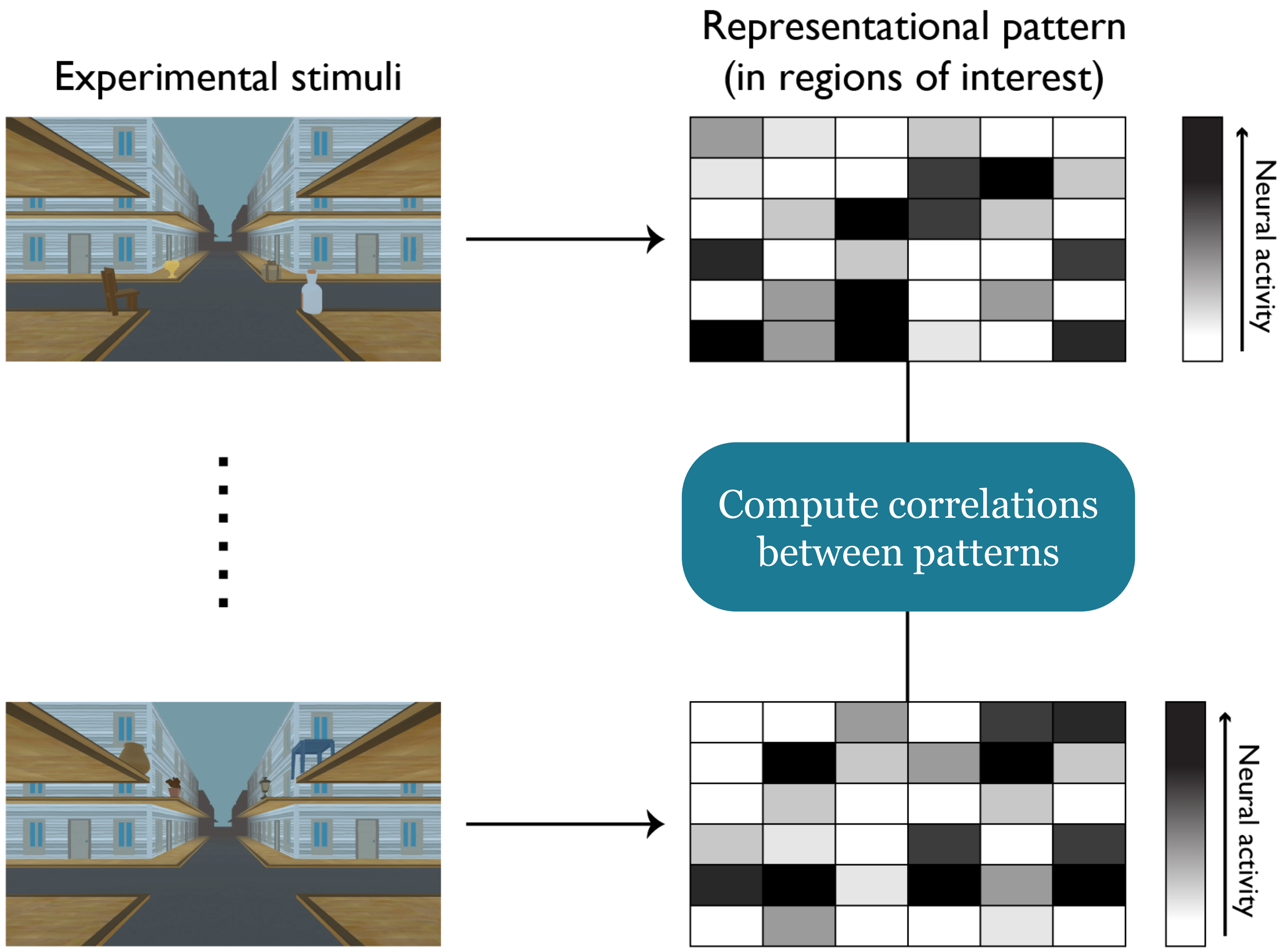


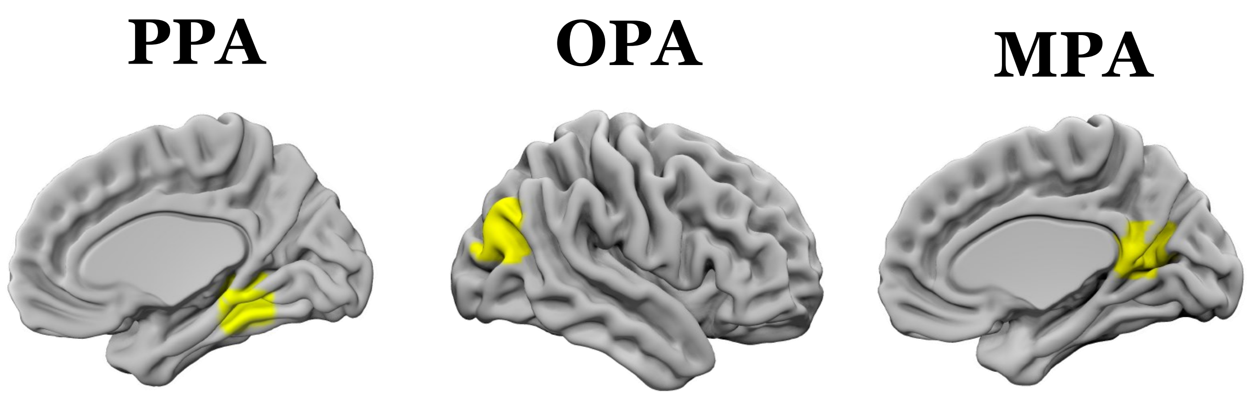
Durteste et al., 2023, BioRxiv

Study 5

Methods

Univariate and representational similarity analyses



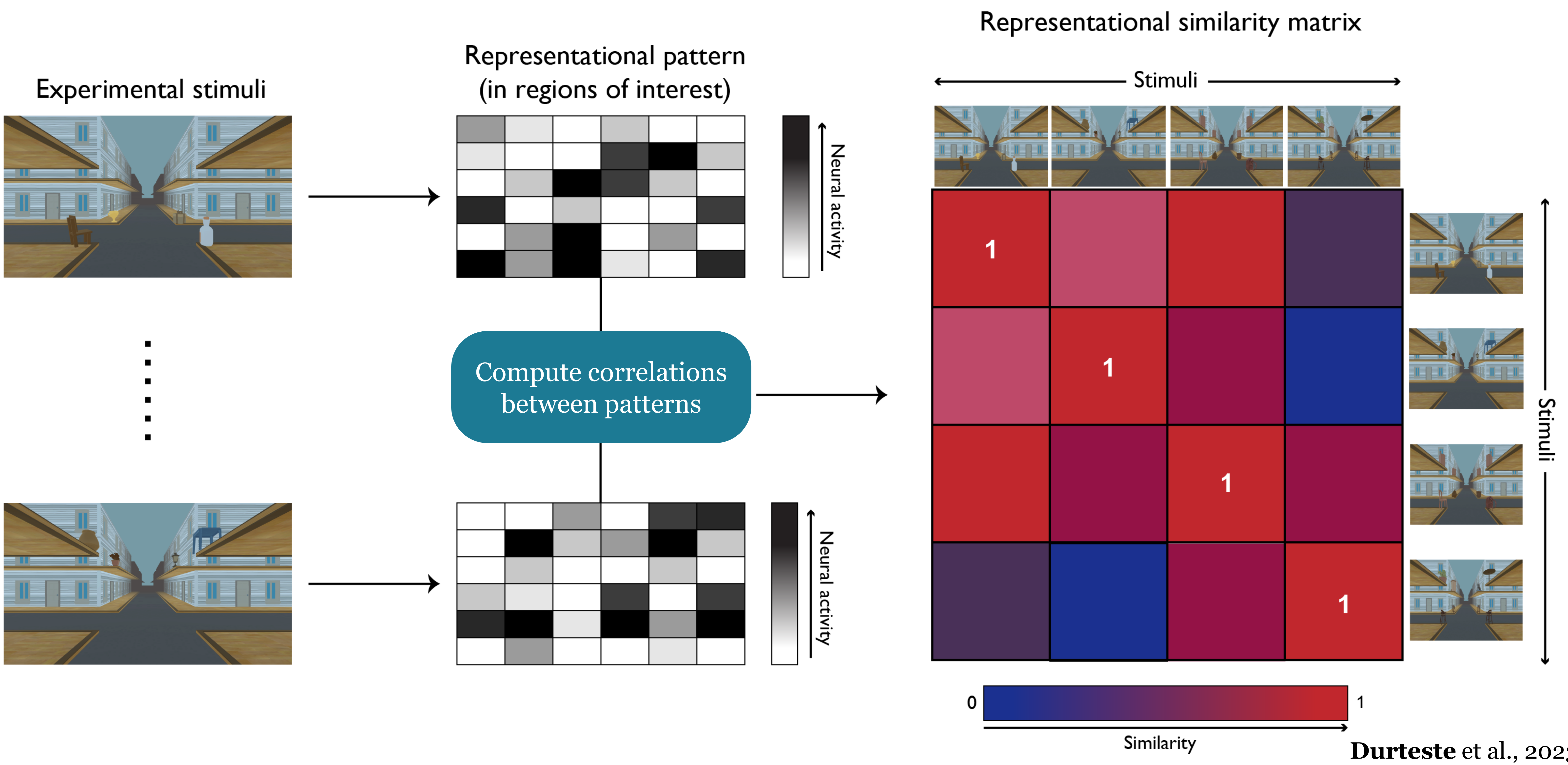


Durteste et al., 2023, BioRxiv

Study 5

Methods

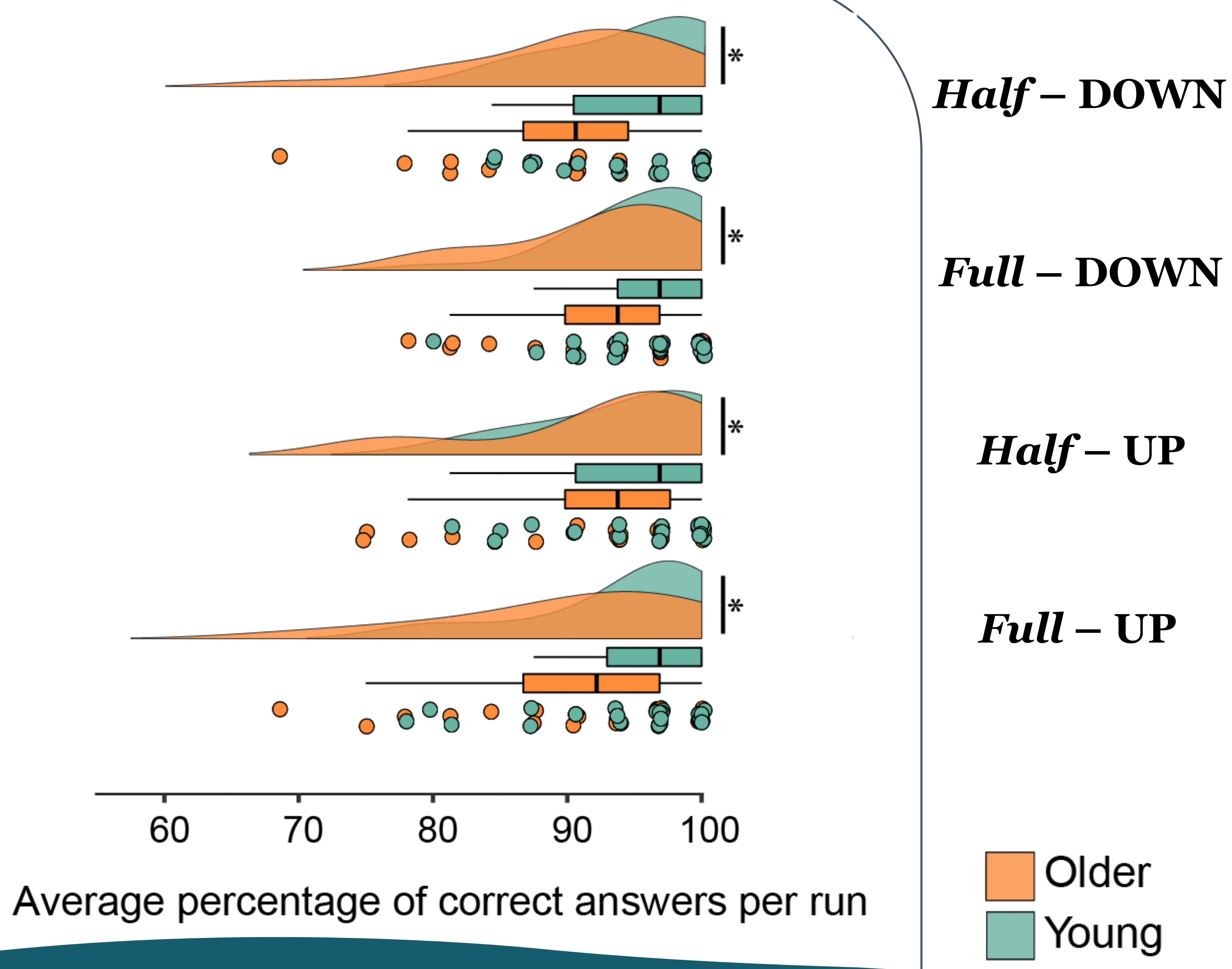
Univariate and representational similarity analyses



Durteste et al., 2023, BioRxiv

Study 5

Behavioural results

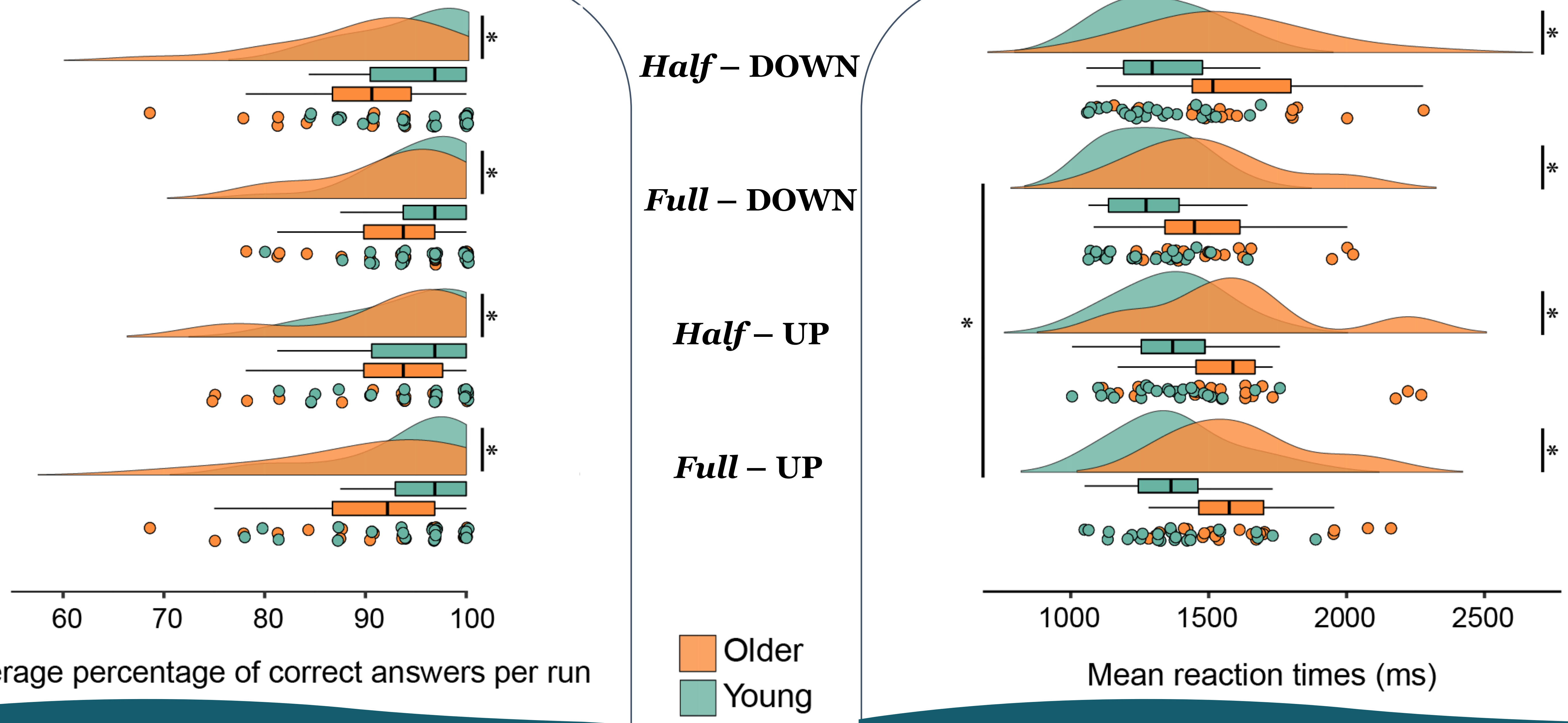


Older participants make more orientation errors than young participants

Durteste et al., 2023, BioRxiv

Study 5

Behavioural results



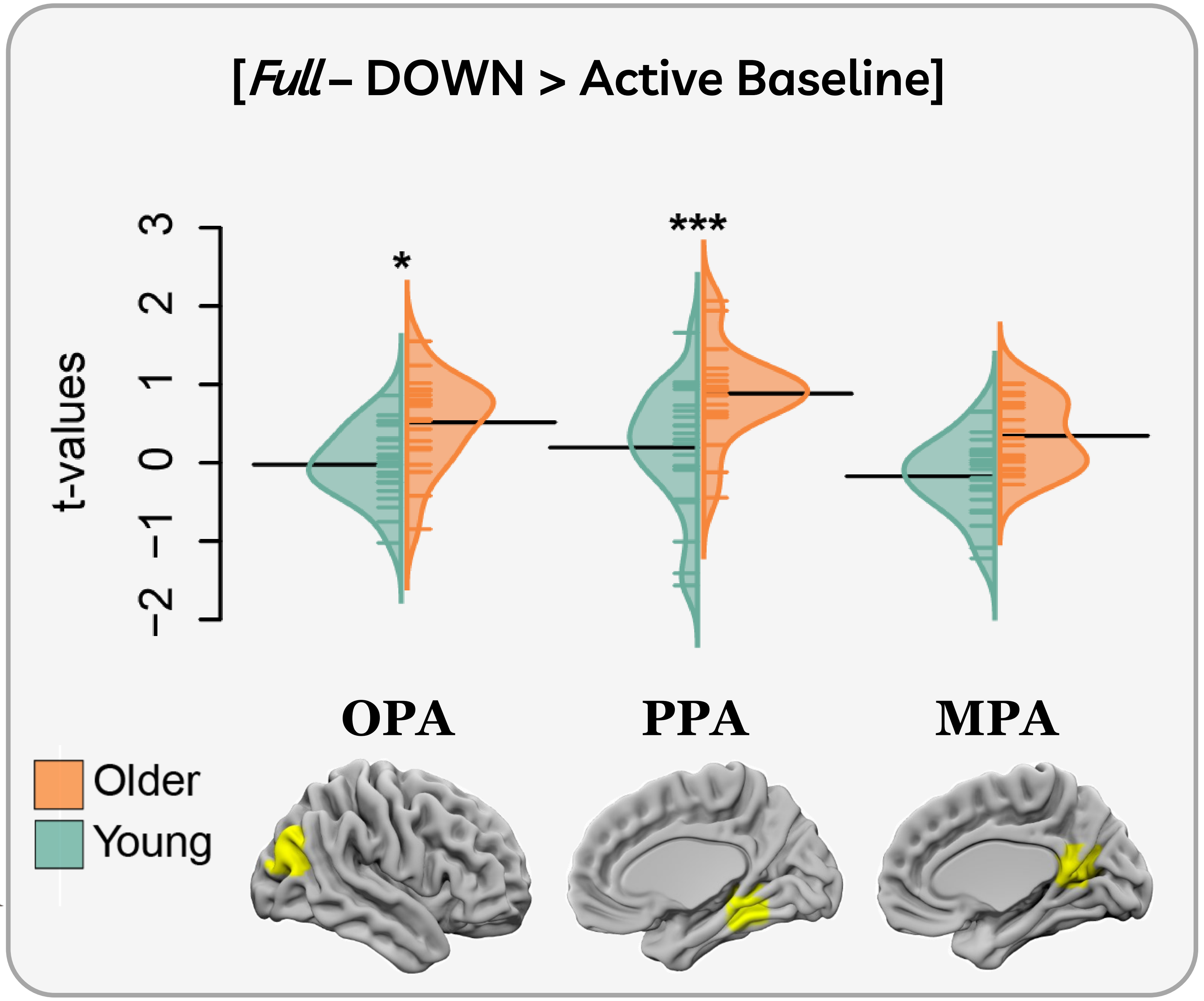
Older participants make more orientation errors than young participants

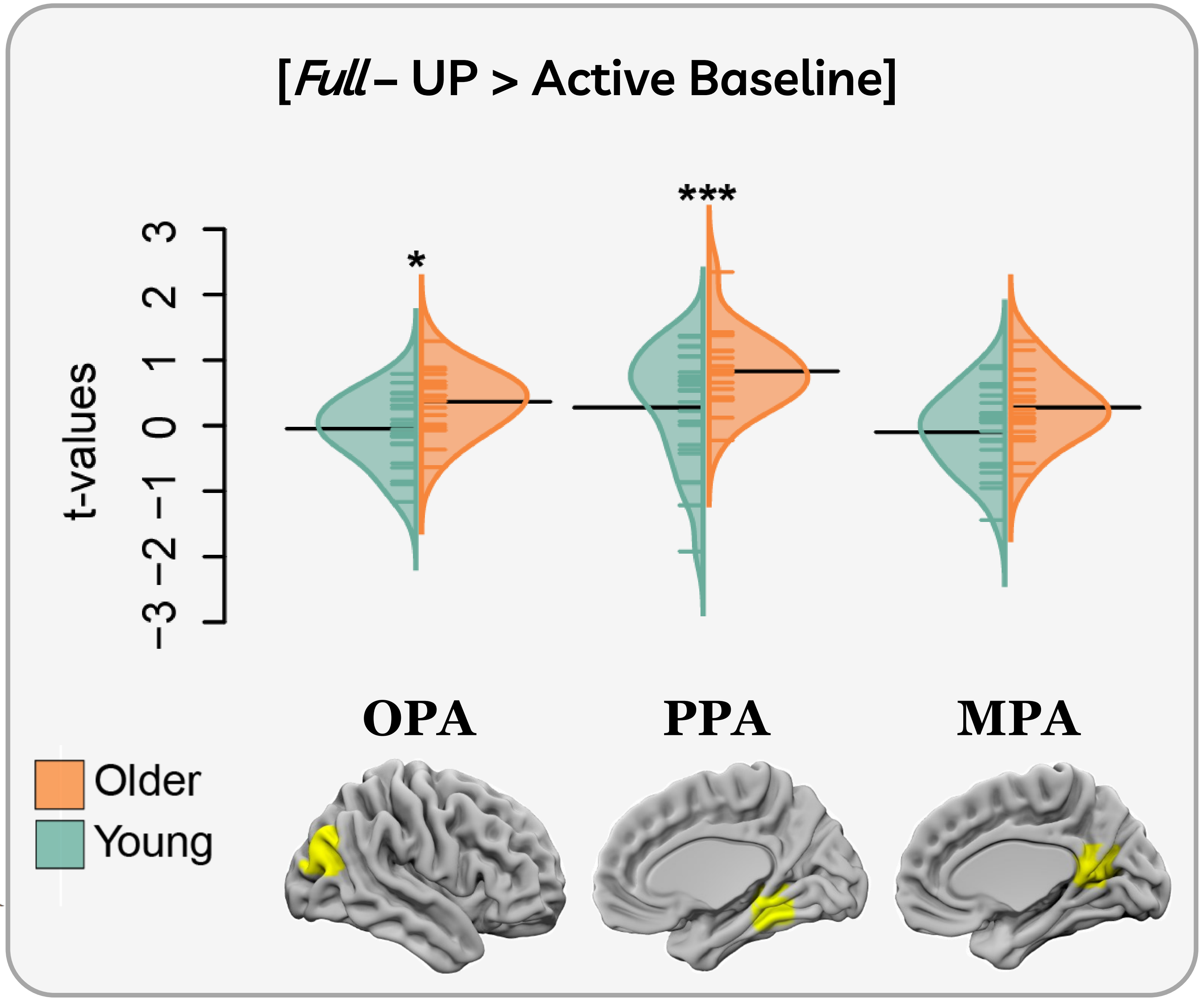
All participants are slower to respond in the *Full* – UP condition

Durteste et al., 2023, BioRxiv

Study 5

Neuroimaging univariate results



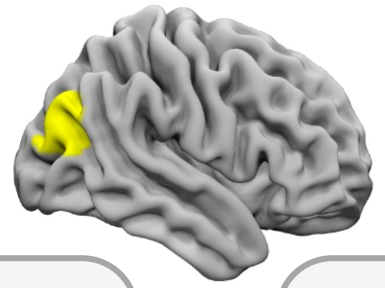


Durteste et al., 2023, BioRxiv

Study 5

Neuroimaging multivariate results

OPA

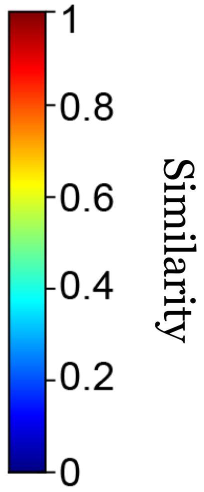


Young

	Half – DOWN	*Full* – DOWN	*Half* – UP	*Full* – UP
Half – DOWN	1	0.81	0.80	0.77
Full – DOWN	0.81	1	0.80	0.77
Half – UP	0.80	0.80	1	0.82
Full – UP	0.77	0.77	0.82	1

Older

	Half – DOWN	*Full* – DOWN	*Half* – UP	*Full* – UP
Half – DOWN	1	0.79	0.75	0.74
Full – DOWN	0.79	1	0.73	0.77
Half – UP	0.75	0.73	1	0.80
Full – UP	0.74	0.77	0.80	1

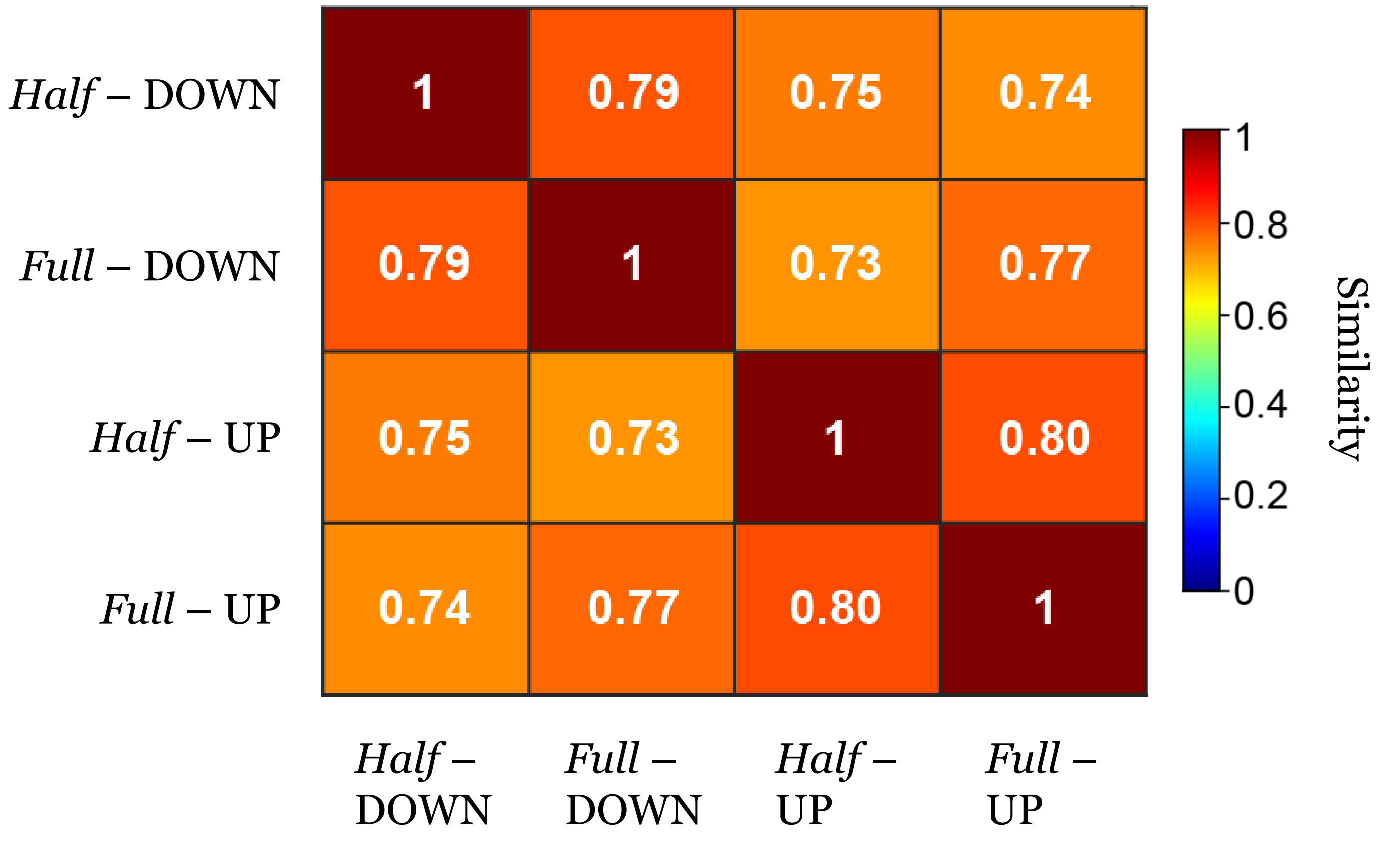


Durteste et al., 2023, BioRxiv

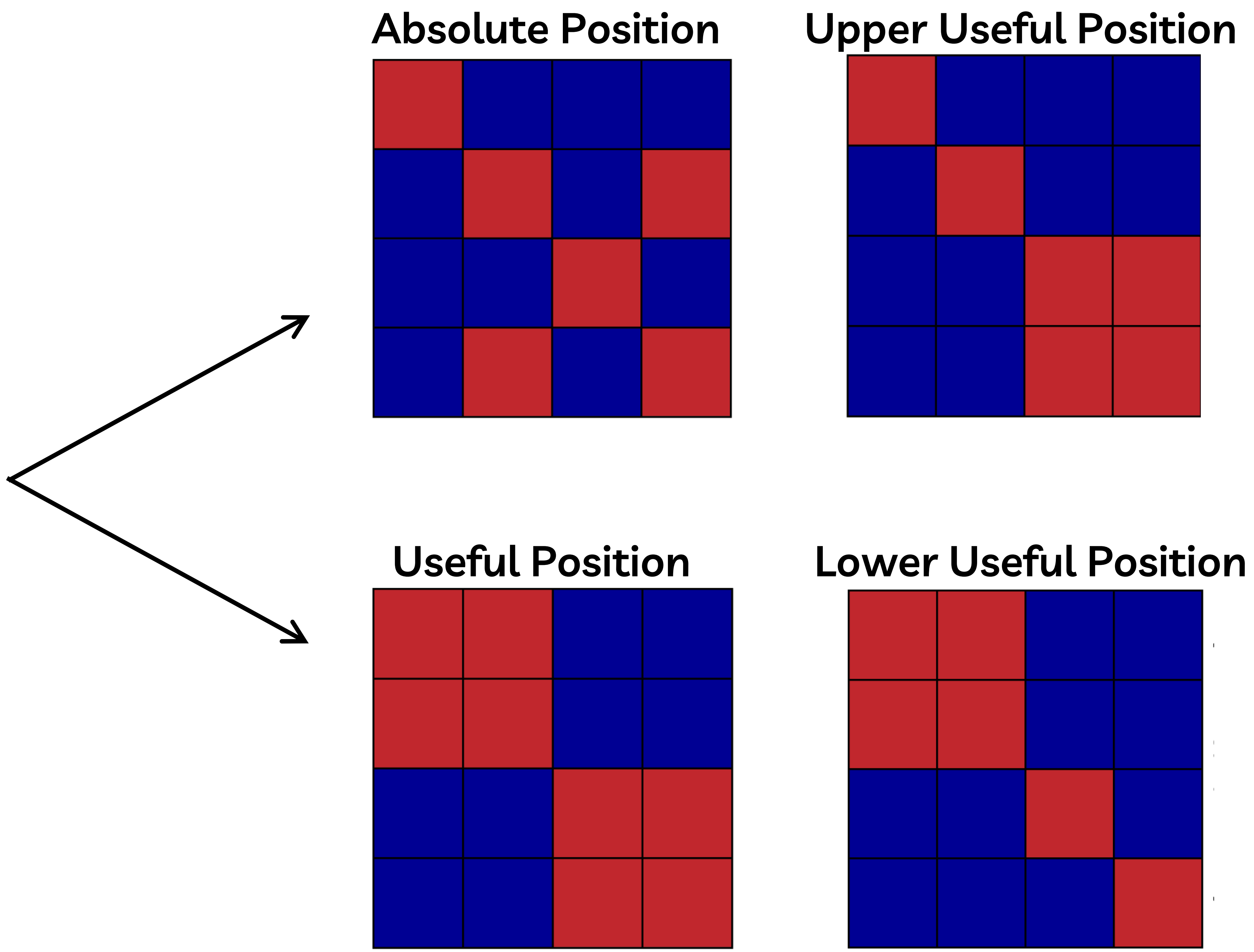
Study 5

Neuroimaging multivariate results

Representational Similarity Matrix



Theoretical Matrices

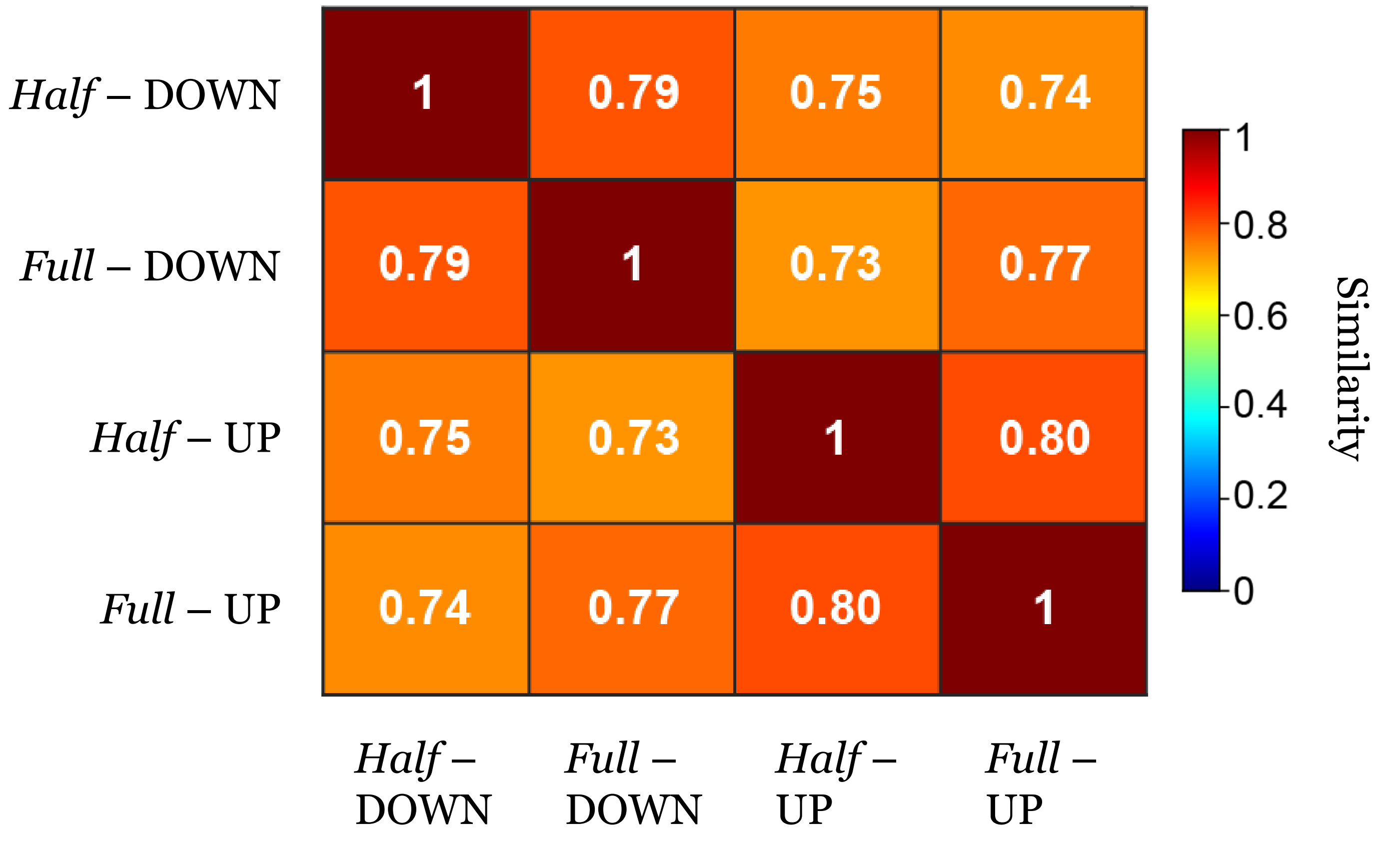


Durteste et al., 2023, BioRxiv

Study 5

Neuroimaging multivariate results

Representational Similarity Matrix



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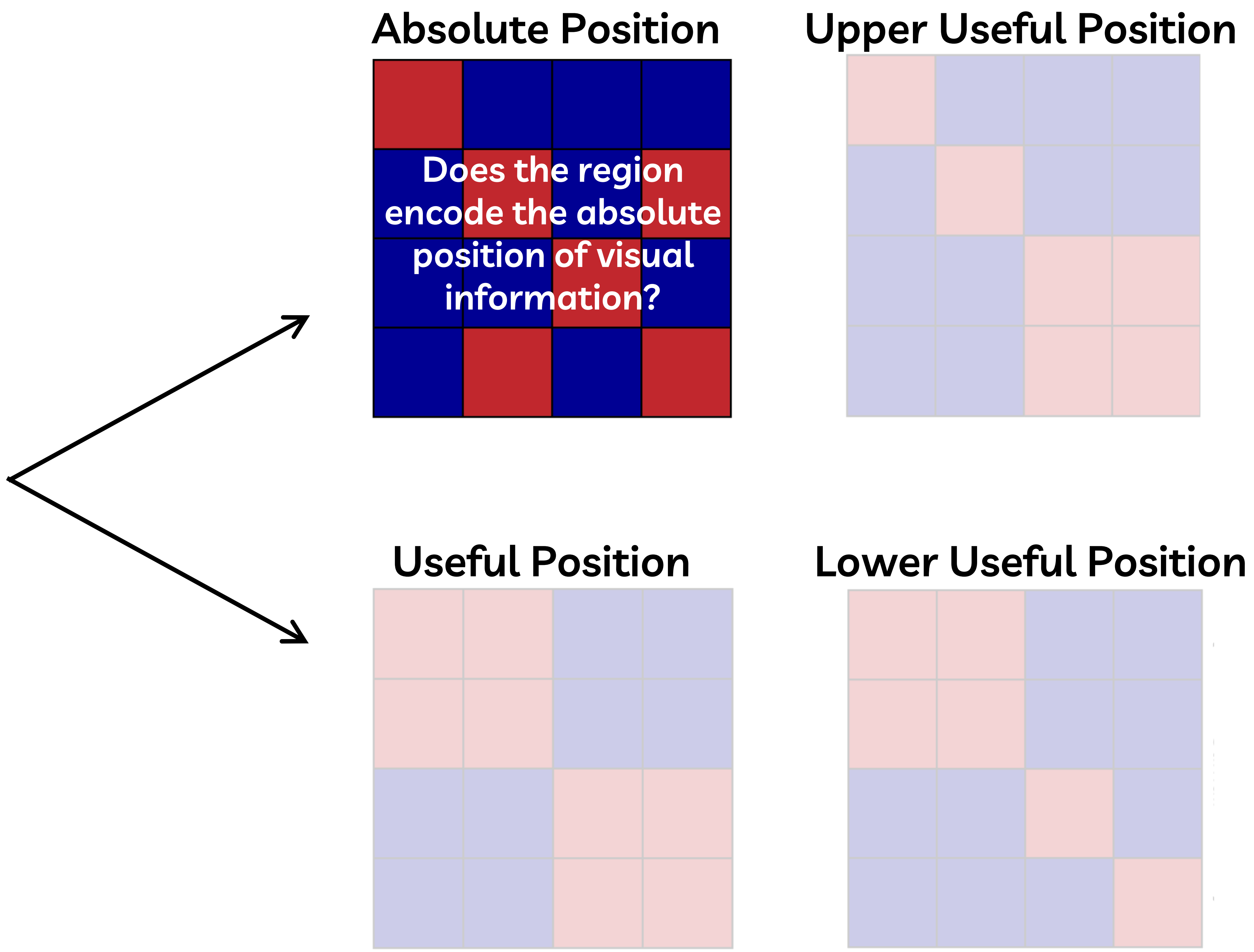

Durteste et al., 2023, BioRxiv

Study 5

Neuroimaging multivariate results

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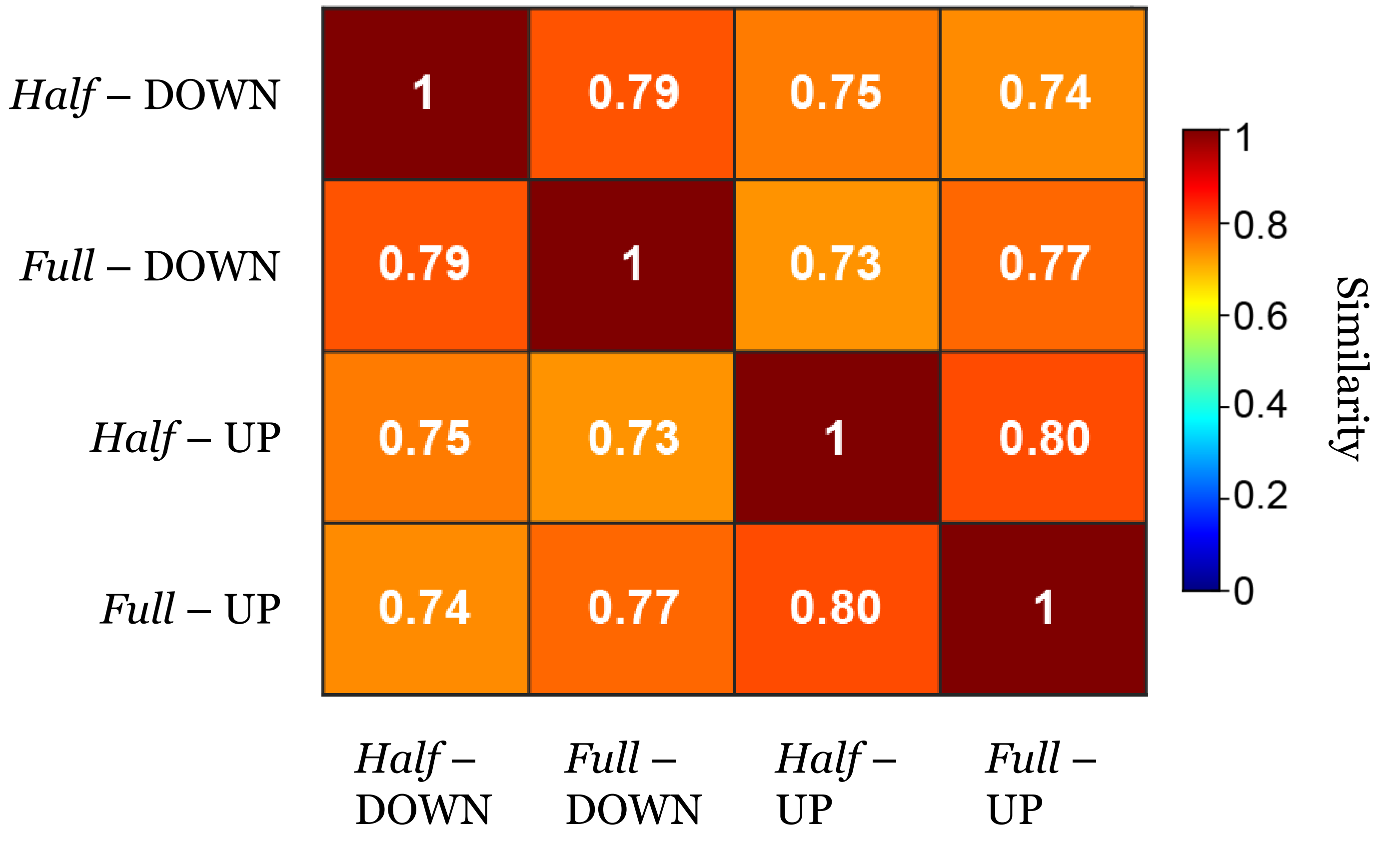

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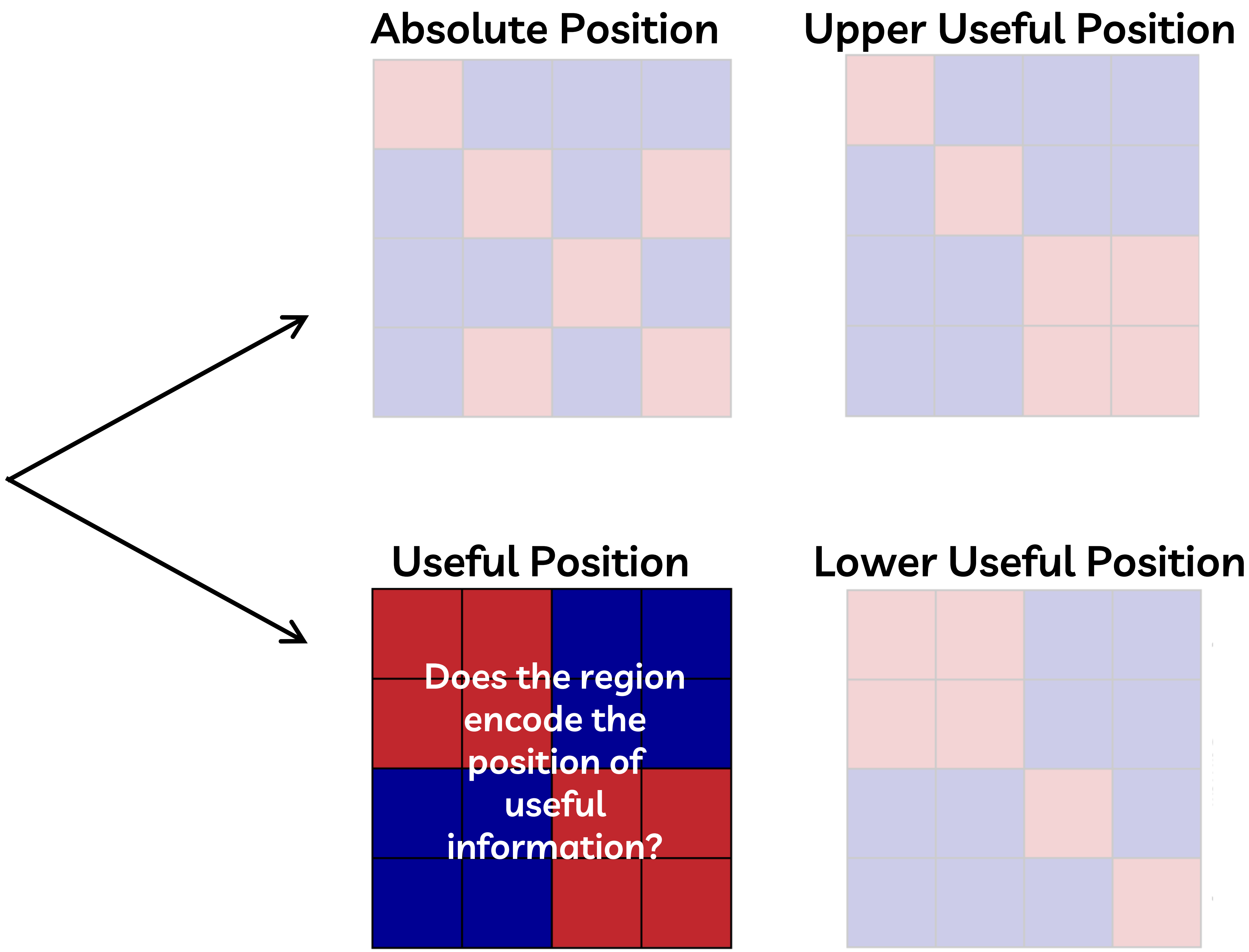

Durteste et al., 2023, BioRxiv

Study 5

Neuroimaging multivariate results

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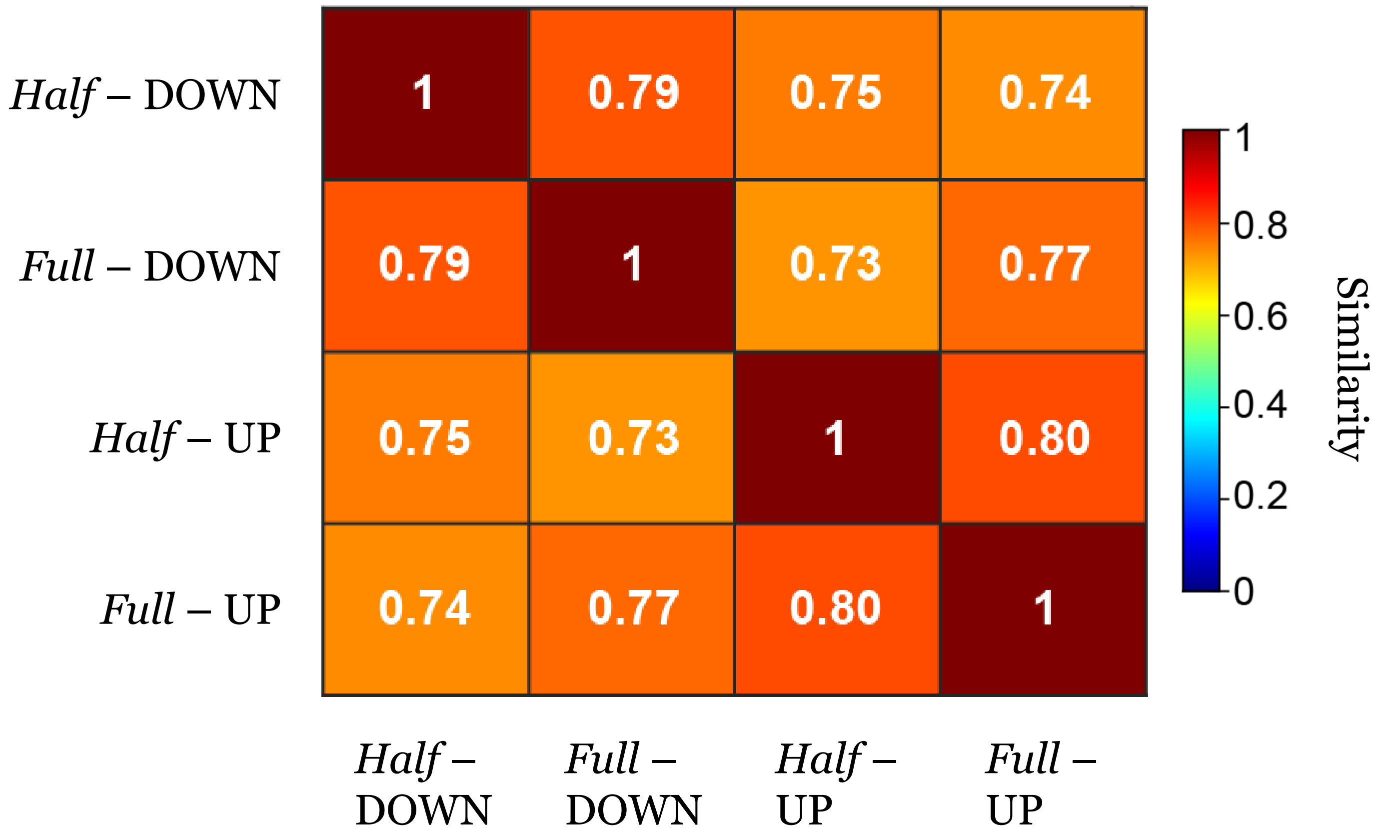
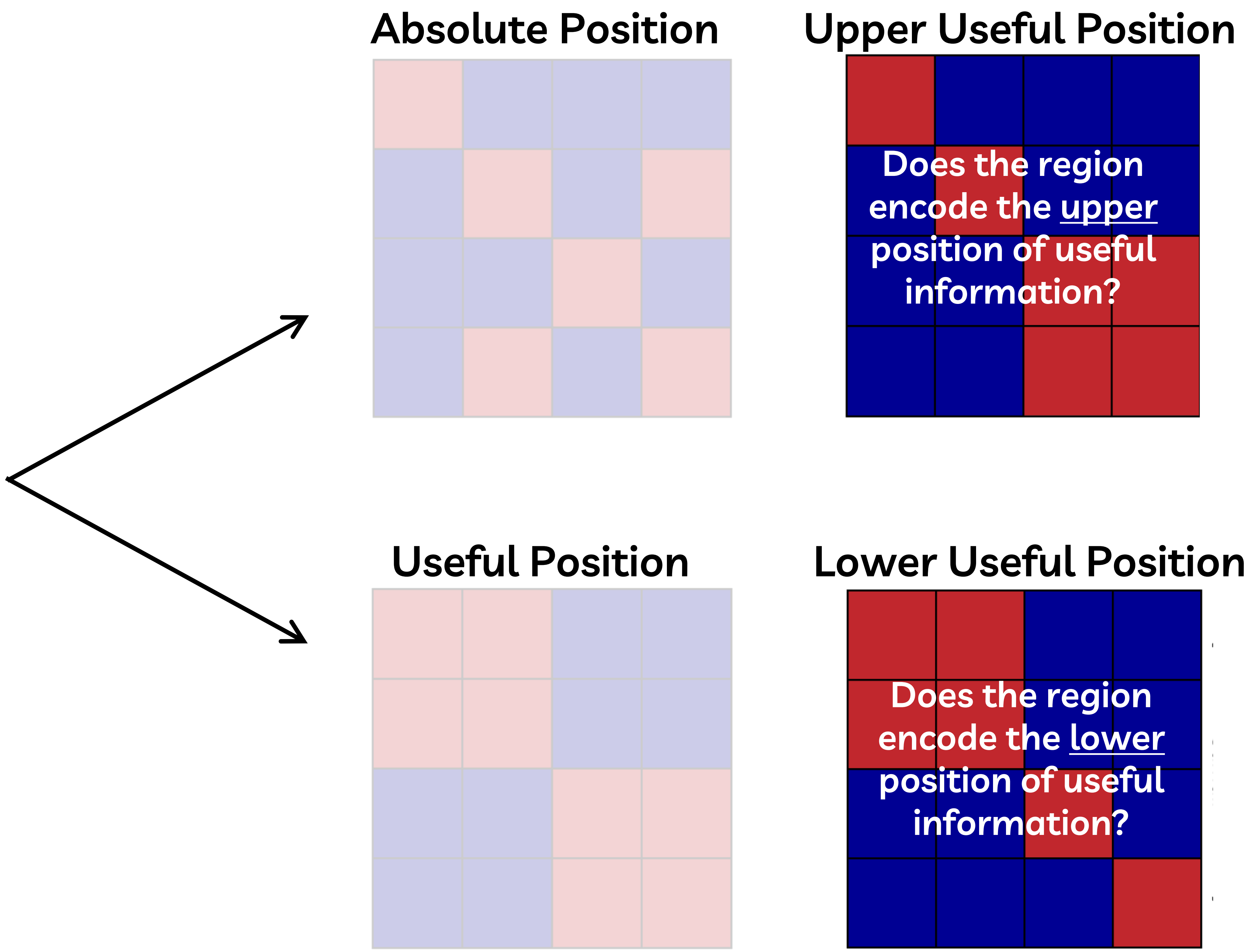
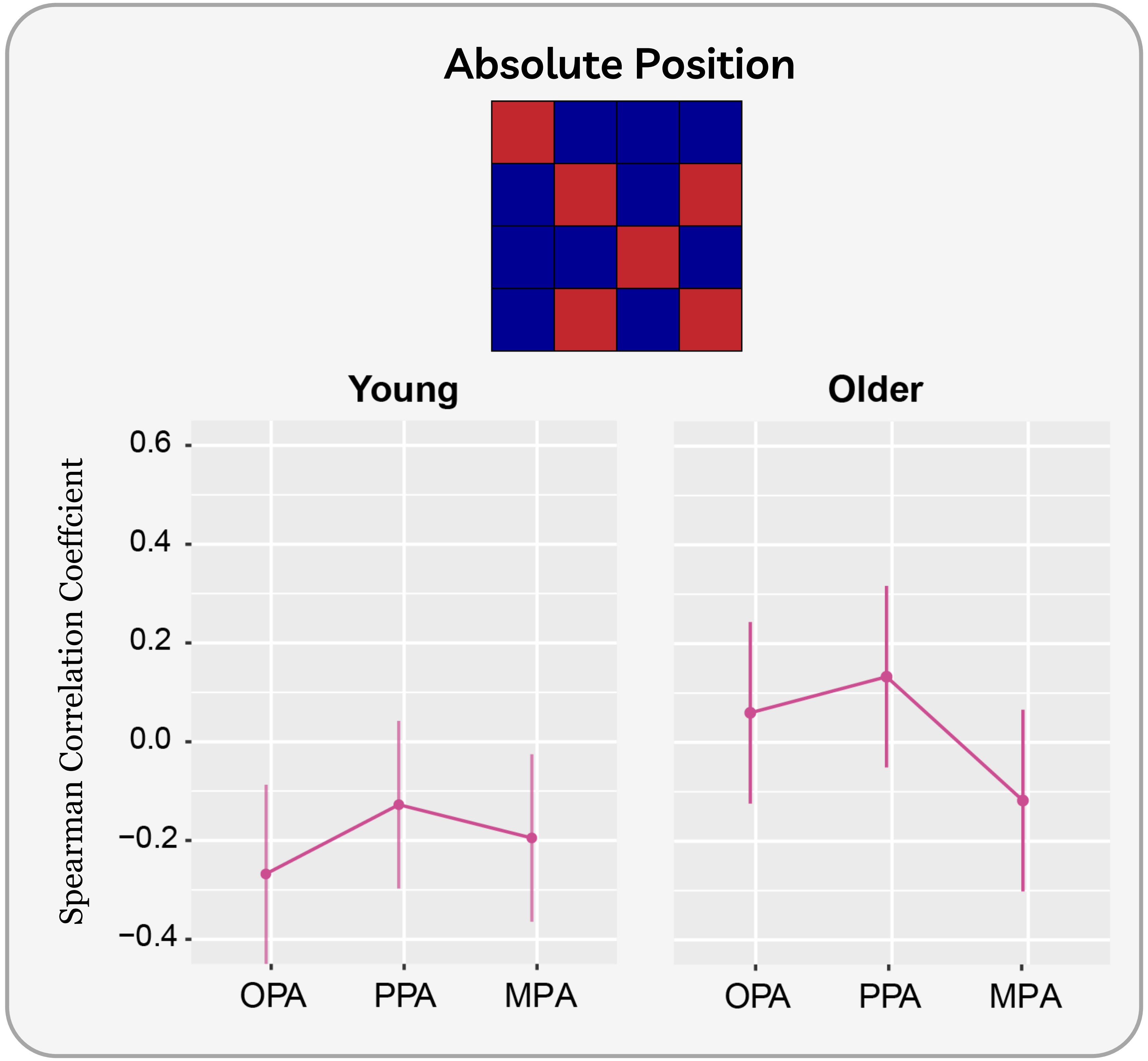


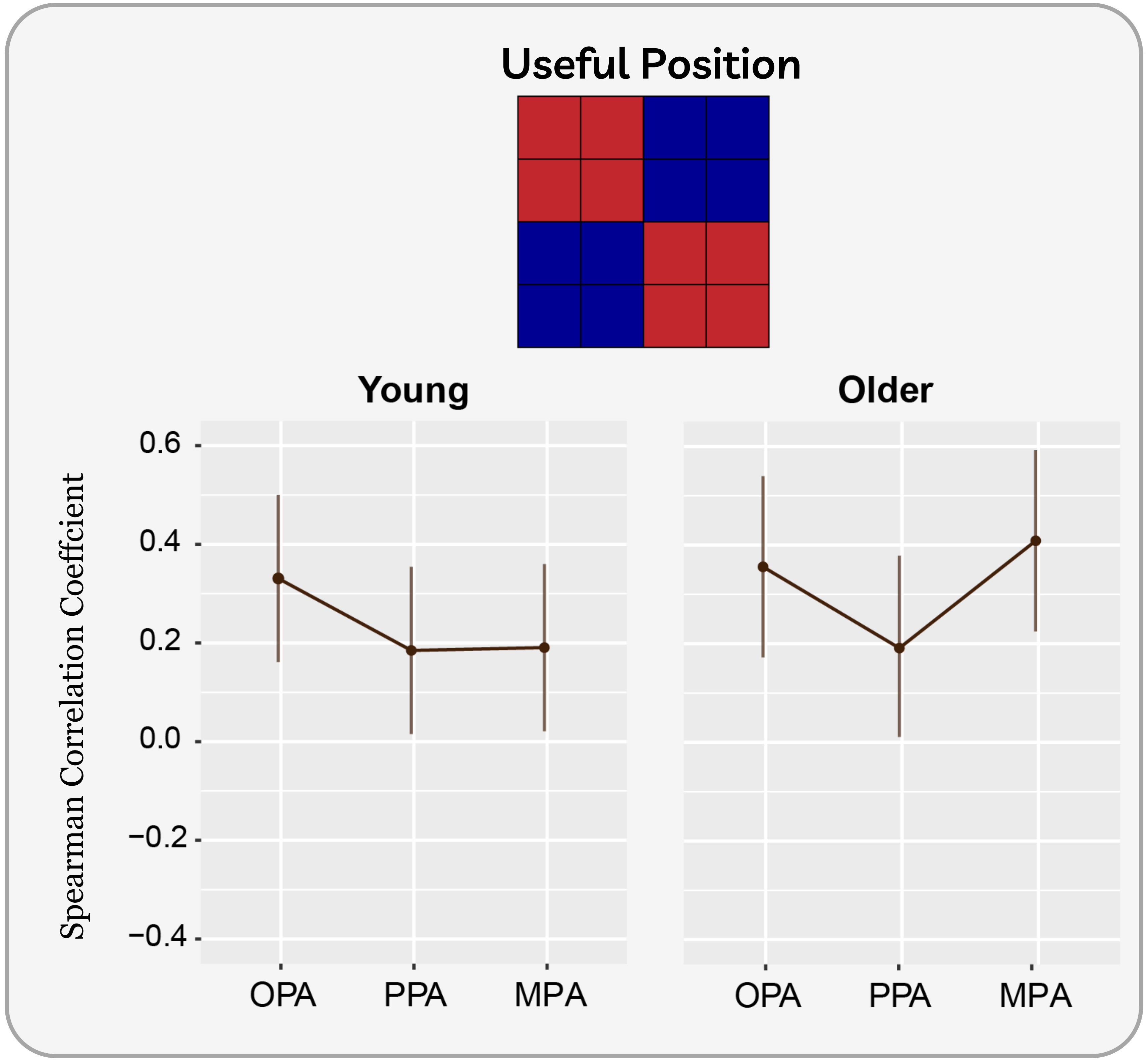
Theoretical Matrices



Study 5

Neuroimaging multivariate results





Durteste et al., 2023, BioRxiv

Study 5

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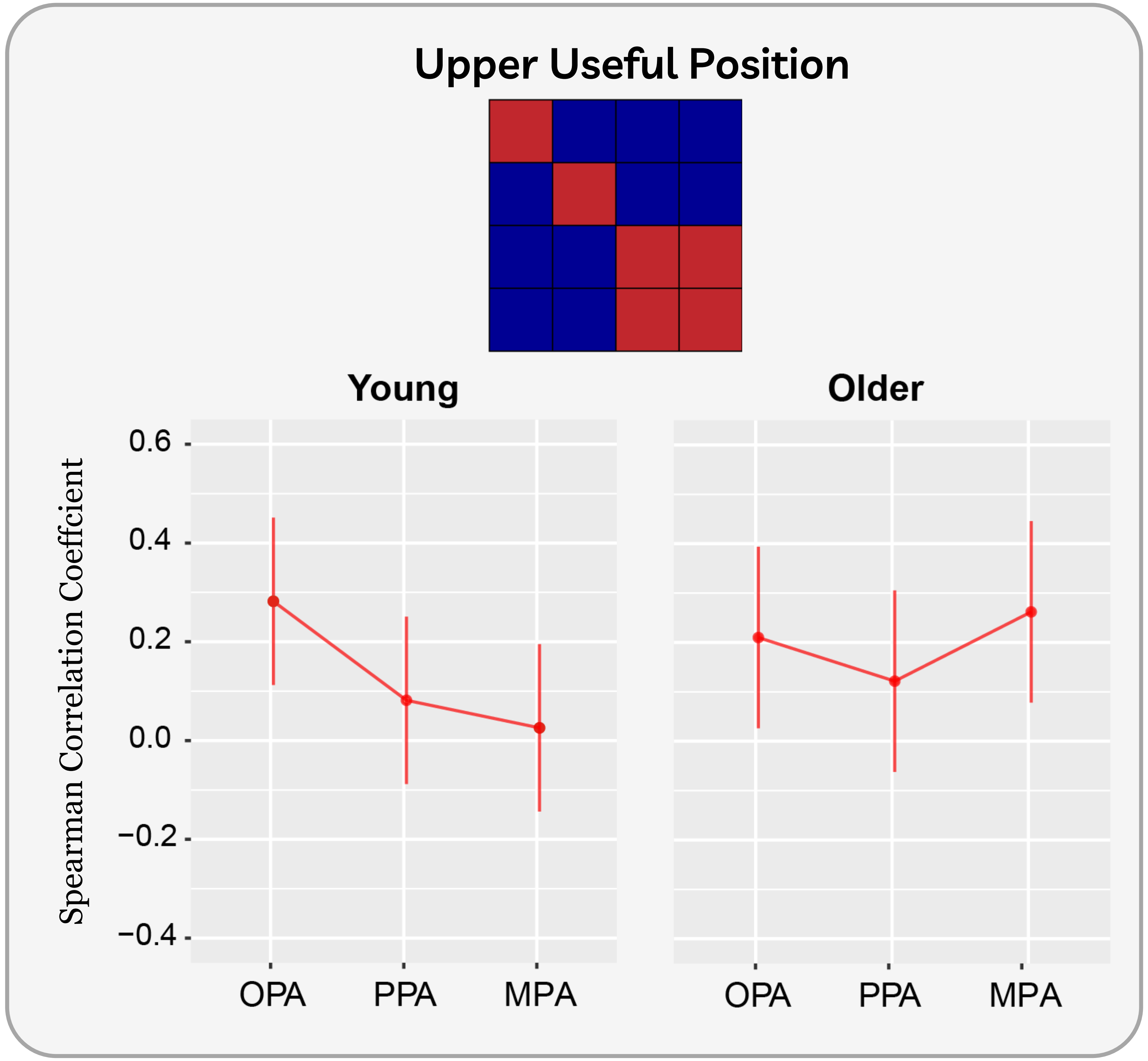
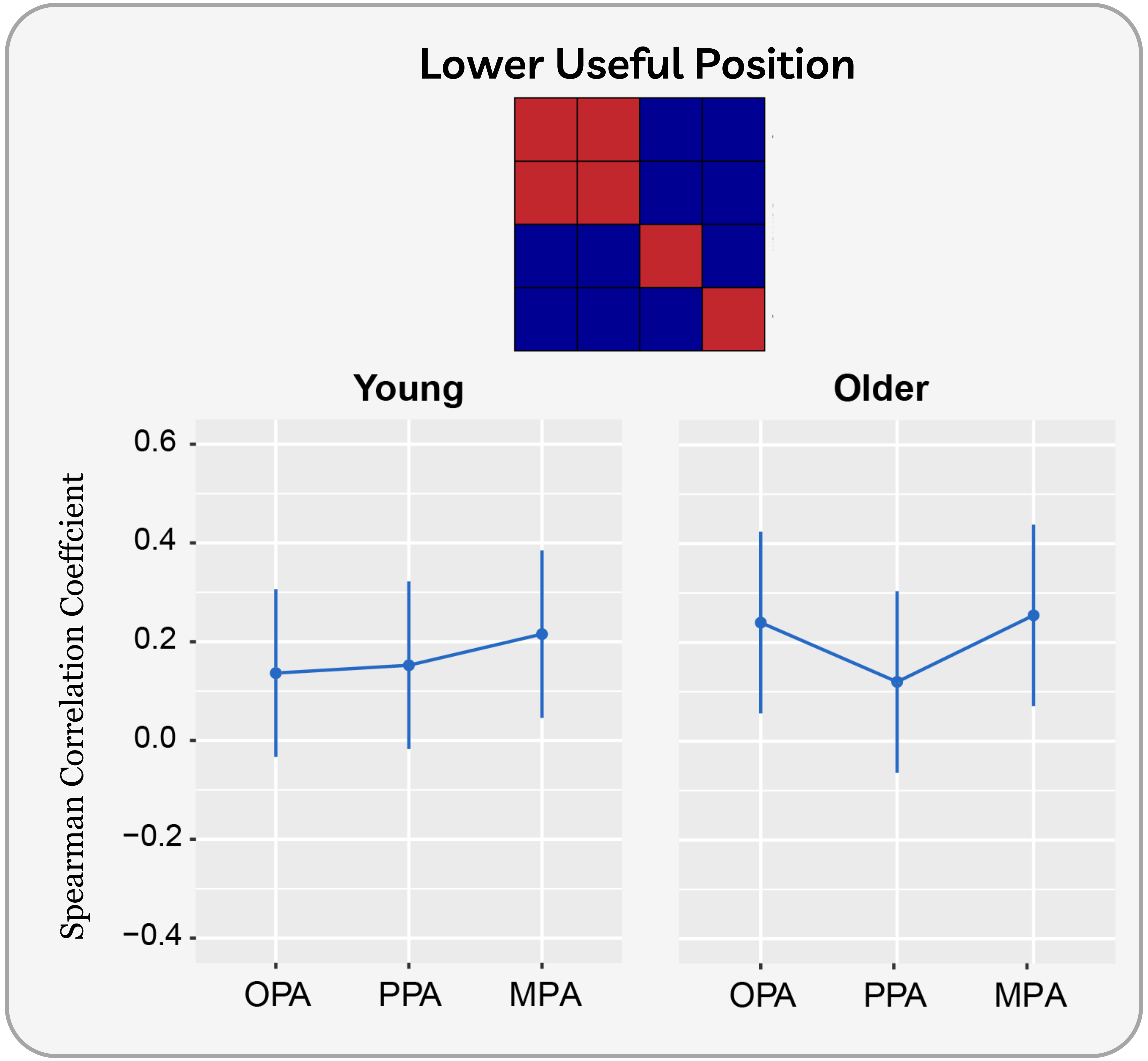


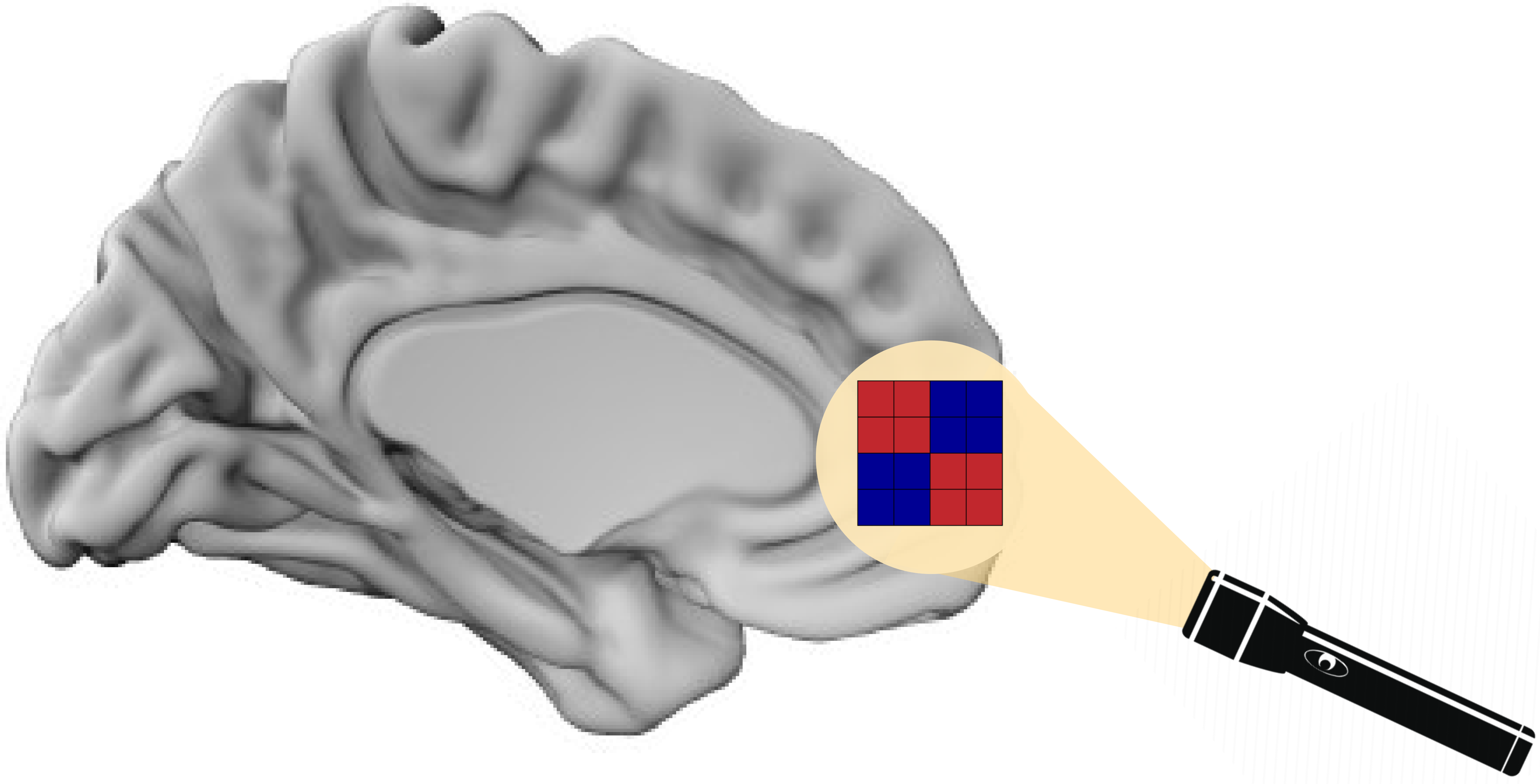


Durteste et al., 2023, BioRxiv

Study 5

Neuroimaging multivariate results

Searchlight-based analysis



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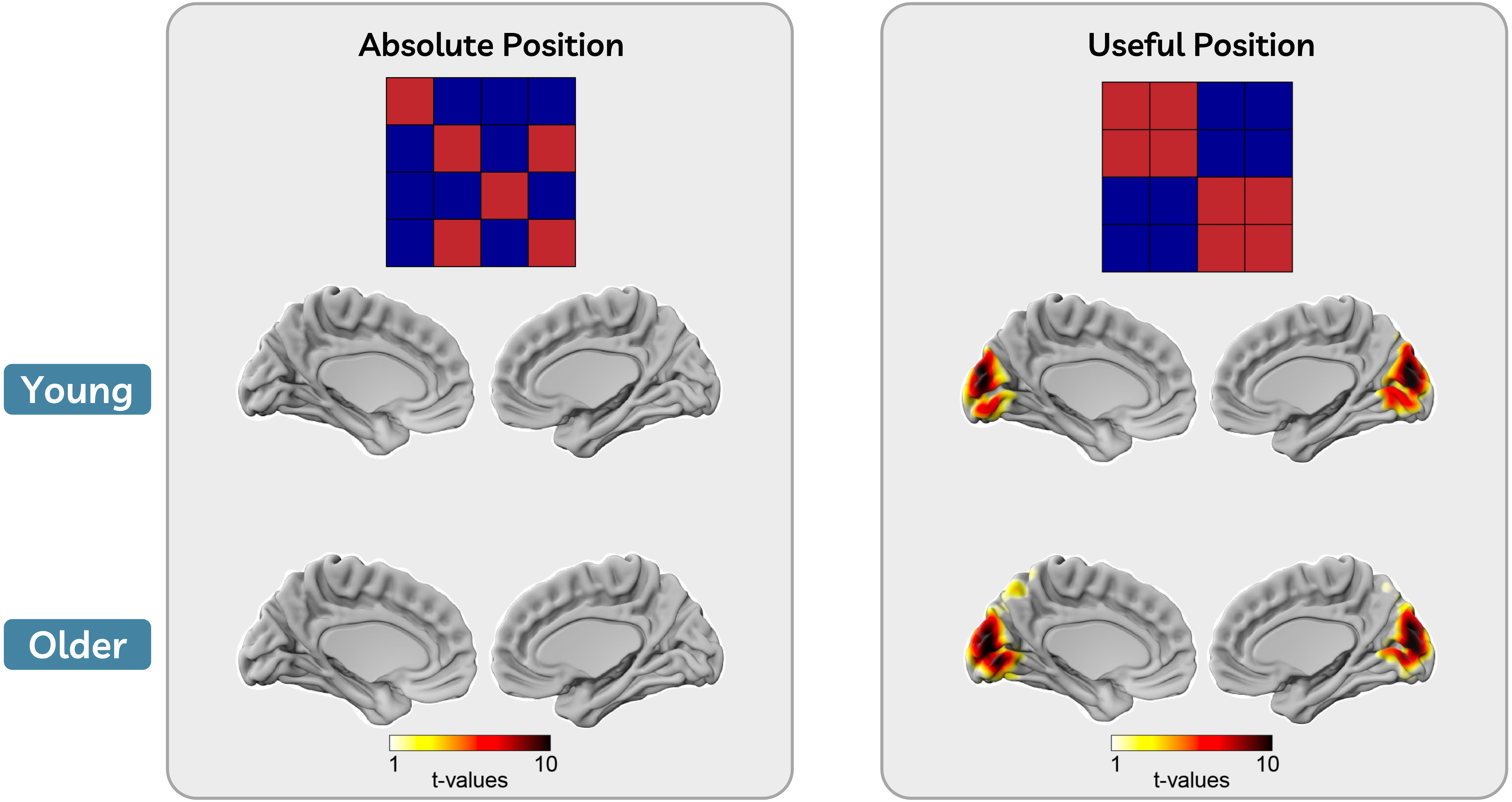
Study 5

Neuroimaging multivariate results



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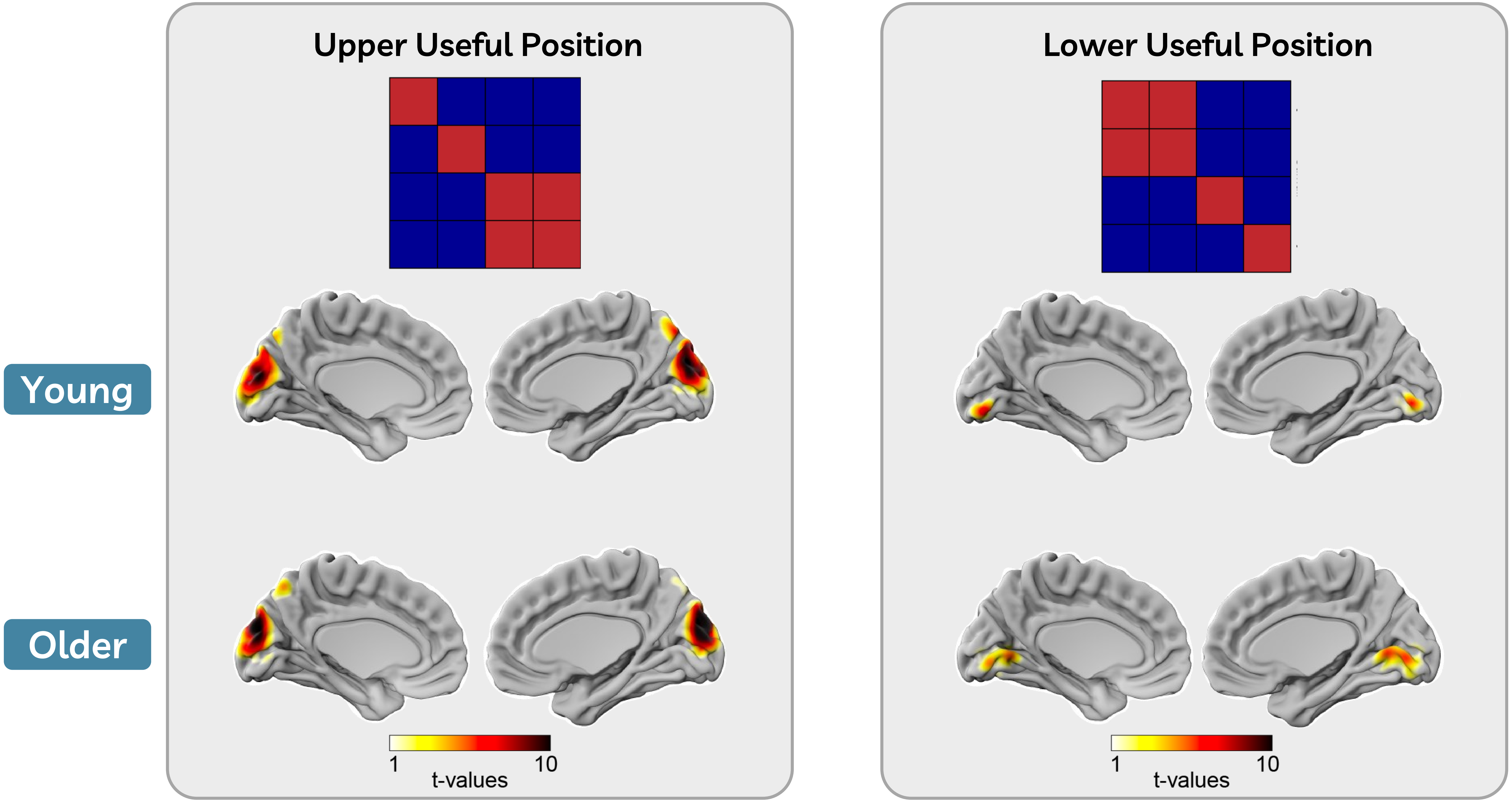
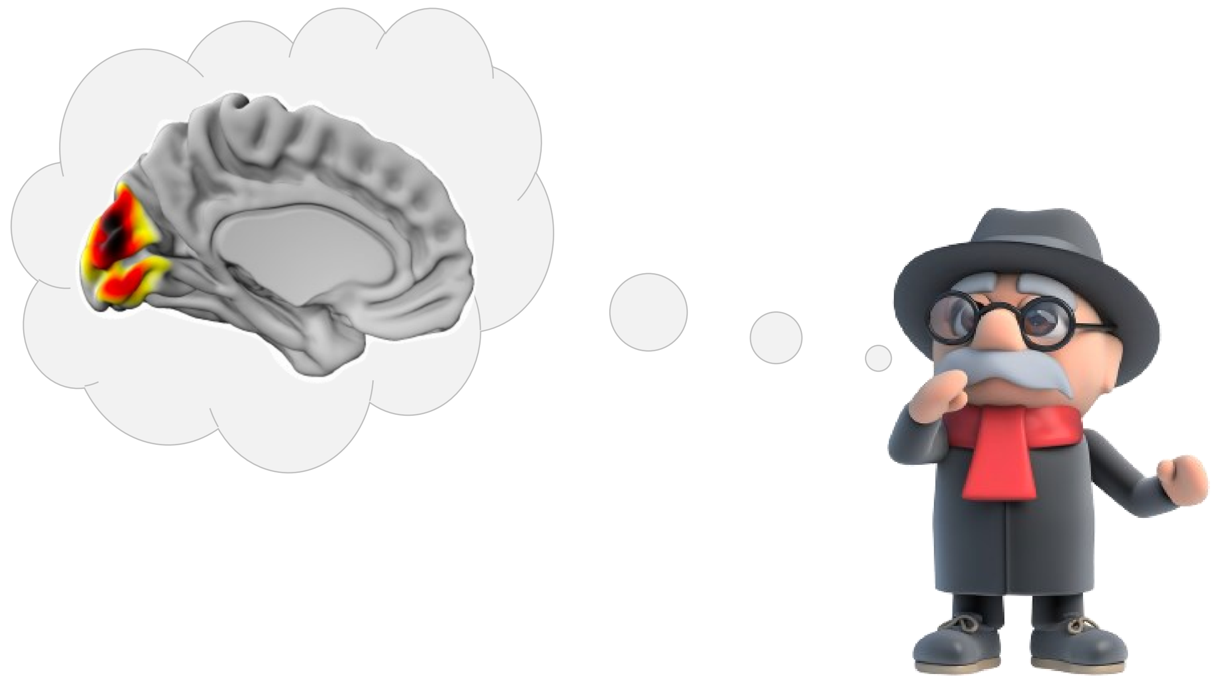


Durteste et al., 2023, BioRxiv

Study 5

Neuroimaging multivariate results

Scene-selective regions parse the vertical position of navigationally-relevant information in young and older adults



Intro

01.

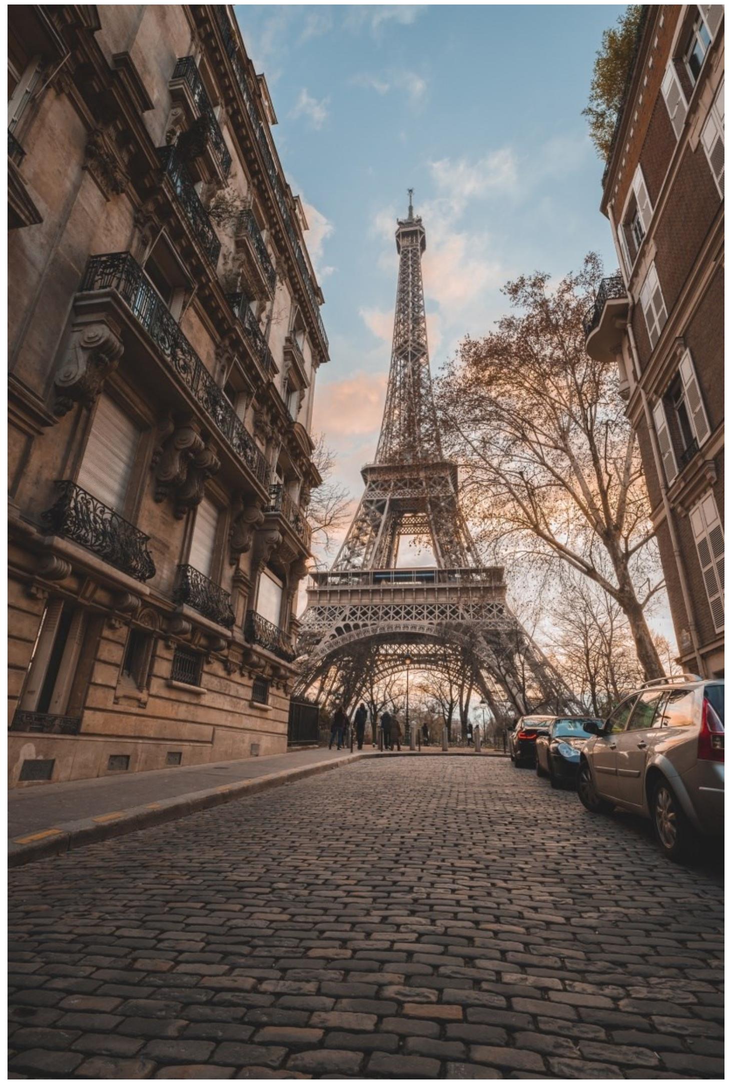
02.

Disc.

Aim 02

Summary

- Importance of the position of visual information for spatial cognition



Intro

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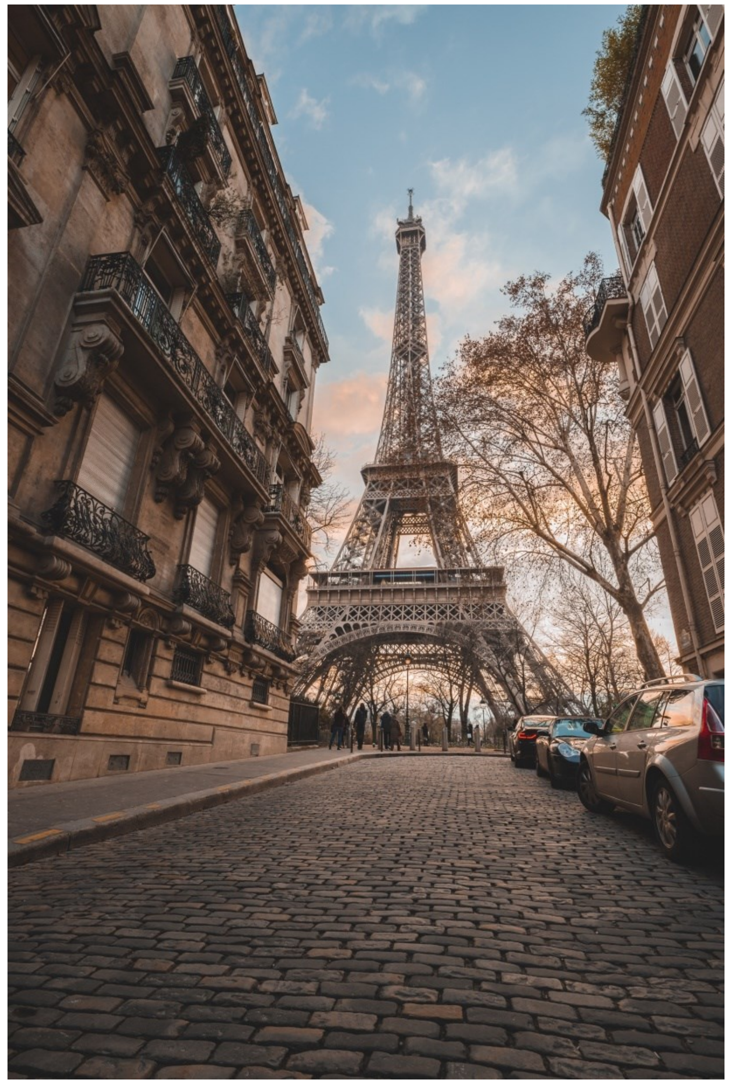
Aim 02

Summary

- Importance of the position of visual information for spatial cognition
- Ageing is associated with a modified use of the upper visual field



Aim 02

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- Importance of the position of visual information for spatial cognition
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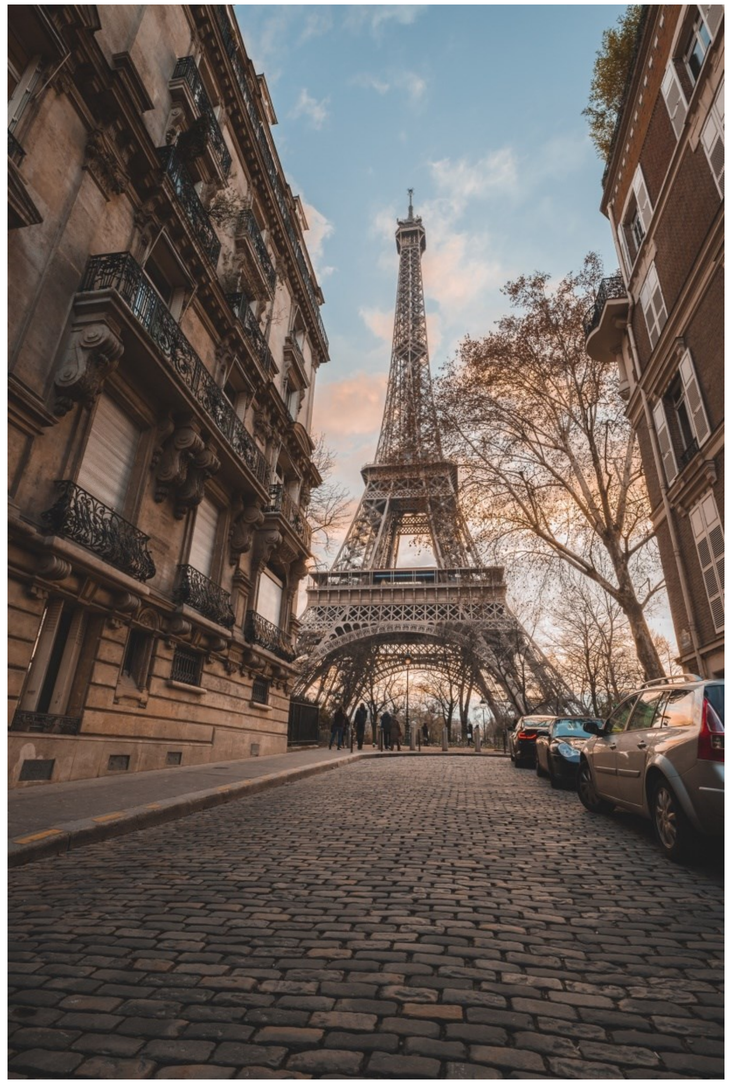
- Scene-selective regions integrate position with navigational relevance



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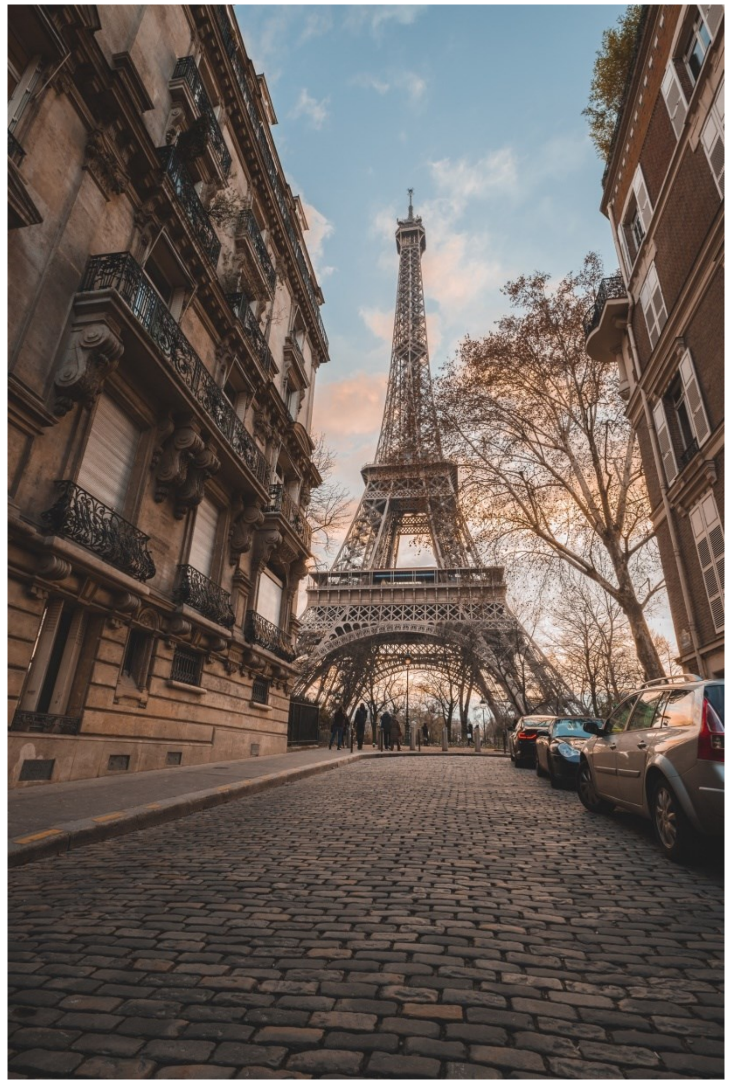


Vertical position is a key object property that guides behaviour and subtending neural patterns

Discussion

« Perceiving the position of static external objects is unimpaired in older adults »
(Lester et al., 2017)

Discussion

~~« Perceiving the position of static external objects is unimpaired in older adults »~~

(Lester et al., 2017)

Behavioural evidence

Neural evidence

Lester et al., 2017, *Neuron*

Discussion

~~« Perceiving the position of static external objects is unimpaired in older adults »~~

(Lester et al., 2017)

Behavioural evidence

- Impaired spatial memory for upper visual field objects
- Systematic downward gaze bias during navigation

Neural evidence

Lester et al., 2017, *Neuron*

Discussion

~~« Perceiving the position of static external objects is unimpaired in older adults »~~

(Lester et al., 2017)

Behavioural evidence

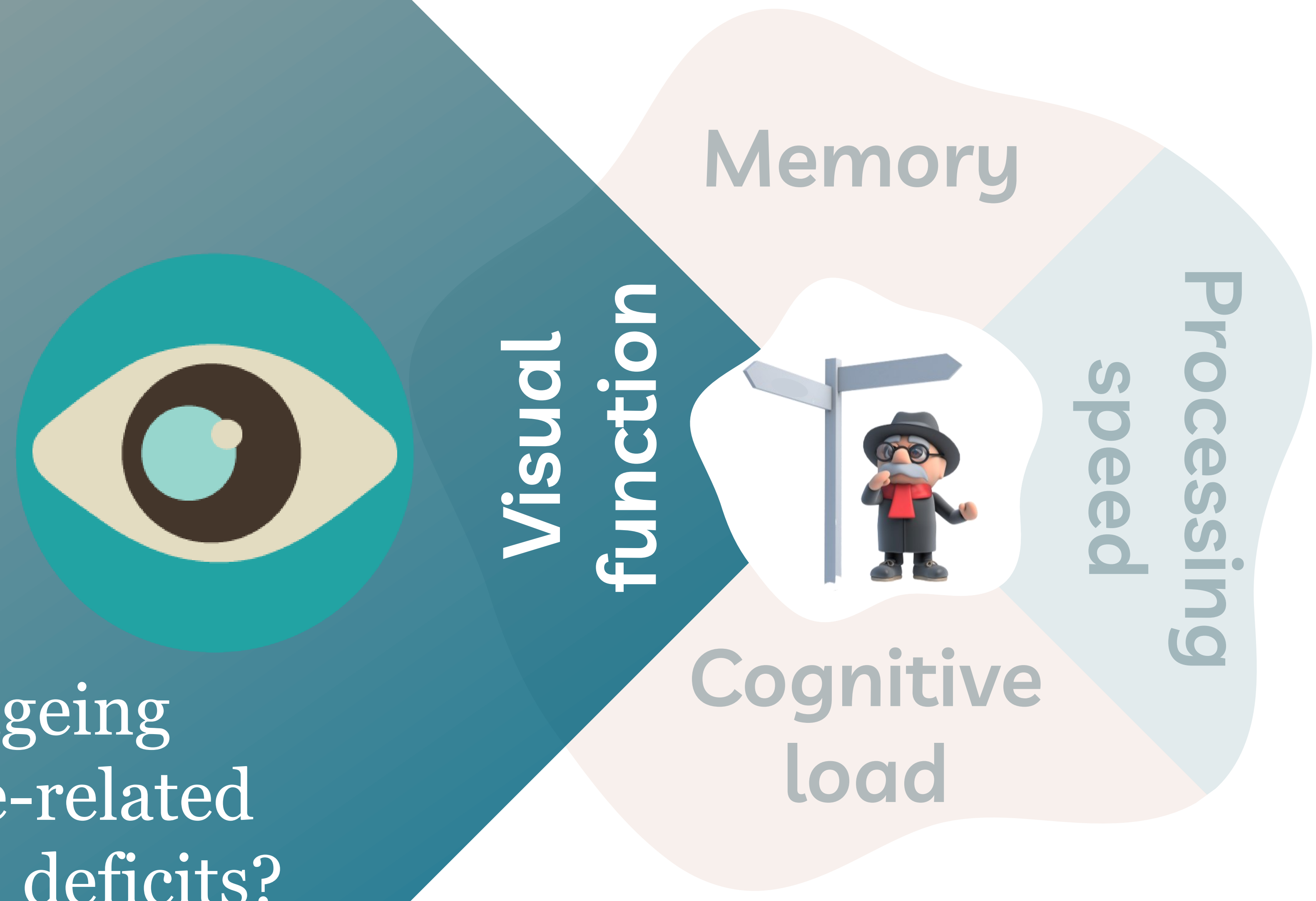
- Impaired spatial memory for upper visual field objects
- Systematic downward gaze bias during navigation

Neural evidence

- Age-related differences in visual regions during navigation
- The vertical position of useful information is encoded in scene-selective regions

Lester et al., 2017, *Neuron*

Discussion

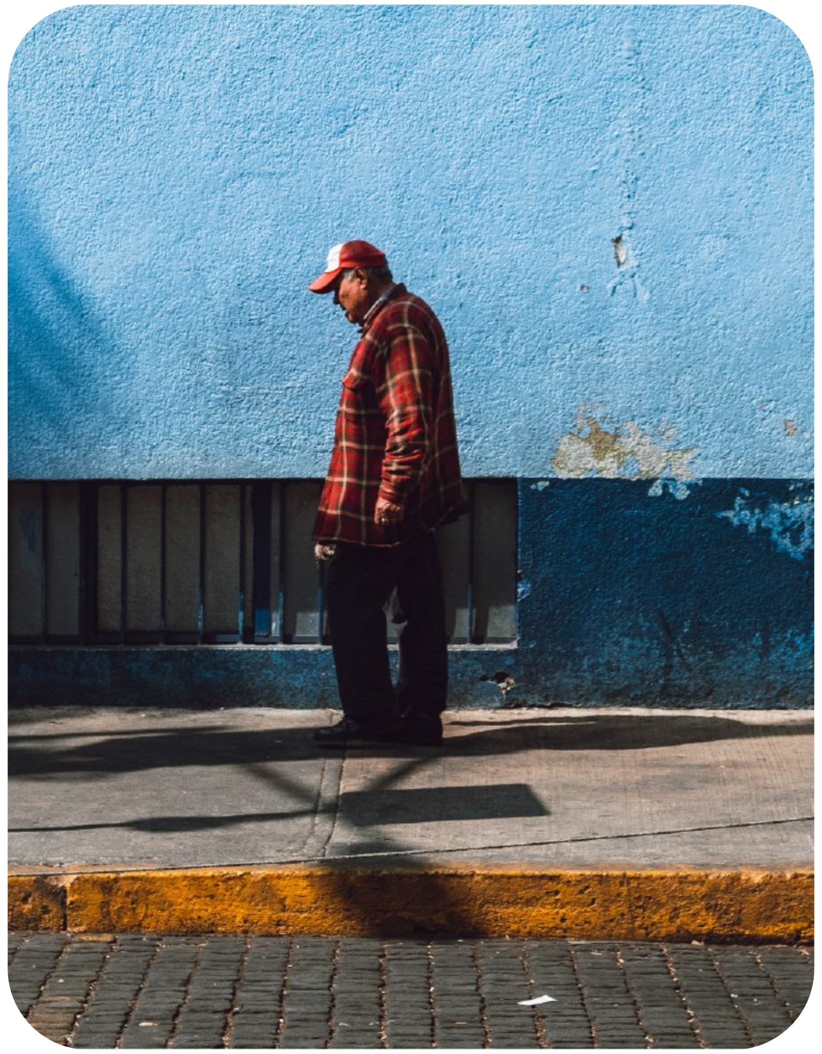


Could visual ageing contribute to age-related spatial navigation deficits?

Colombo et al., 2017, *Neurosci. Biobehav. Rev.*; Lester et al., 2017, *Neuron*

Perspectives

The source of age-related upper visual field decline



1 **Retinal factors?**

Retinal ganglion cells account for < 10% of perceptual variations around the visual field.

Kupers et al., 2022, *Plos Comp. Biol.*; Himmelberg et al., 2022, *Nat. Comm.*; Saftari and Kwon, 2018, *J. Physiol. Anthropol.*

Perspectives

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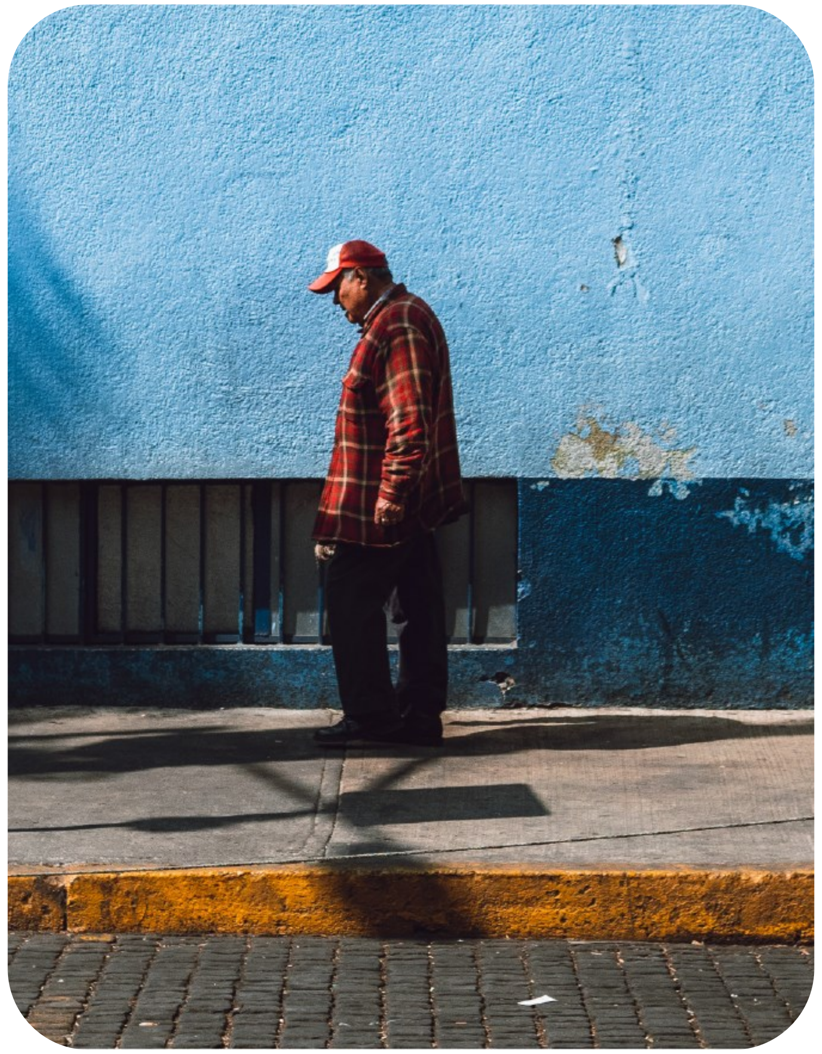

1. **Retinal factors?** — Retinal ganglion cells account for < 10% of perceptual variations around the visual field.

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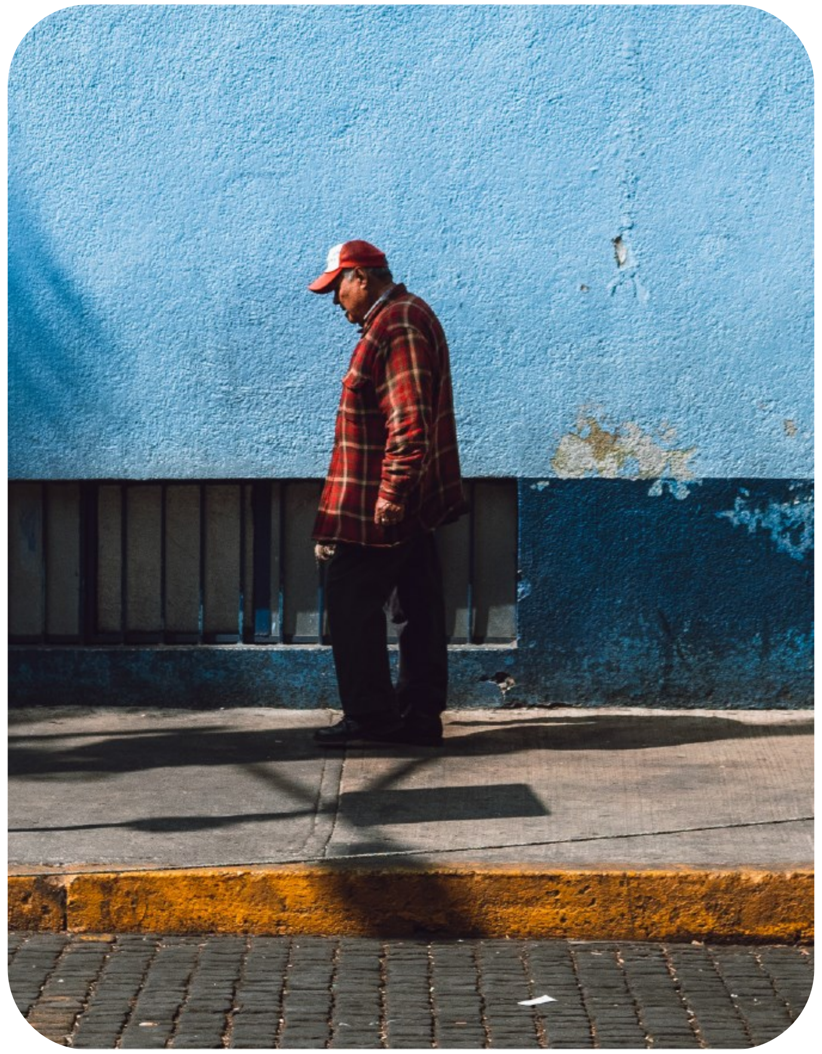

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Retinal ganglion cells account for < 10% of perceptual variations around the visual field.

2 **Brain dynamics?**
Remodelling of the visual system: less space dedicated to processing the upper visual field.

3 **Environmental adaptations?**
Rounding of the back, eyelid drooping, fear of falling lead to greater lower visual field use.

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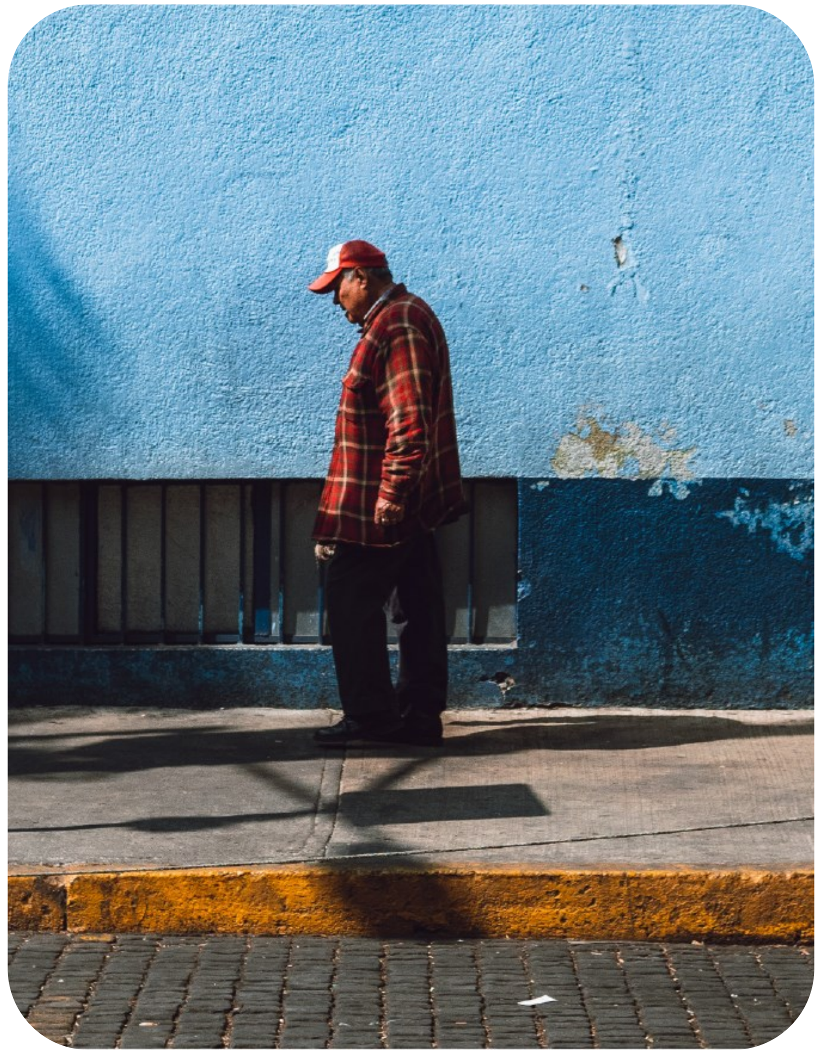
Perspectives

The source of age-related upper visual field decline



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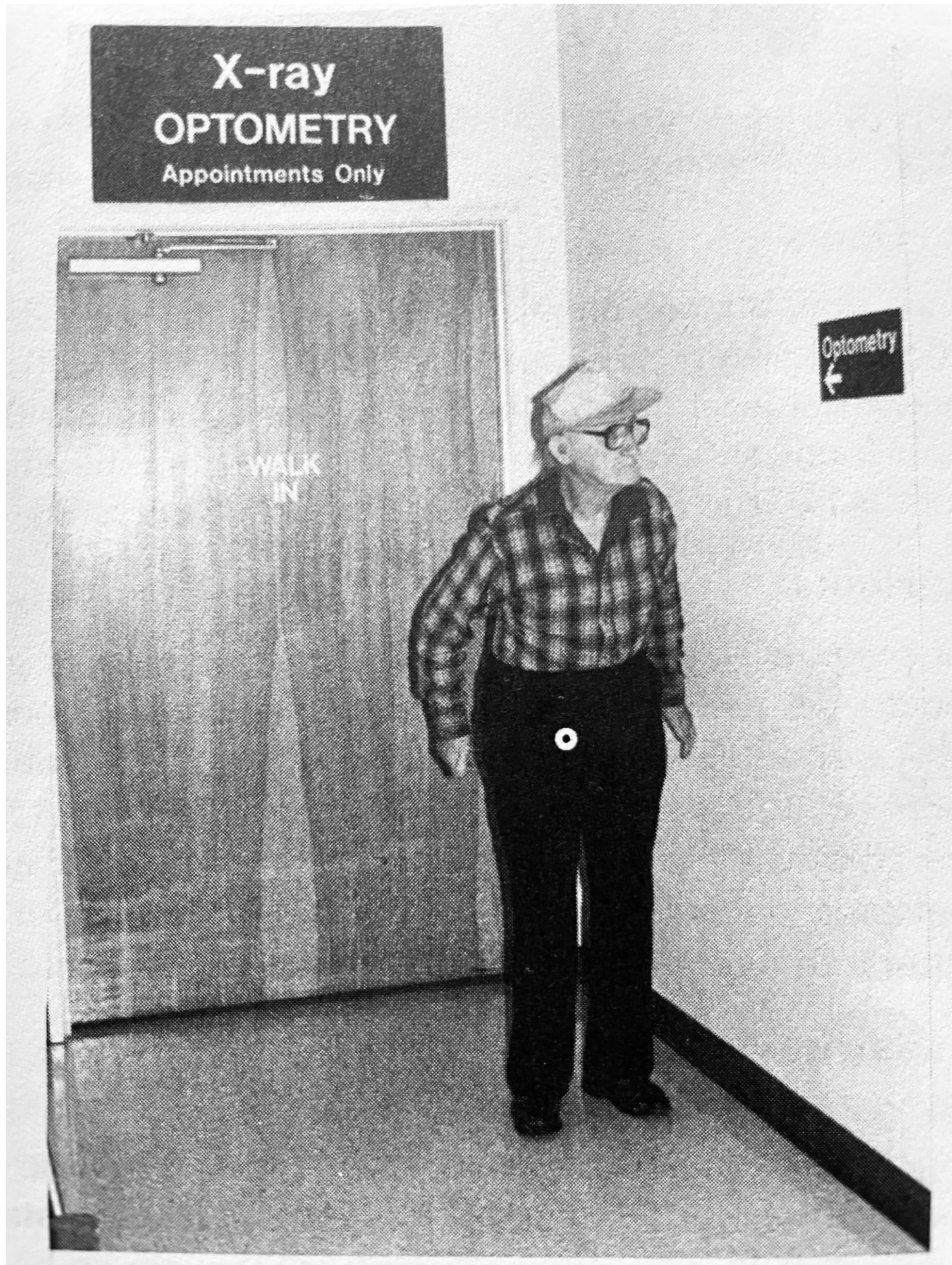
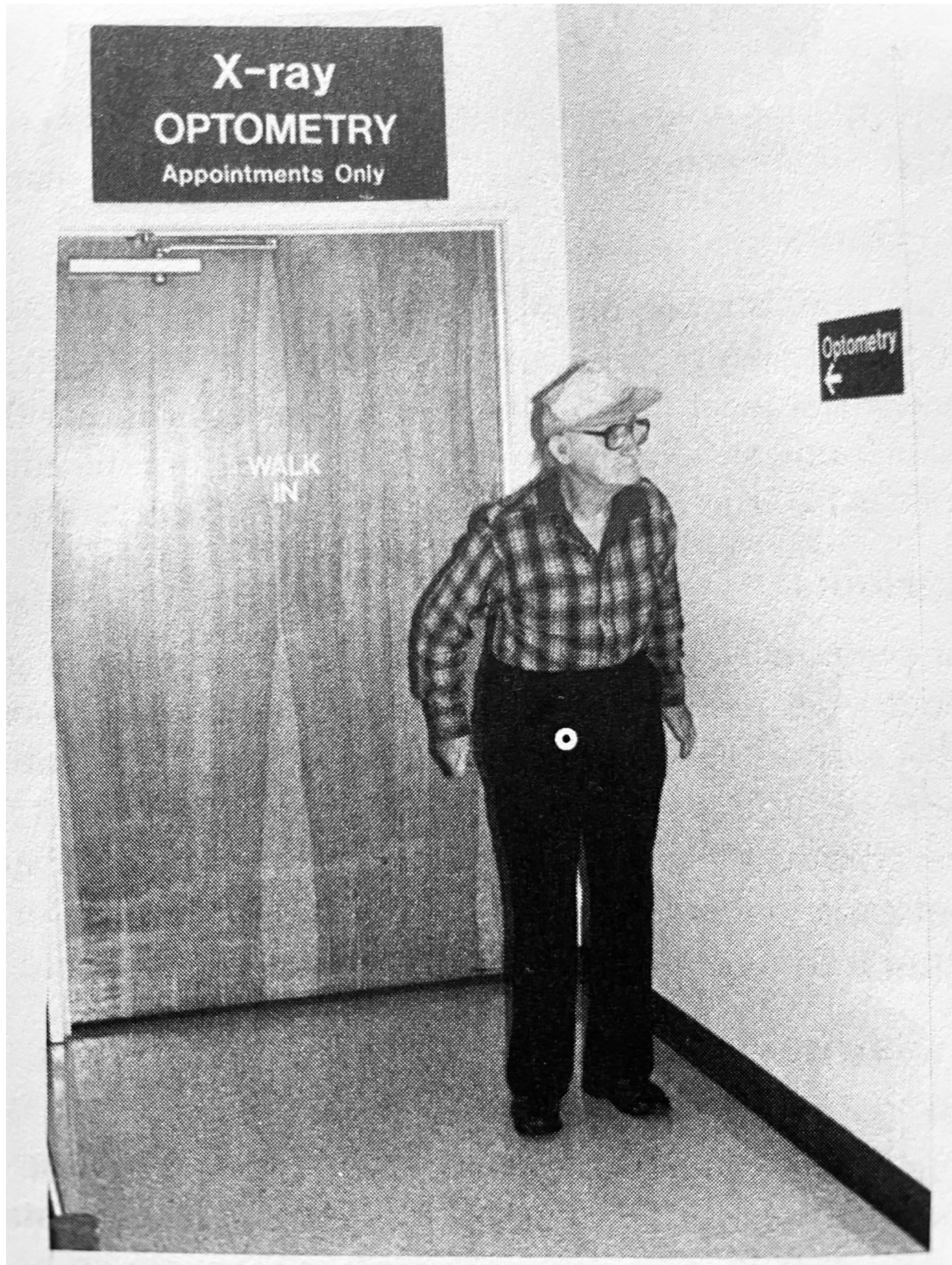
Perspectives



“Size and placement of signs are important considerations for the elderly. A sign placed above a door is too high for an elder to see.”

Melore, 1997; Barnes et al., 2016, *J. Archit. Plann. Res.*; Yu et al., 2010, *Vis. Res.*

Perspectives



"Size and placement of signs are important considerations for the elderly. A sign placed above a door is too high for an elder to see."

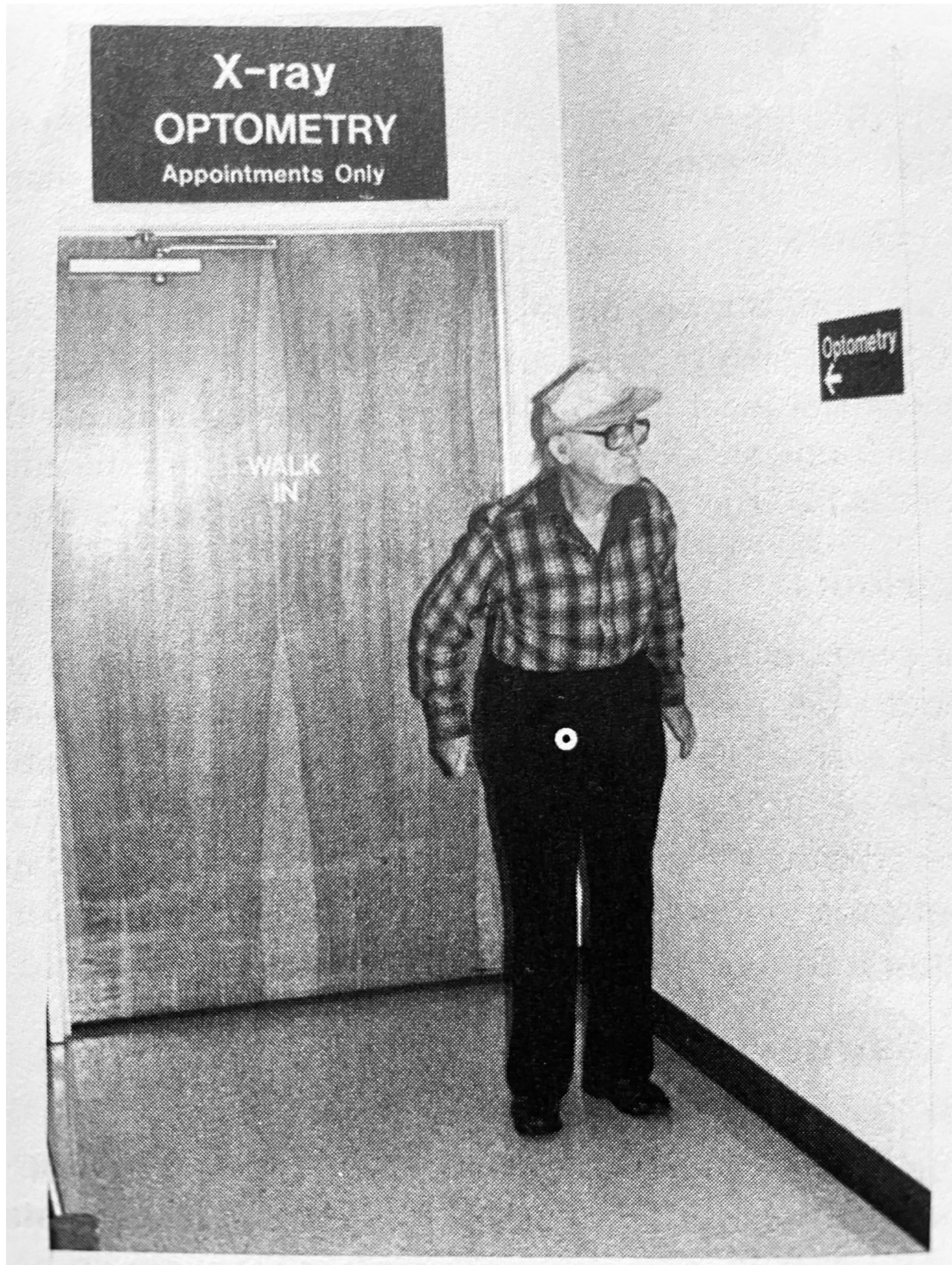
Age-friendly designs

Public spaces described as confusing and non-descript.

Emphasis should be placed on landmark properties.

Melore, 1997; Barnes et al., 2016, *J. Archit. Plann. Res.*; Yu et al., 2010, *Vis. Res.*

Perspectives



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Age-friendly designs

Public spaces described as confusing and non-descript.

Emphasis should be placed on landmark properties.

Training programs

Could the upper visual field be stimulated in older adults?

Perceptual training can enlarge the visual fields for reading.

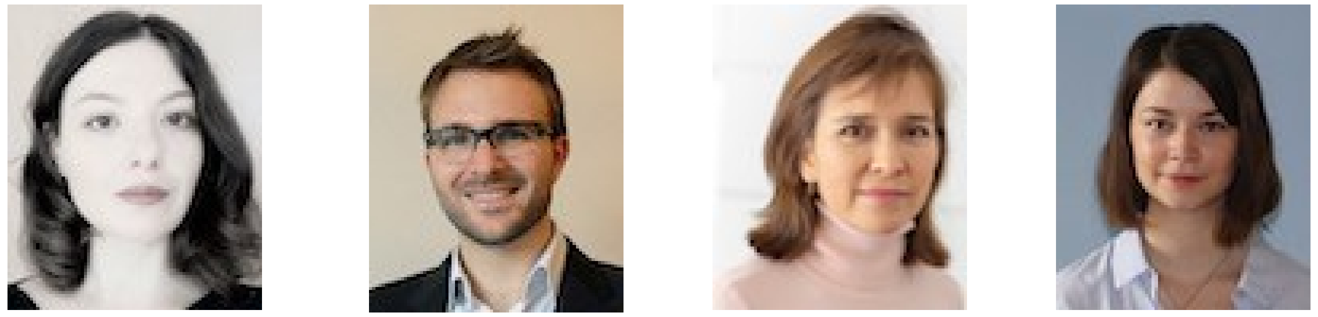
Melore, 1997; Barnes et al., 2016, *J. Archit. Plann. Res.*; Yu et al., 2010, *Vis. Res.*

Thank you for your attention

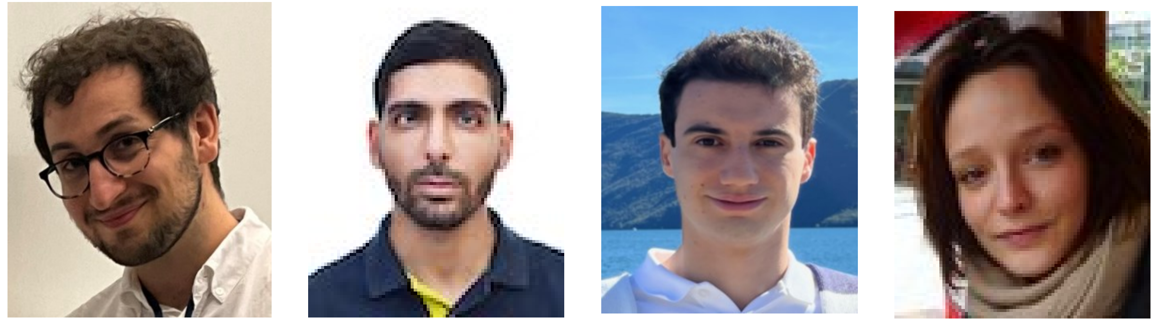
A warm thank you to all the participants who lent me their brain!

Supervisors
Angelo Arleo, Stephen Ramanoël, Dr Christophe Habas

Participant recruitment
Fabienne Tzvetkov-Ricard, Jérôme Gillet, Sonia Combariza, Aude Tremolada



Collaborators
Alexandre Delaux, Bilel Benziane, Luca Liebi, Marcia Bécu



Students
Louise Van Poucke, Emma Massy, Emma Sapoval

MRI support
Dr. Rosalie Nguyen, Dr. Sophie Espinoza, Prof. Jean-Noël Vallée, Hervé Bargy and everyone else at the MRI facility!

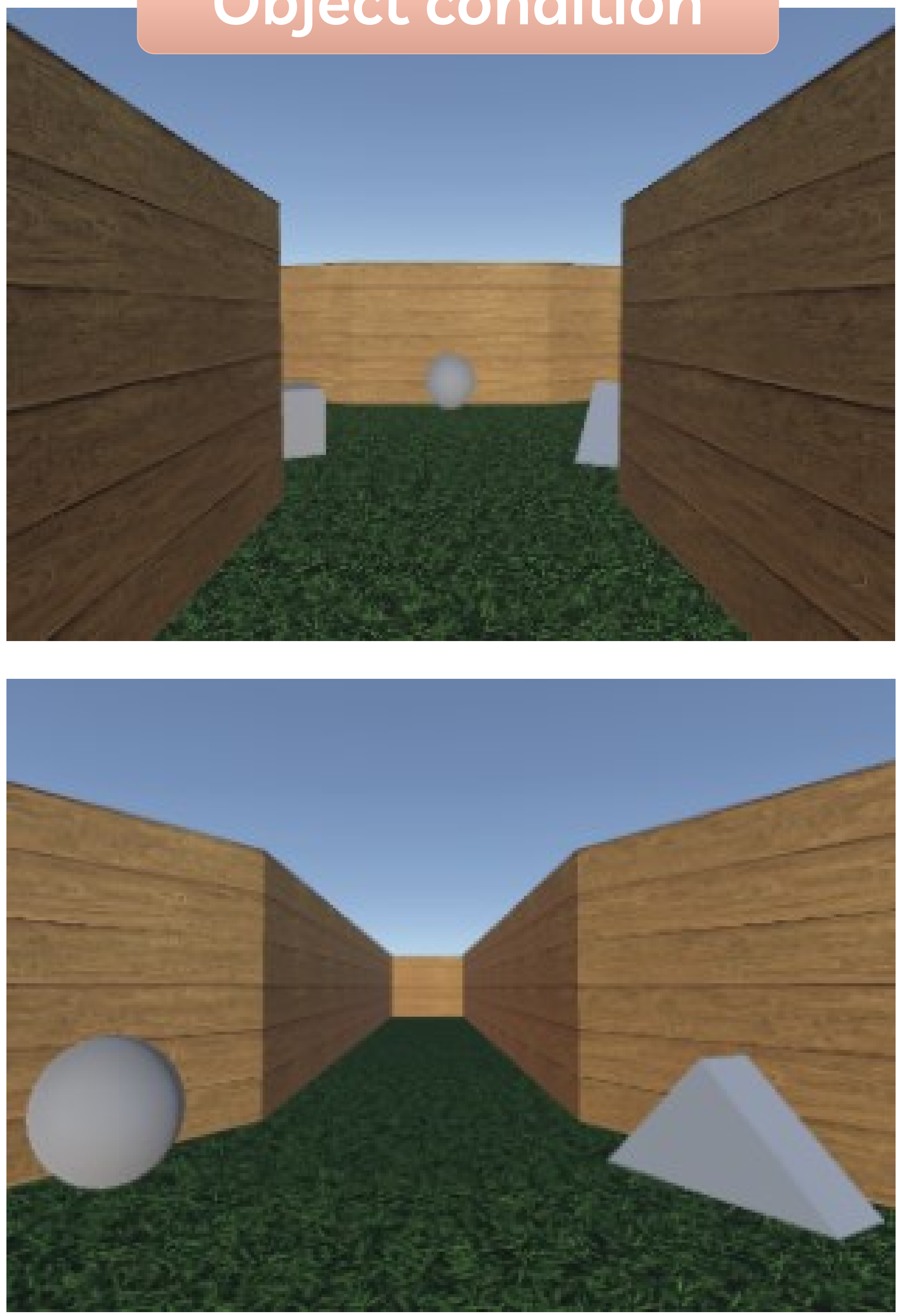
QUINZE-VINGTS
CENTRE HOSPITALIER NATIONAL D'OPHTALMOLOGIE

Supplementary Slides

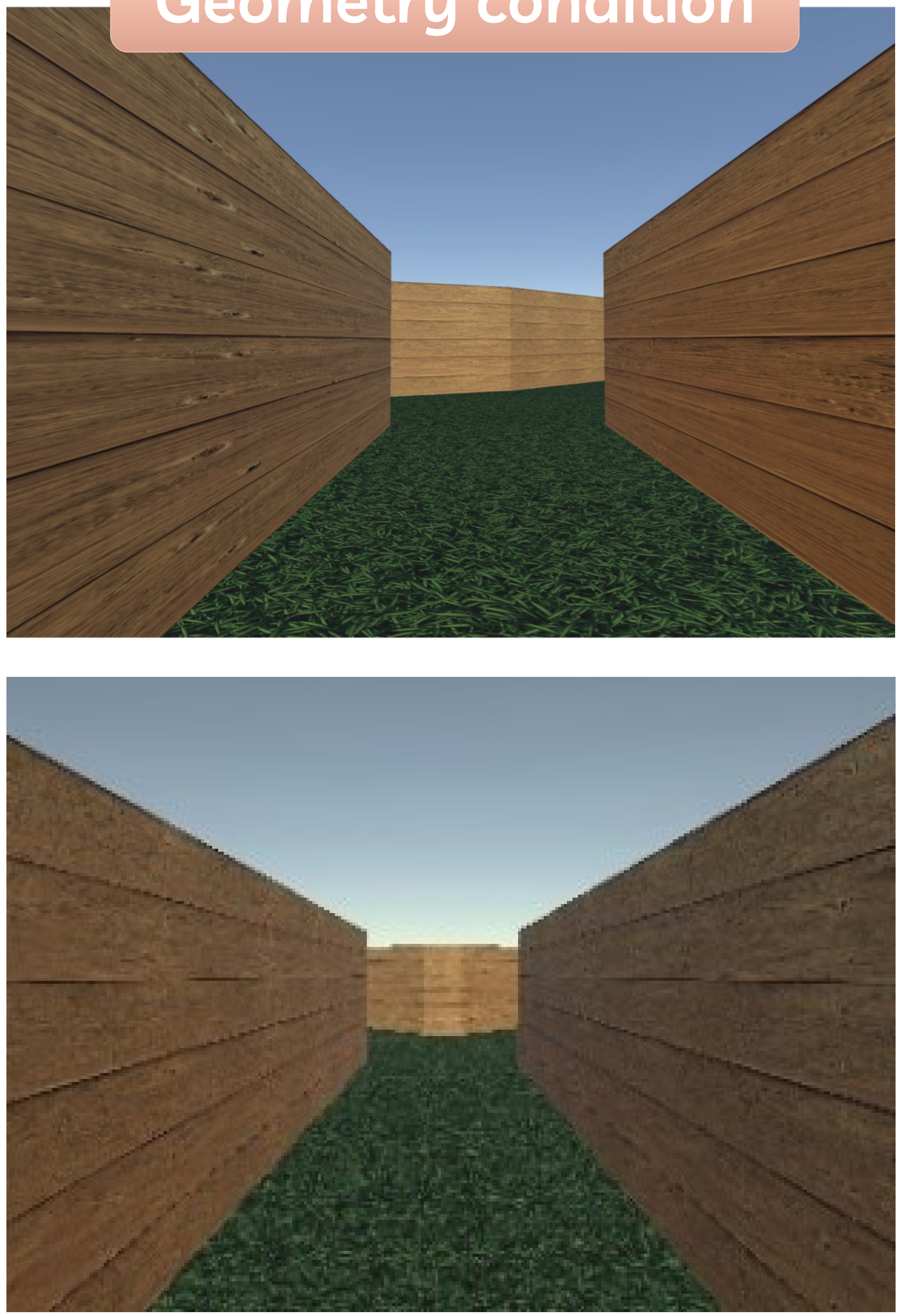
Study 1

Methods

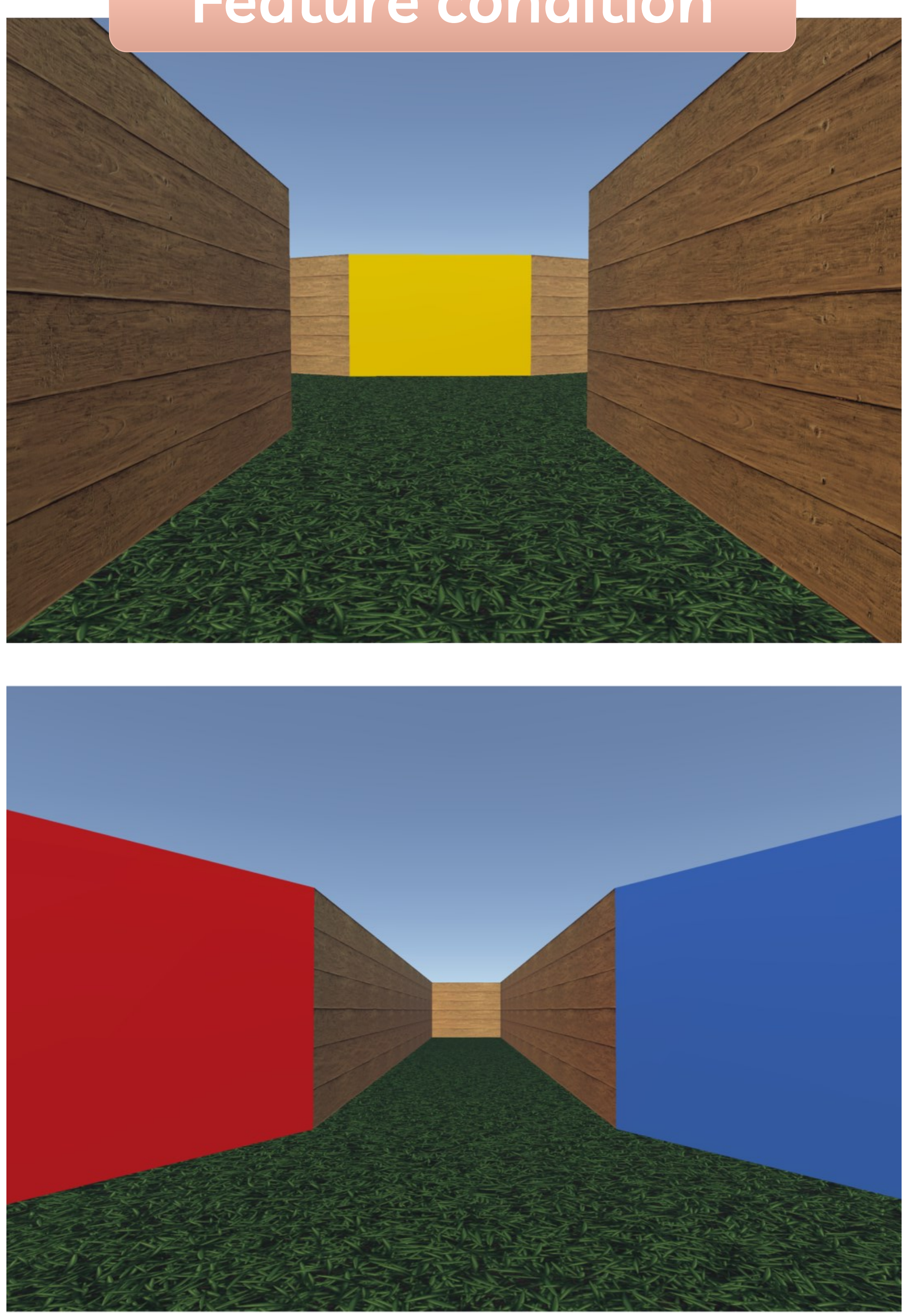
Object condition



Geometry condition



Feature condition



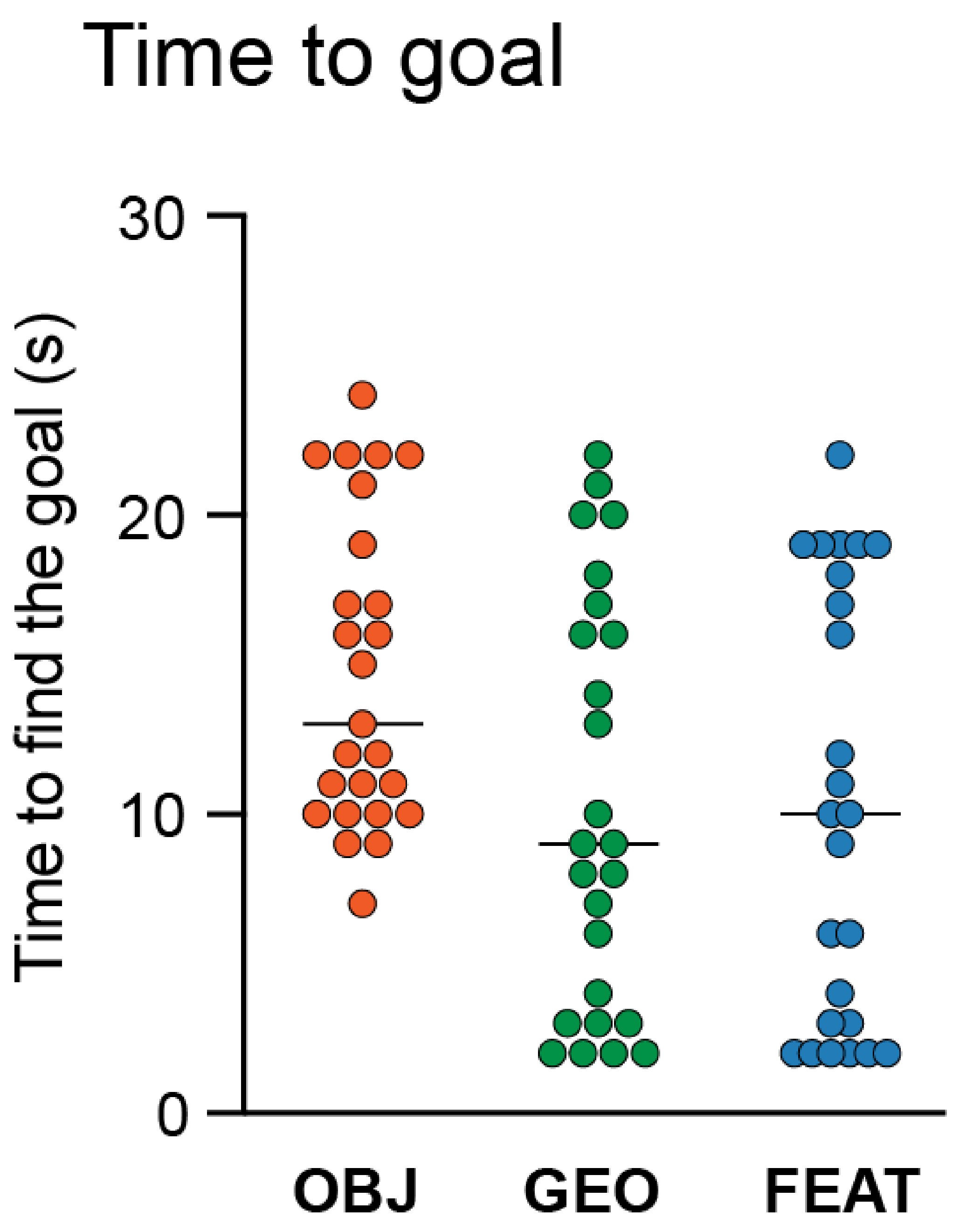
Study 1

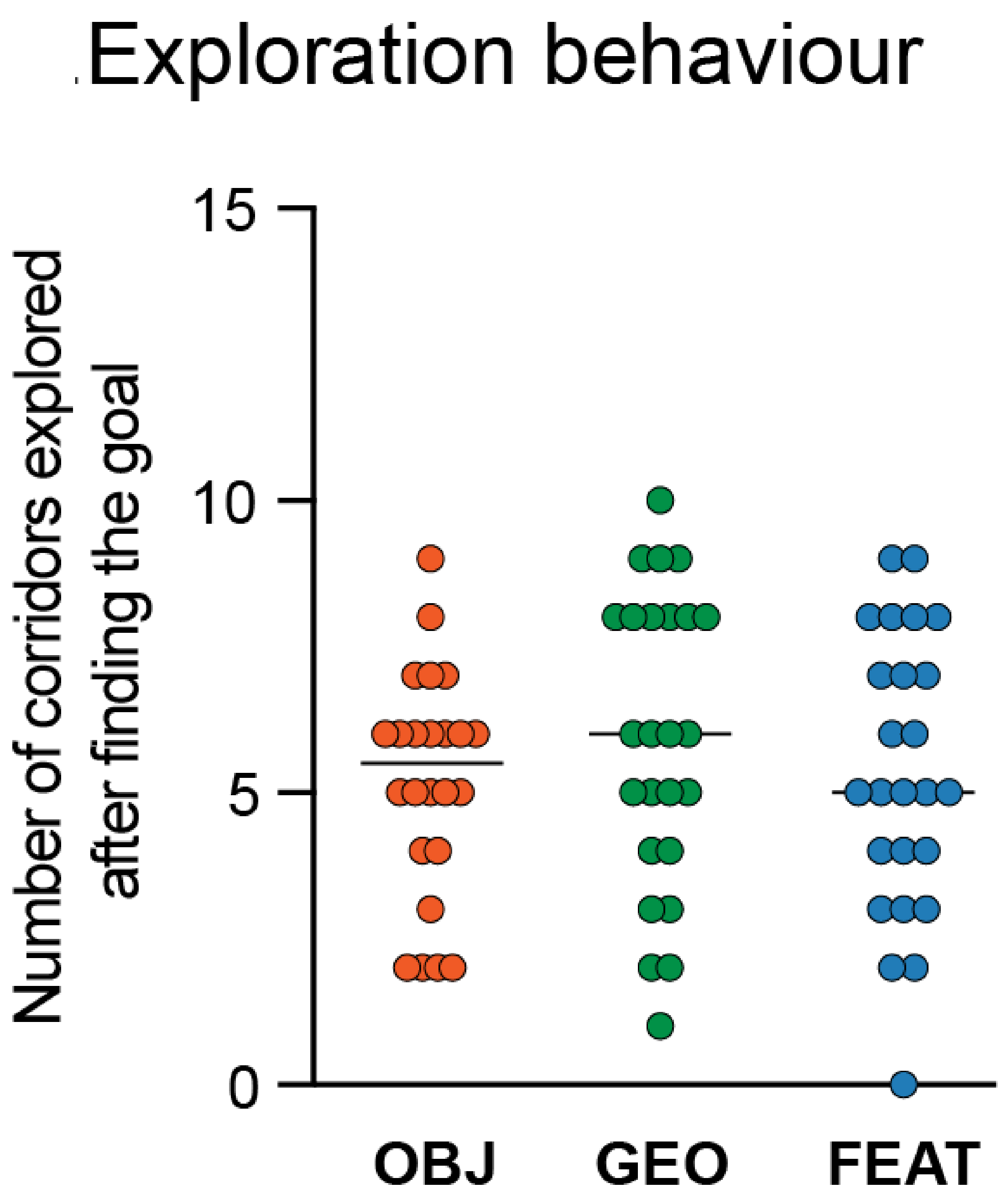
Baseline characteristics

Variables	Mean (±SEM)
Age	25.4 (± 0.5)
Males / Females	18 / 7
Total brain volume (cm3)	1301(± 18)
MMSE	30.0 (± 0.0)
3D mental rotation	18.3 (± 0.9)
Corsi forward	7.2 (± 0.2)
Corsi backward	6.2 (± 0.3)
Perspective taking test	15.3 (± 1.7)

Study 1

Behavioural results

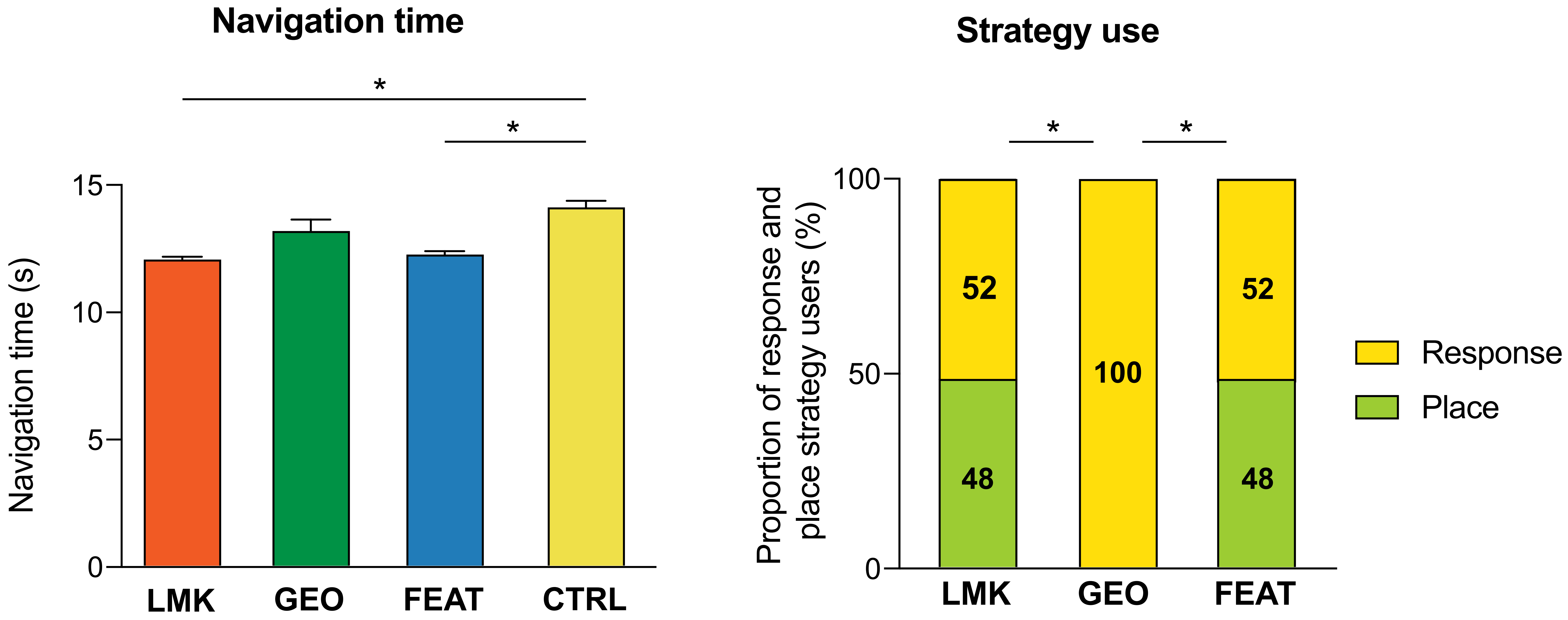




Participants' behavioural performance during the encoding phase.

Study 1

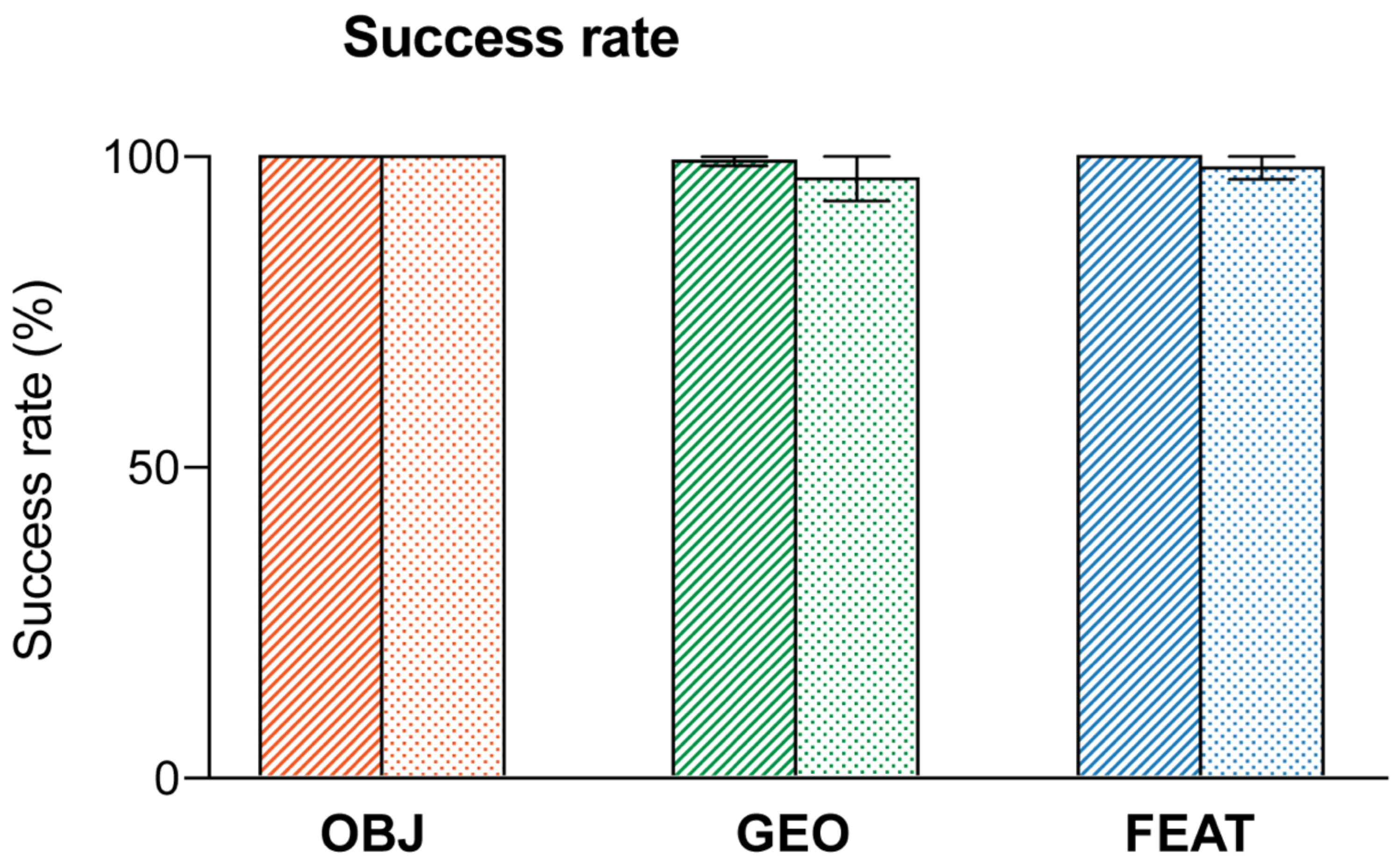
Behavioural results

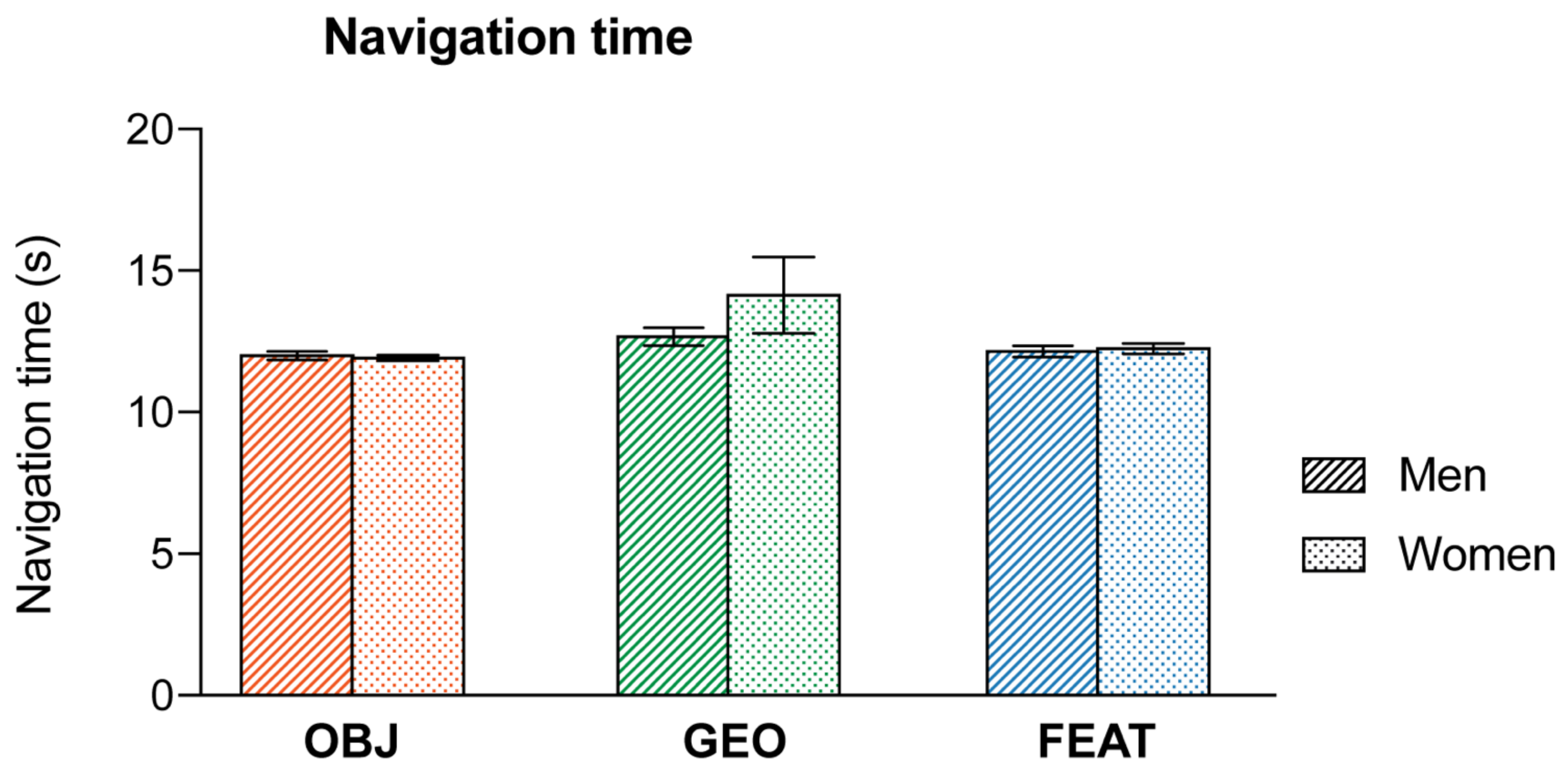


Participants' behavioural performance during the test phase.

Study 1

Behavioural results

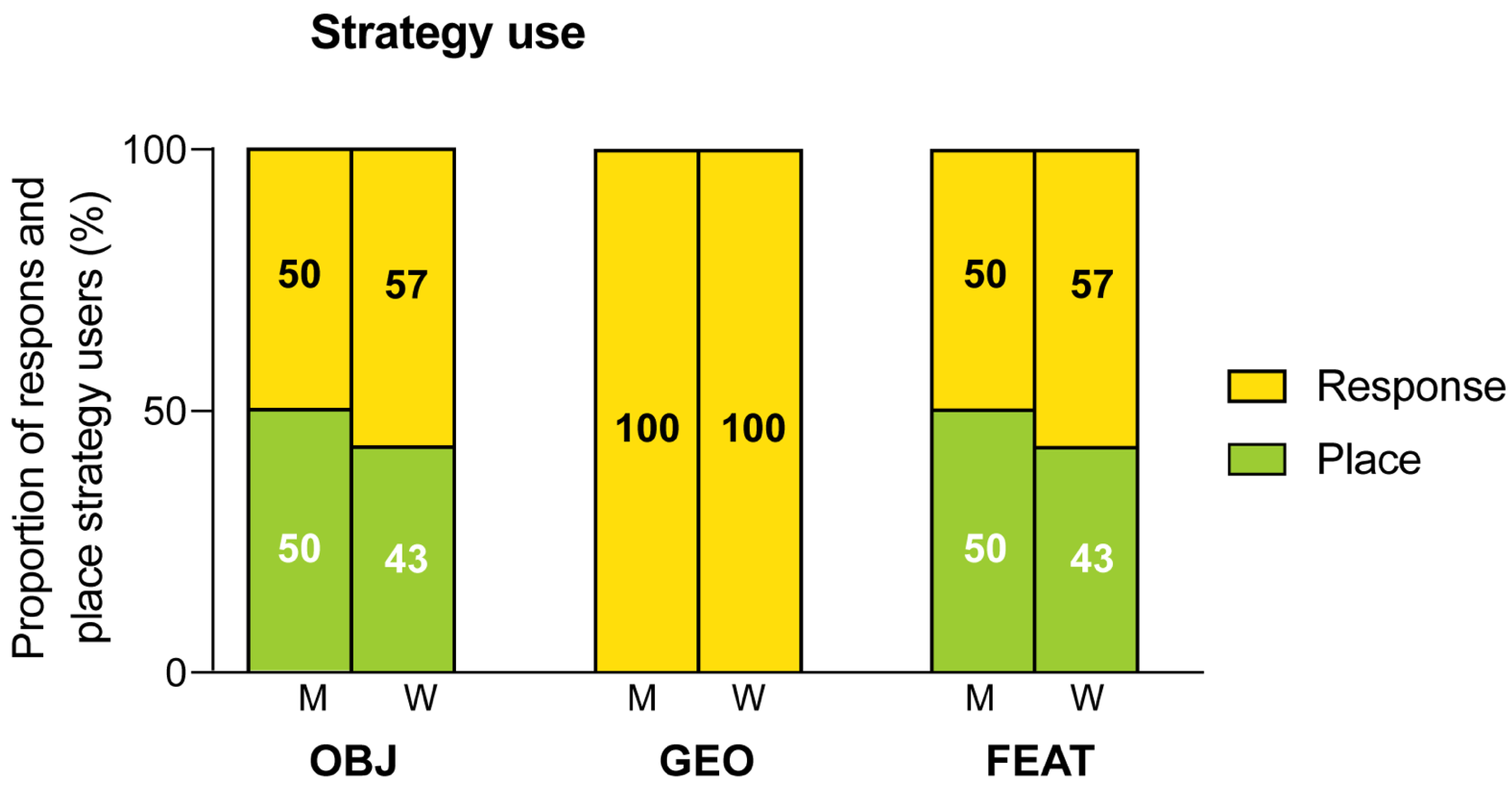




No significant sex-related differences in navigational performance.

Study 1

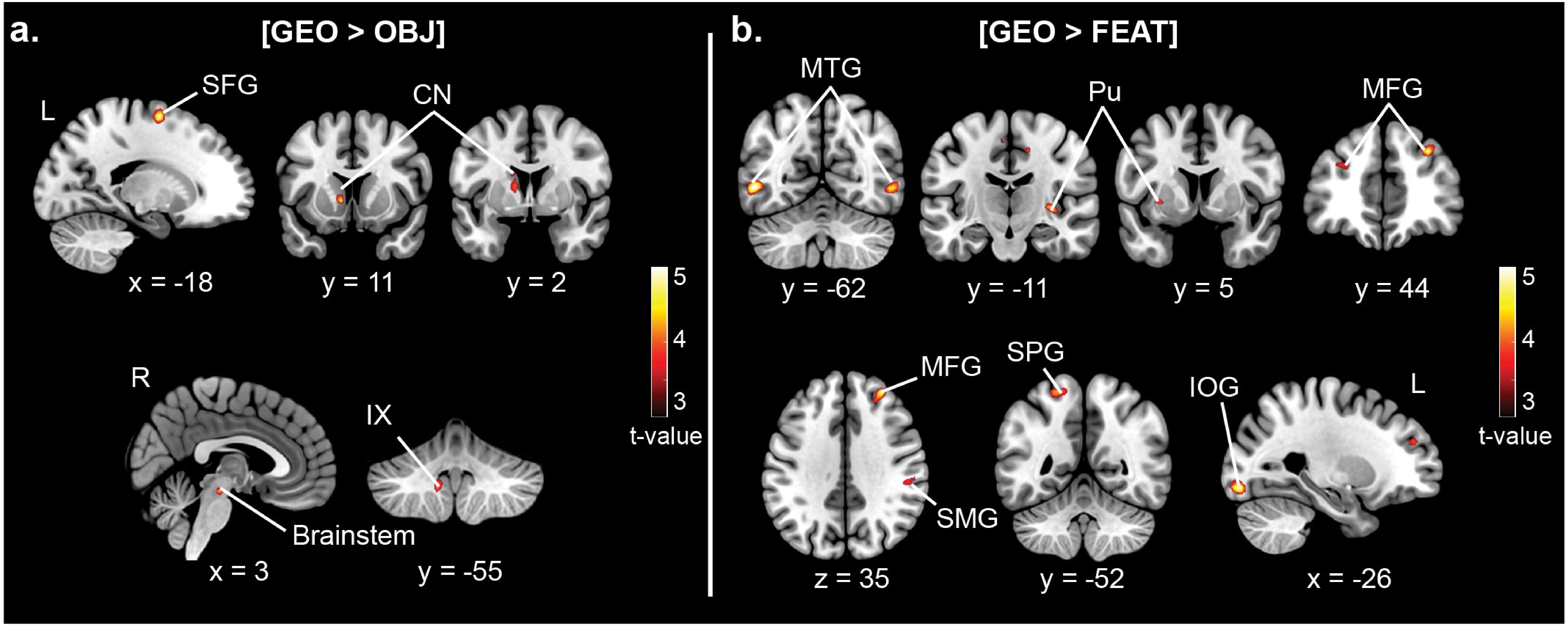
Behavioural results



All participants used a response-based strategy during the geometry condition.

Study 1

Neuroimaging results

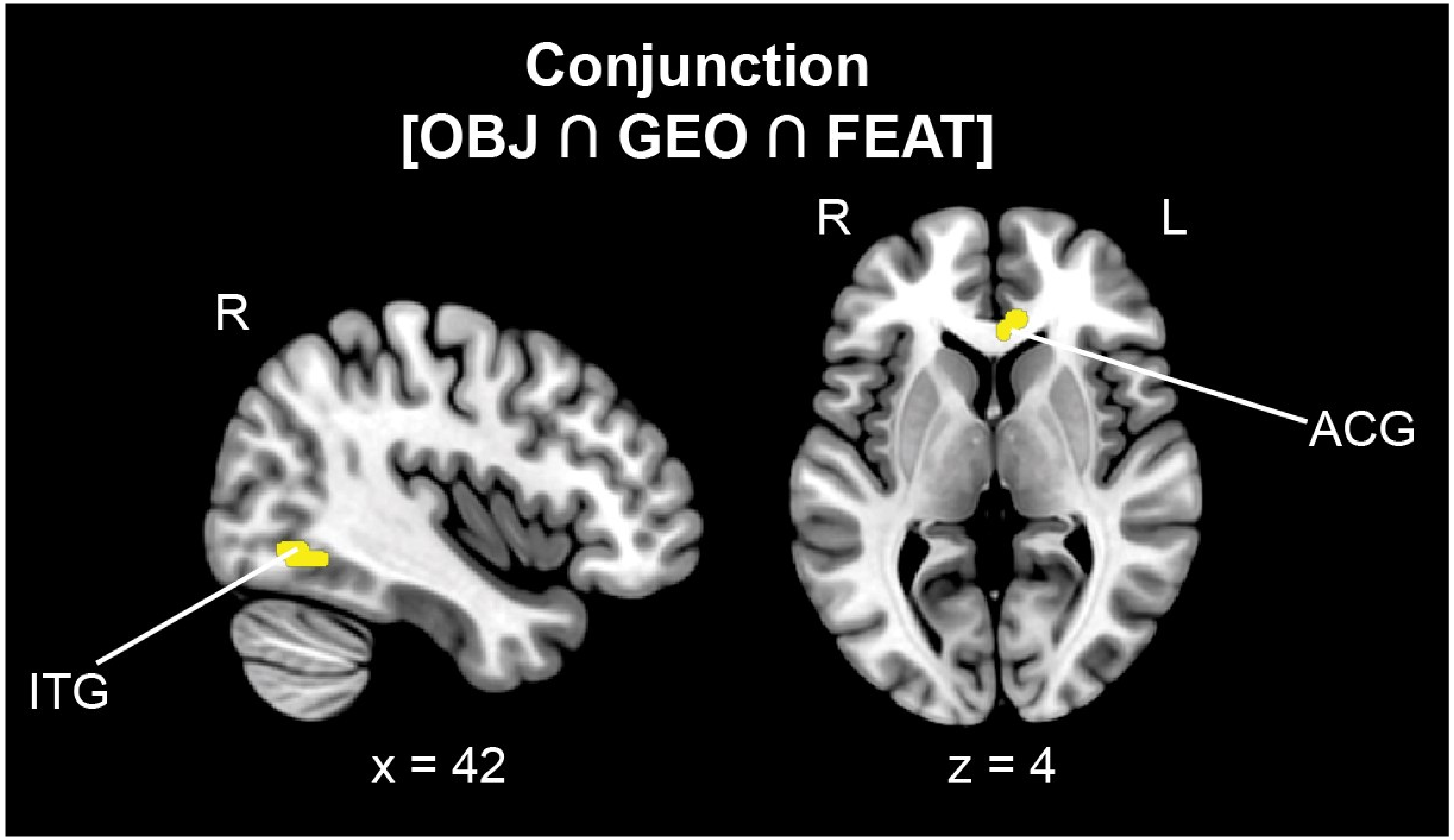


Whole-brain analyses: direct comparison between cue conditions

($p < 0.001$ uncorrected, k = 10 voxels)

Study 1

Neuroimaging results



(p < 0.001 uncorrected, k = 10 voxels)

Study 1

Neuroimaging results

Whole-brain analyses: [Landmark > Fixation]

		H	BA	k	x	y	z	t
Group Analyses [LMK > Fix]								
[Young > Old]	*No significant activation*							
[Old > Young]	Middle Frontal Gyrus	R		22	24	47	-1	6.06
	Angular Gyrus	L		223	-30	-64	47	5.66
	[Superior Parietal Gyrus]				-33	-55	44	5.59
	[Supramarginal Gyrus]				-48	-43	44	5.32
	Middle Frontal Gyrus	R		34	39	38	17	5.37
					33	47	20	4.47
	Cerebellum	R	-	23	36	-73	-22	5.19
	Middle Frontal Gyrus	L		127	-42	5	41	5.14
					-45	26	26	5.13
					-45	5	50	5.12
	Superior Parietal Gyrus	R		36	30	-55	44	4.89
	[Angular Gyrus]				30	-64	53	4.64

($p < 0.001$ uncorrected, k = 10 voxels)

Study 1

Neuroimaging results

Whole-brain analyses:
[Control > Fixation]

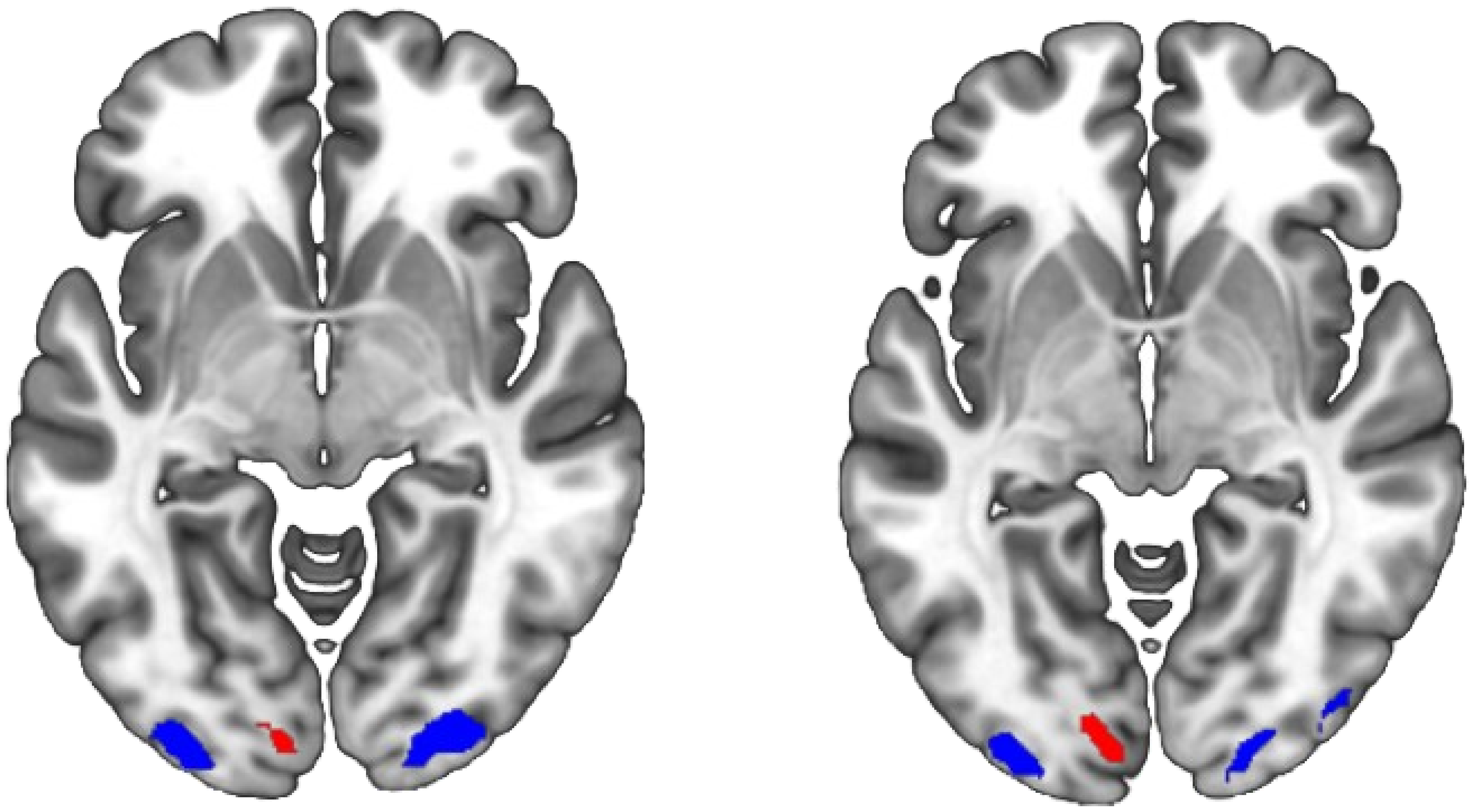
		H	BA	k	x	y	z	t
Group Analyses [CTRL > Fix]								
[Young > Old]	*No significant activation*							
[Old > Young]	Middle Frontal Gyrus	L	8	80	-27	32	56	5.56
	[Middle Frontal Gyrus]				-36	23	56	4.58
	[Superior Frontal Gyrus]		6		-18	32	62	4.05
	Superior Temporal Gyrus	R	-	18	36	17	-19	4.71
	Superior Frontal Gyrus	R	10	32	12	56	-10	4.56
	[Middle Frontal Gyrus]				15	44	-4	4.02
	Inferior Temporal Gyrus	L	37	25	-54	-49	-13	4.39
	Supramarginal Gyrus	R	40	31	42	-40	41	4.23
	[Superior Parietal Gyrus]		7		33	-46	38	4.21
	Superior Frontal Gyrus	L	32	14	-12	41	2	4.16
	[Middle Frontal Gyrus]				-18	41	-4	4.10
	Inferior Frontal Gyrus	L	46	38	-36	35	14	4.15
					-48	41	11	3.85
	Precuneus	R	31	12	9	-58	38	4.00
	Middle Frontal Gyrus	L	8	20	-51	20	41	3.92
					-48	11	50	3.81
	Inferior Frontal Gyrus	L	45	12	-57	23	8	3.79

($p < 0.001$ uncorrected, k = 10 voxels)

Study 1

Neuroimaging results

Whole-brain analysis: [Landmark > Control]; [Landmark]

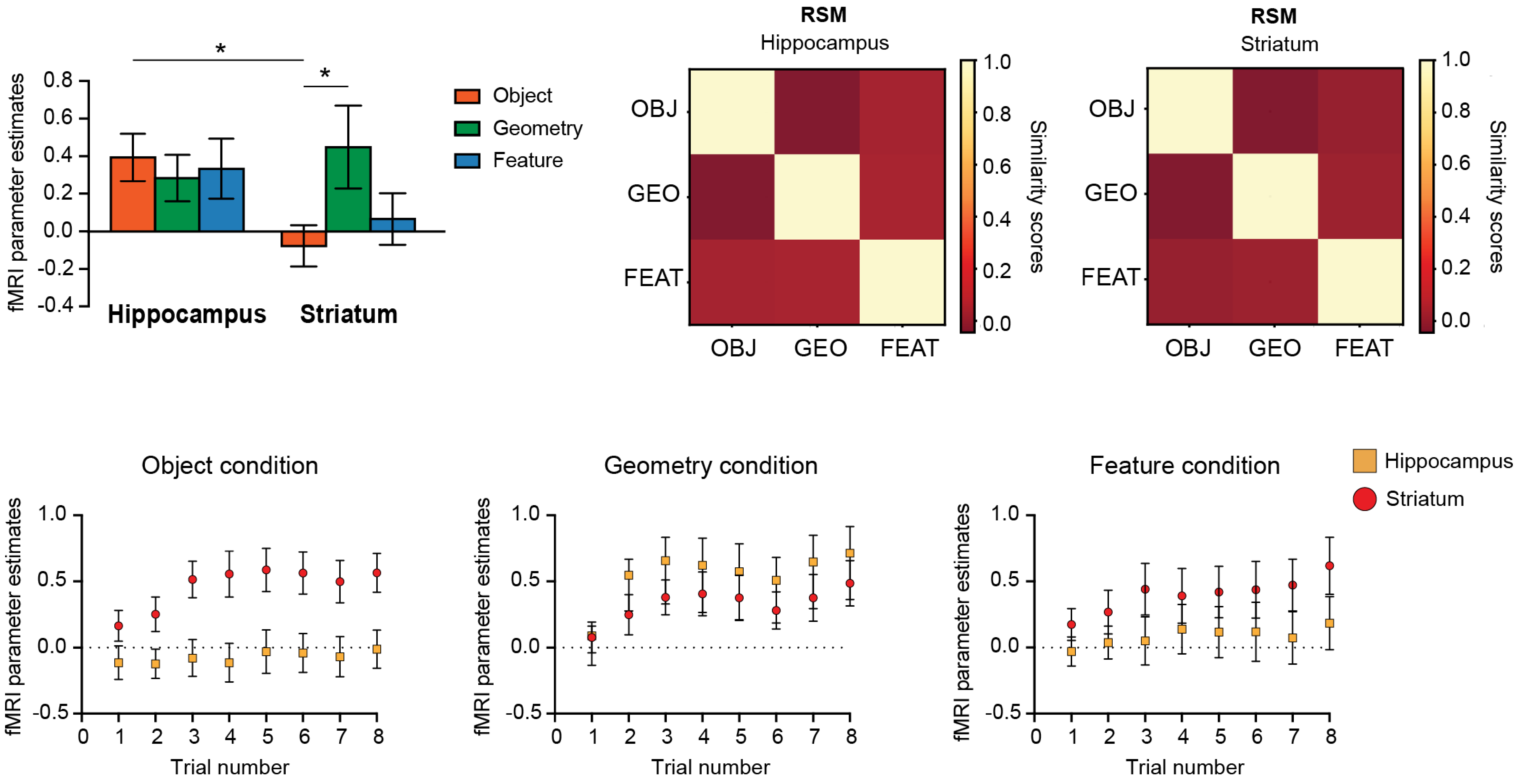


Cortical representation of the central visual field

Cortical representation of the peripheral visual field

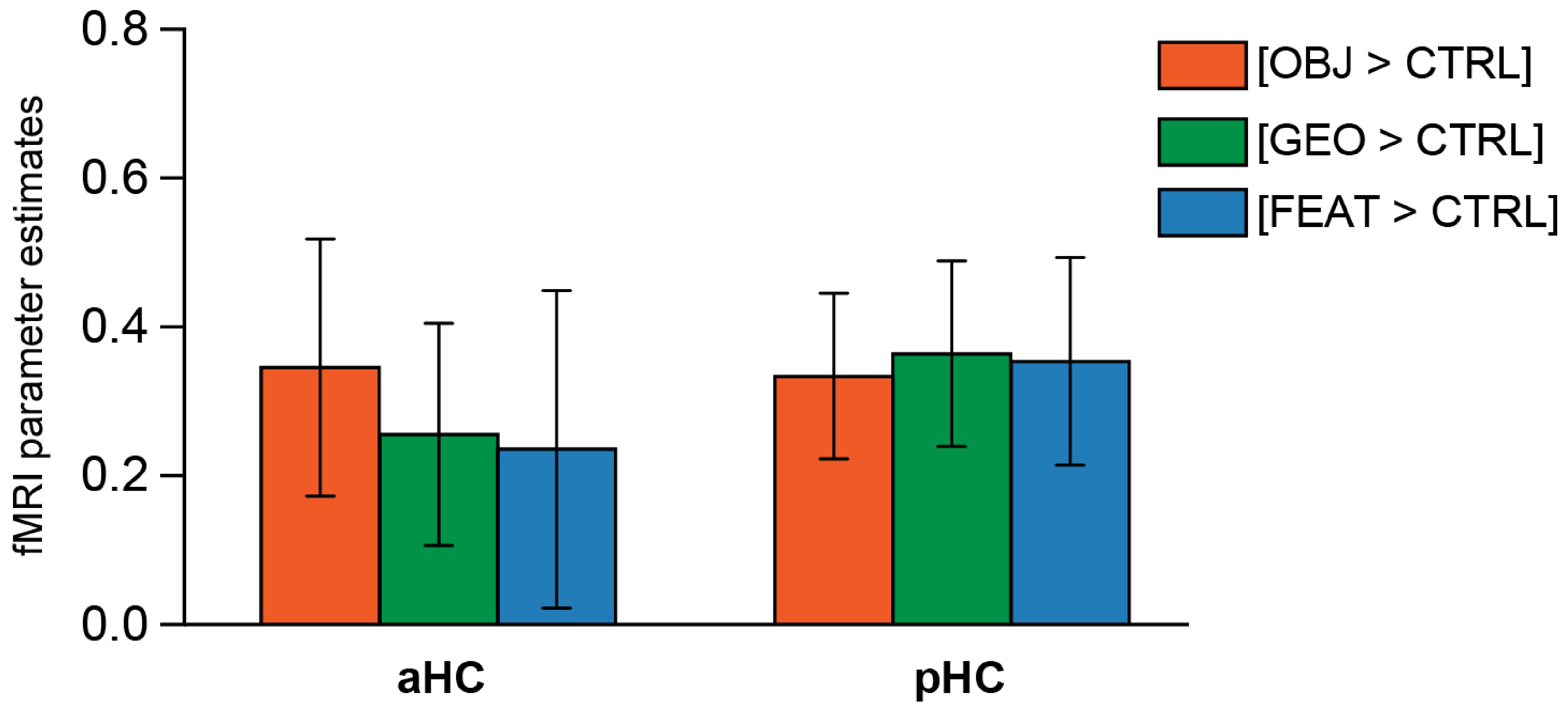
Study 1

Neuroimaging results



Study 1

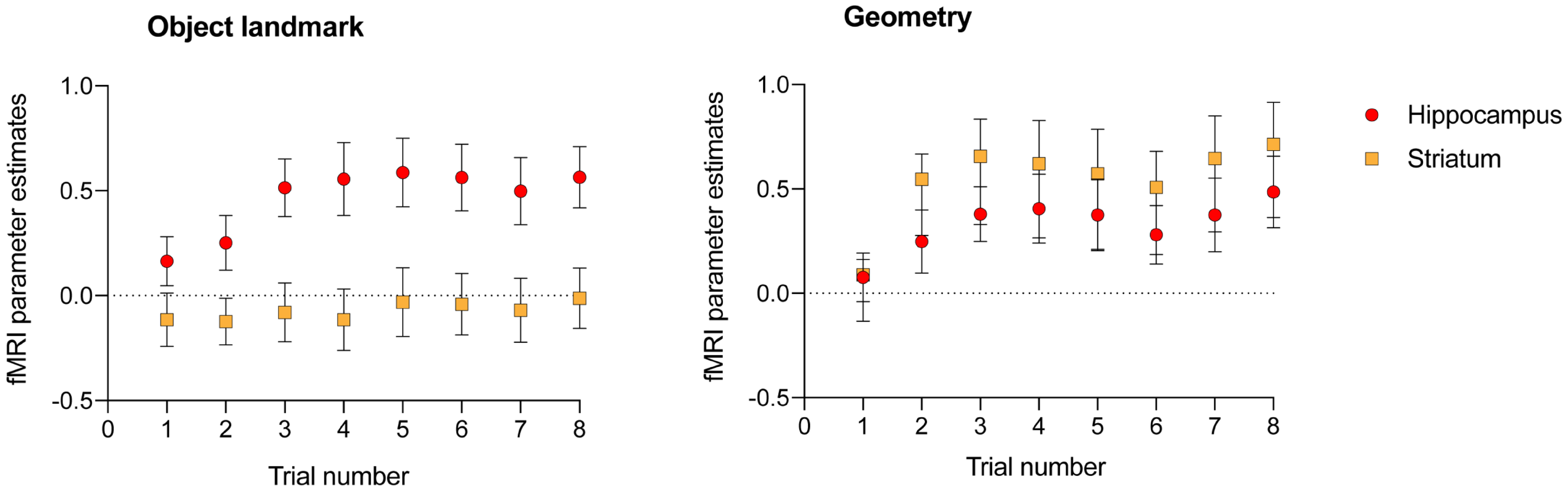
Neuroimaging results



Results from univariate ROI analysis looking at subregions of the hippocampus

Study 1

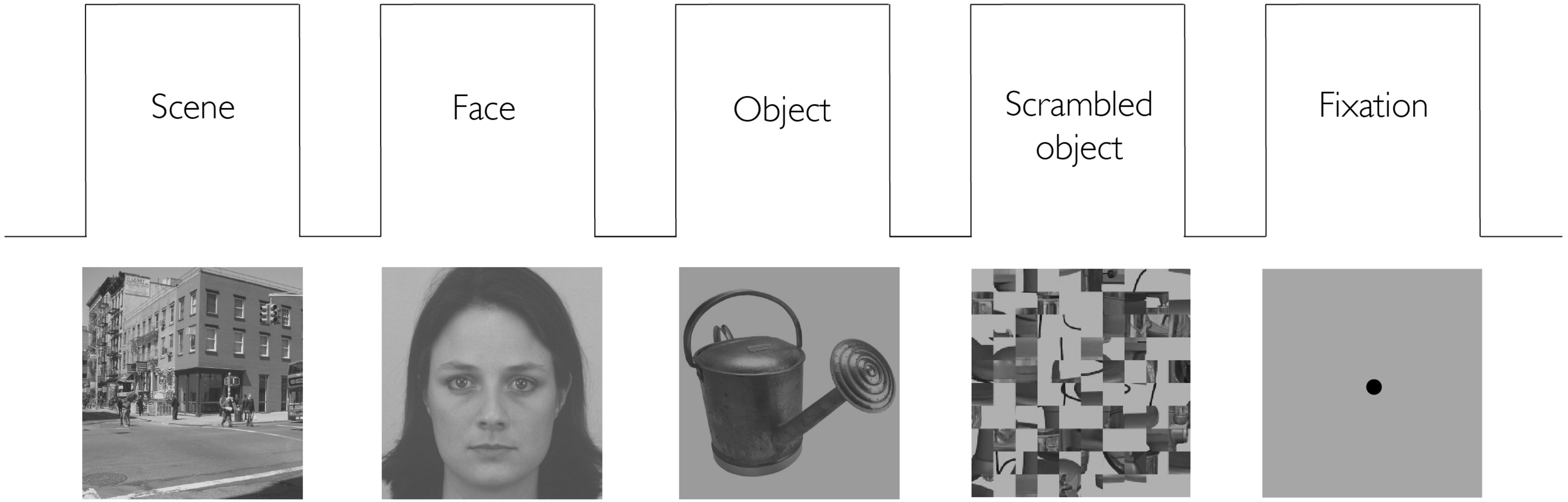
Neuroimaging results



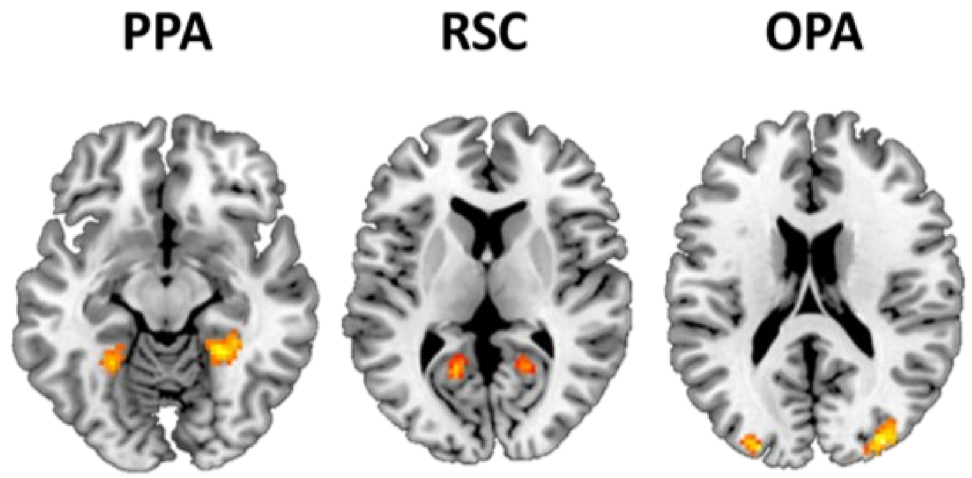
Concomitant hippocampal and striatal activity during the geometry condition.

Study 2

Methods: Functional Localizer



One-back repetition task



[Scene > Face + Object]

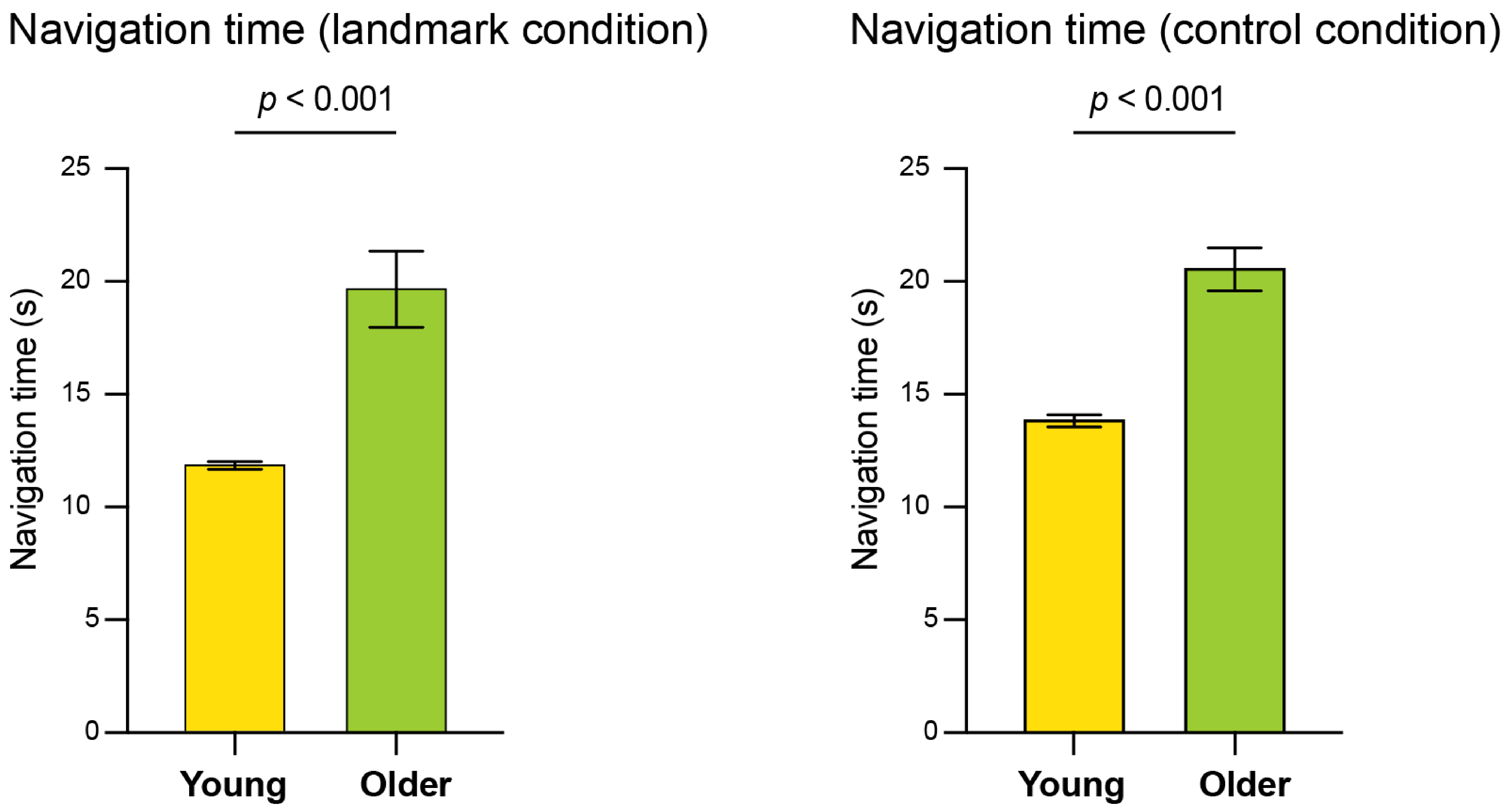
Study 2

Baseline characteristics

	Groups				
	Mean (± SEM)				
Sex (M/F)	Young 18/7	Older 7/10	*p*-value	ES*	95% CI of the difference
Age [1]	25.4 (±0.5)	73.0 (±0.9)	$p < 0.001$	14.8	[45.6, 49.7]
Total brain volume (cm3) [1]	1301 (±18)	1061 (±23)	$p < 0.001$	-2.67	[-297.6, -183.3]
MMSE [2]	30.0 (±0.0)	28.8 (±0.4)	$p < 0.001$	-0.61	[-2.0, -0.0]
3D mental rotation [1]	18.3 (±0.9)	12.7 (±1.2)	$p < 0.001$	-1.20	[-8.8, -2.7]
Corsi forward [2]	7.2 (±0.2)	4.4 (±0.2)	$p < 0.001$	-0.80	[-4.0, -2.0]
Corsi backward [2]	6.2 (±0.3)	4.6 (±0.2)	$p < 0.001$	-0.54	[-2.0, -1.0]
Perspective taking [2]	15.3 (±1.7)	46.1 (±6.7)	$p < 0.001$	0.65	[16.8, 35.7]

Study 2

Behavioural results



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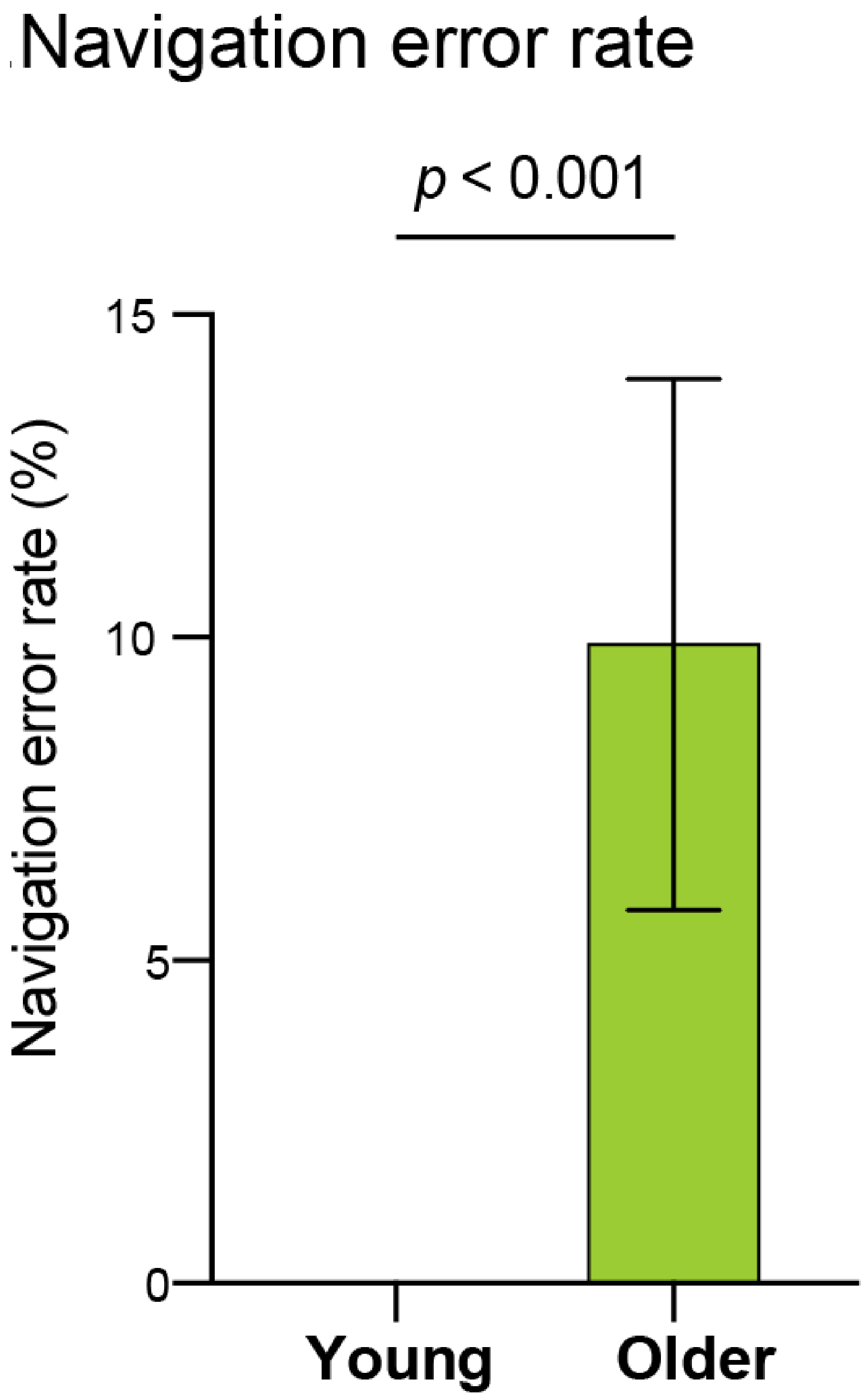
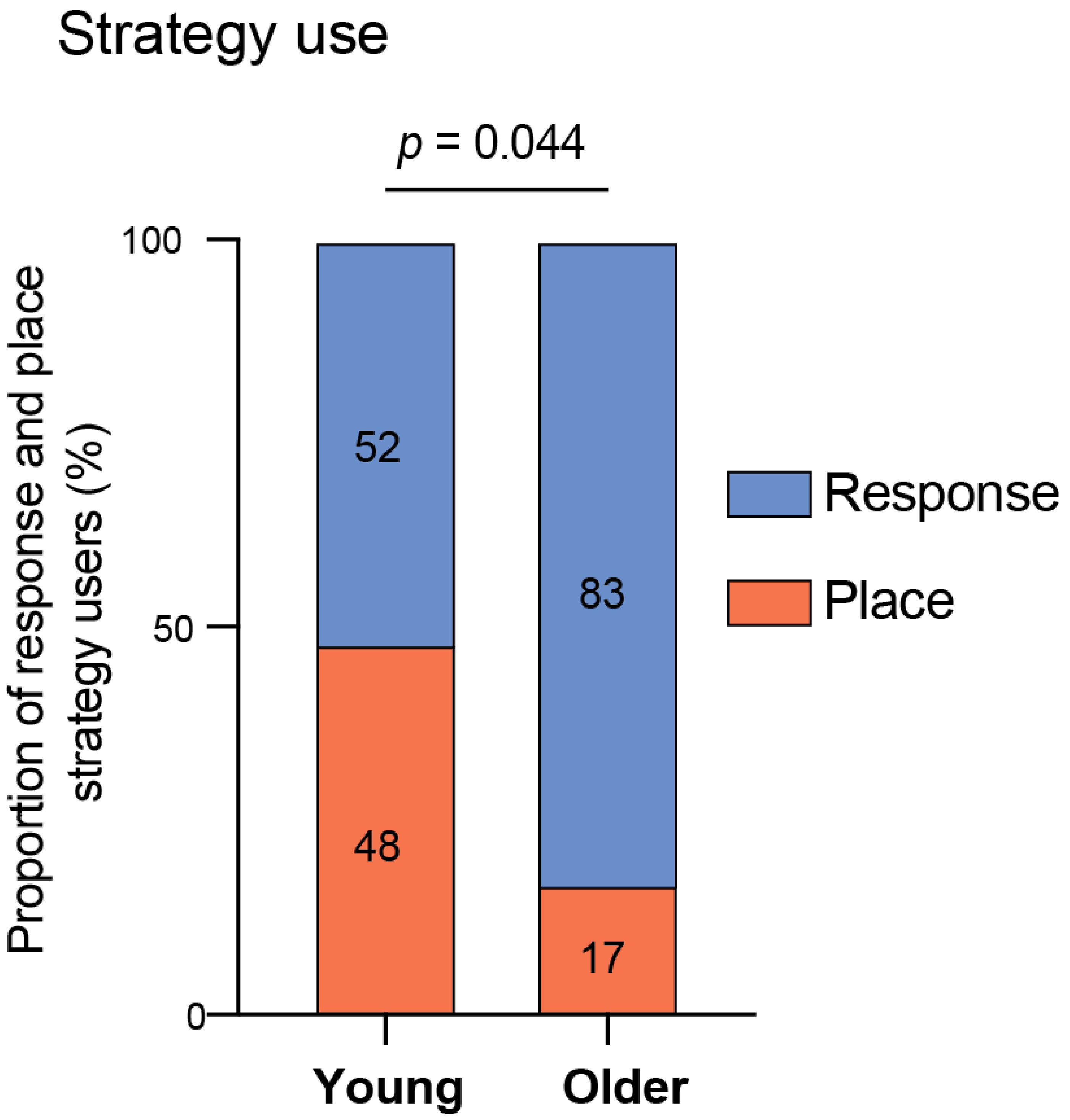
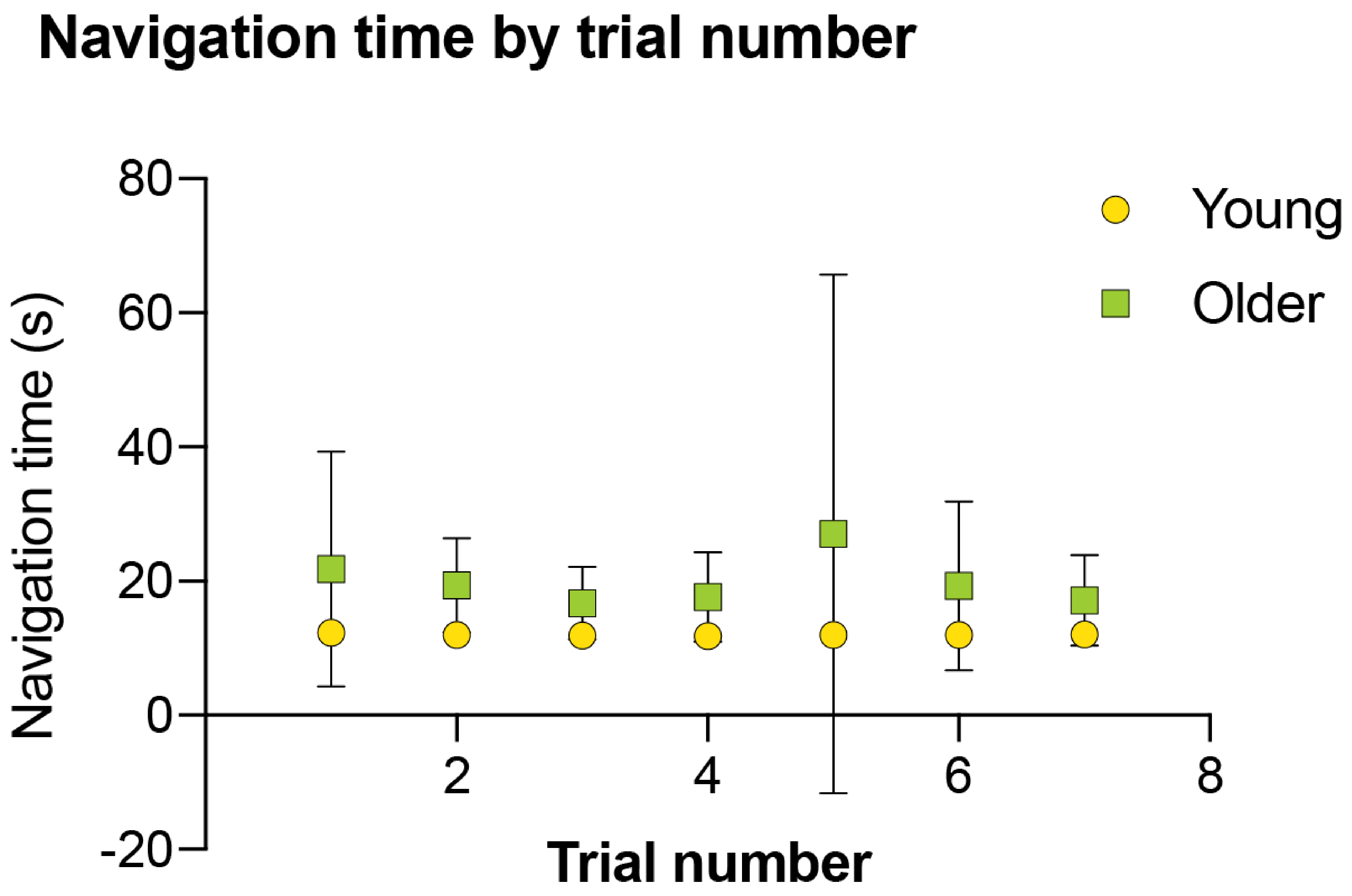




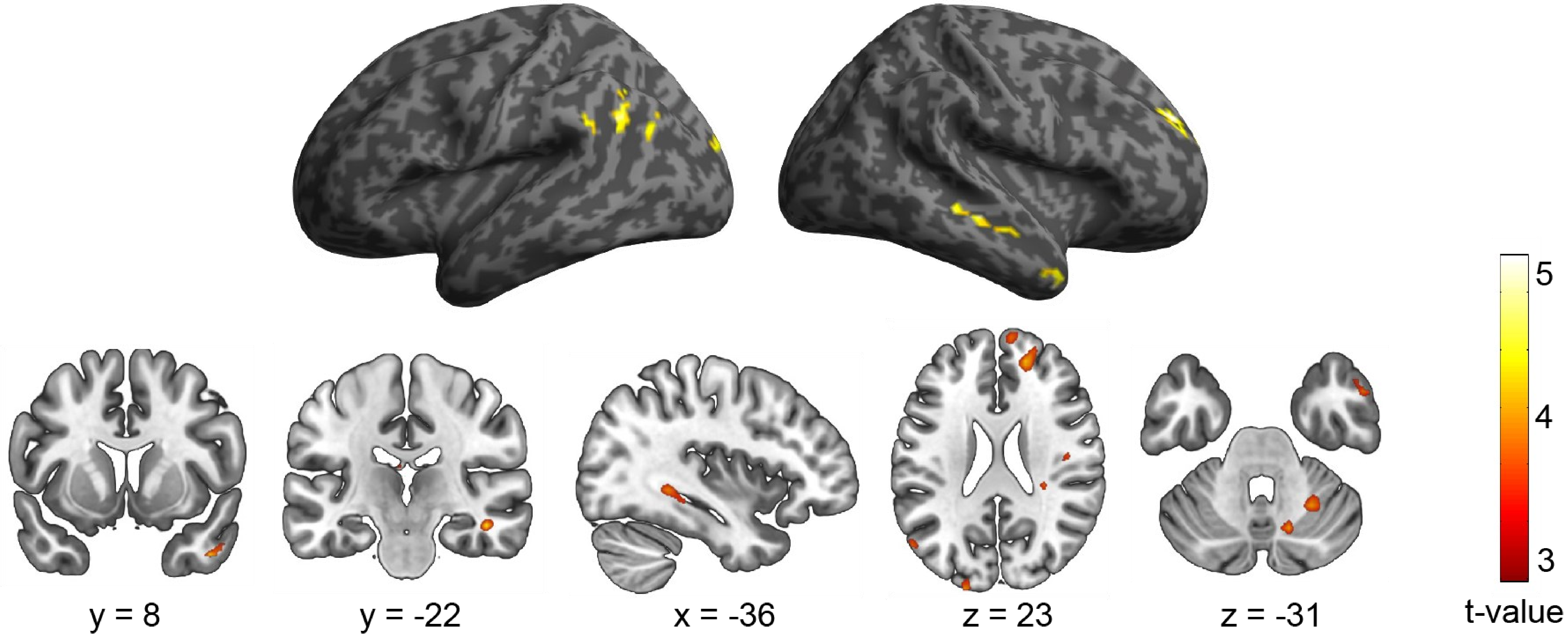
Study 2

Behavioural results



Study 2

Neuroimaging results



Cerebral regions whose activity for the contrast [Landmark > Control] was predicted by navigation time
($p < 0.001$ uncorrected, $k = 10$ voxels)

Study 2

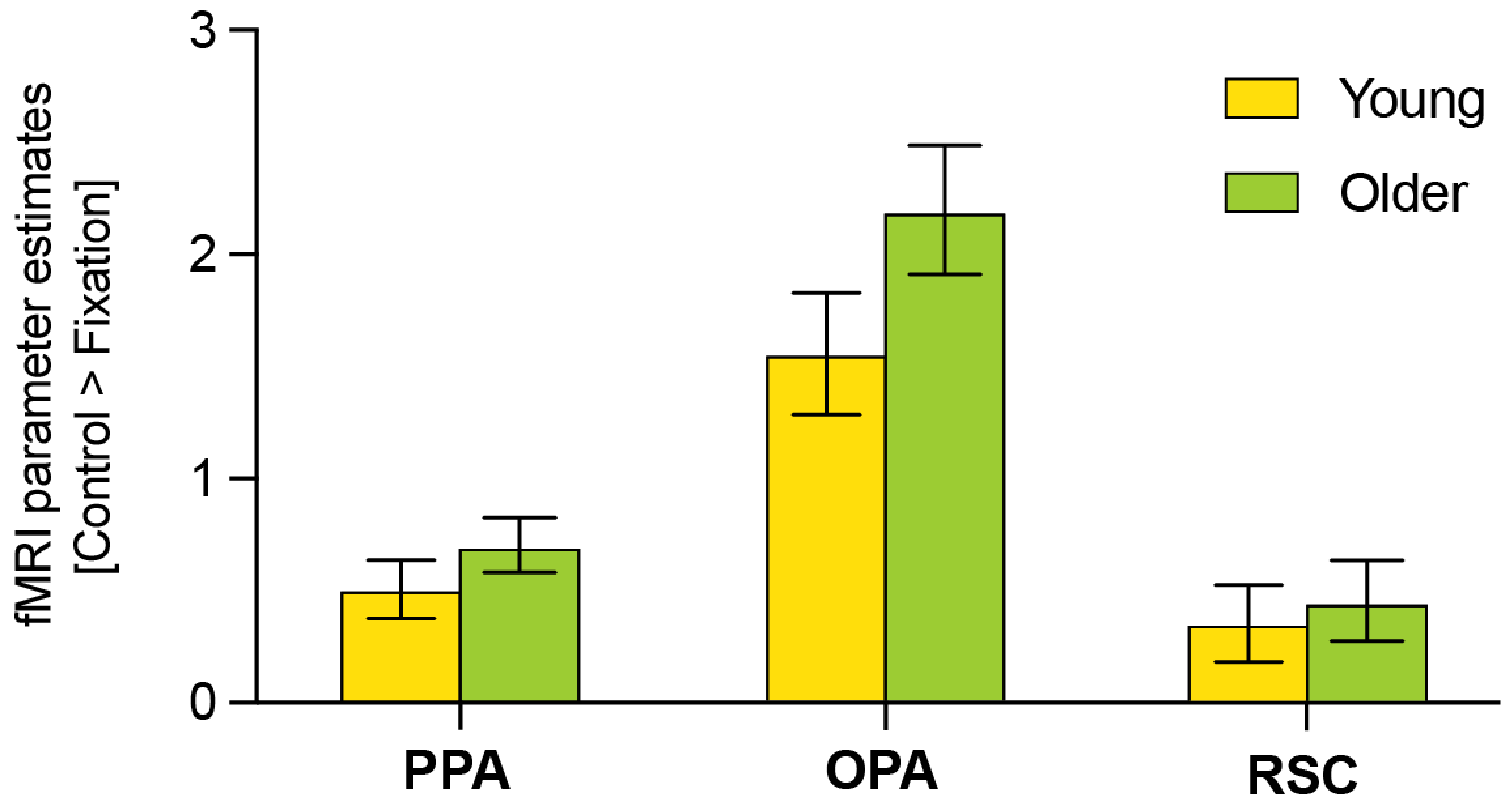
Neuroimaging results

Group analyses [Landmark > Control]	H	BA	k	x	y	z	t	ES [95%-CI]
Within-group [Young]								
Inferior Occipital Gyrus	R	18	65	30	-88	-10	5.07	4.49[3.04, 5.95]
Superior Temporal Gyrus	L	38	21	-48	20	-25	4.54	2.55[1.63, 3.47]
				-42	11	-22	4.01	2.52[1.49, 3.55]
Cerebellum Crus I-II	R	-	19	33	-82	-34	4.49	2.75[1.74, 3.76]
Middle Occipital Gyrus	L	18	37	-30	-97	-7	4.42	3.38[2.12, 4.64]
[Inferior Occipital Gyrus]		19		-39	-85	-13	3.54	3.25[1.74, 4.76]
Inferior Temporal Gyrus (Amygdala/Hippocampus)	L	53/54	15	-30	-1	-22	4.37	1.43[0.89, 1.97]
Middle Occipital Gyrus	R	19	16	48	-79	2	4.20	1.85[1.13, 2.57]
Within-group [Older]								
No significant activation								
Between-group [Young > Older]								
Inferior Temporal Gyrus (Amygdala/Hippocampus)	L	-	12	-33	2	-25	3.86	2.49[1.43, 3.56]
				-36	-7	-25	3.82	2.13[1.12, 3.05]
Between-group [Older > Young]								
No significant activation								

Study 2

Neuroimaging results

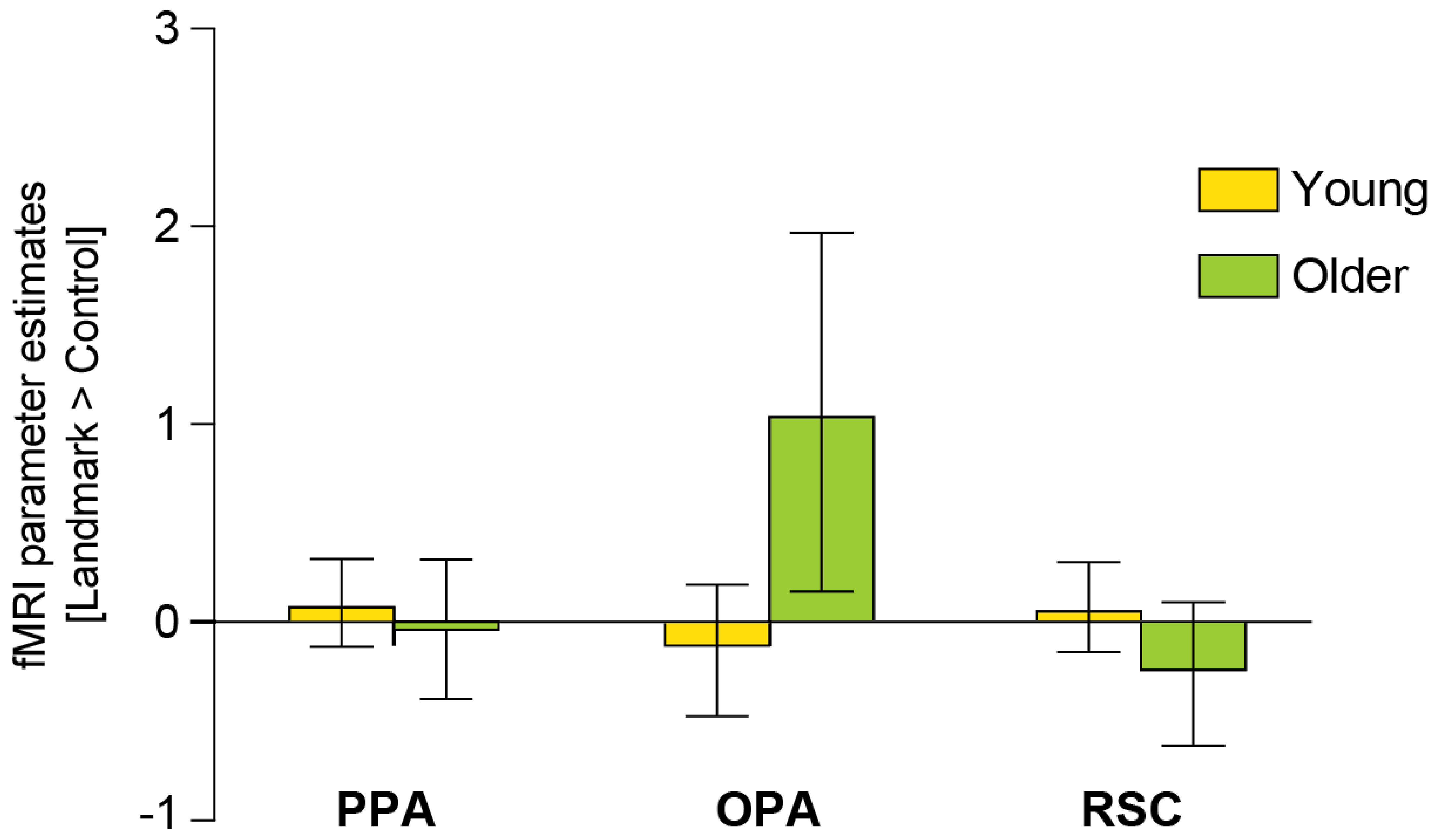
[Control > Fixation]



Results from univariate ROI analyses contrasting landmark and control conditions to fixation.

Study 2

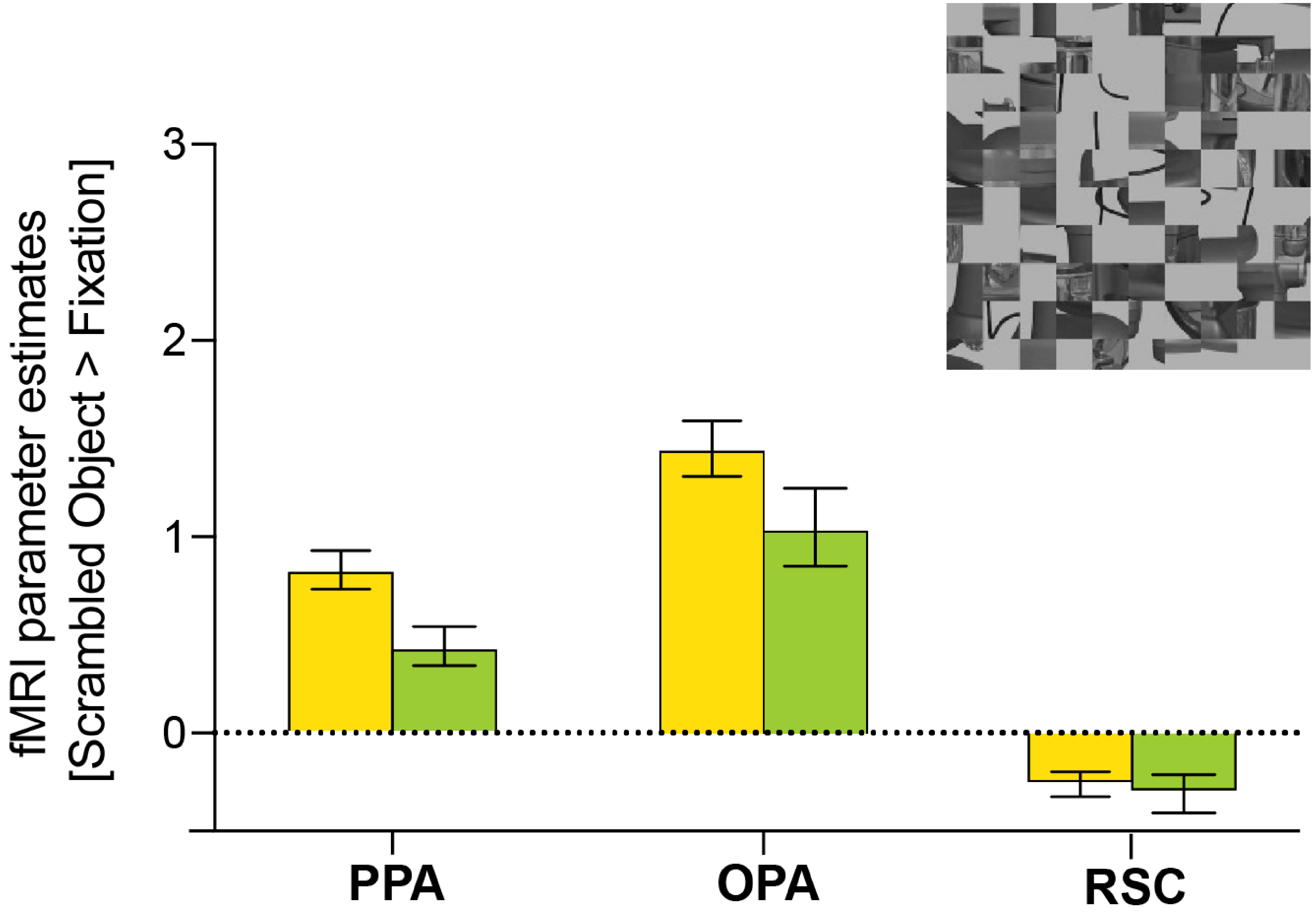
Neuroimaging results



Results from univariate ROI analyses contrasting the landmark condition to the control condition

Study 2

Neuroimaging results

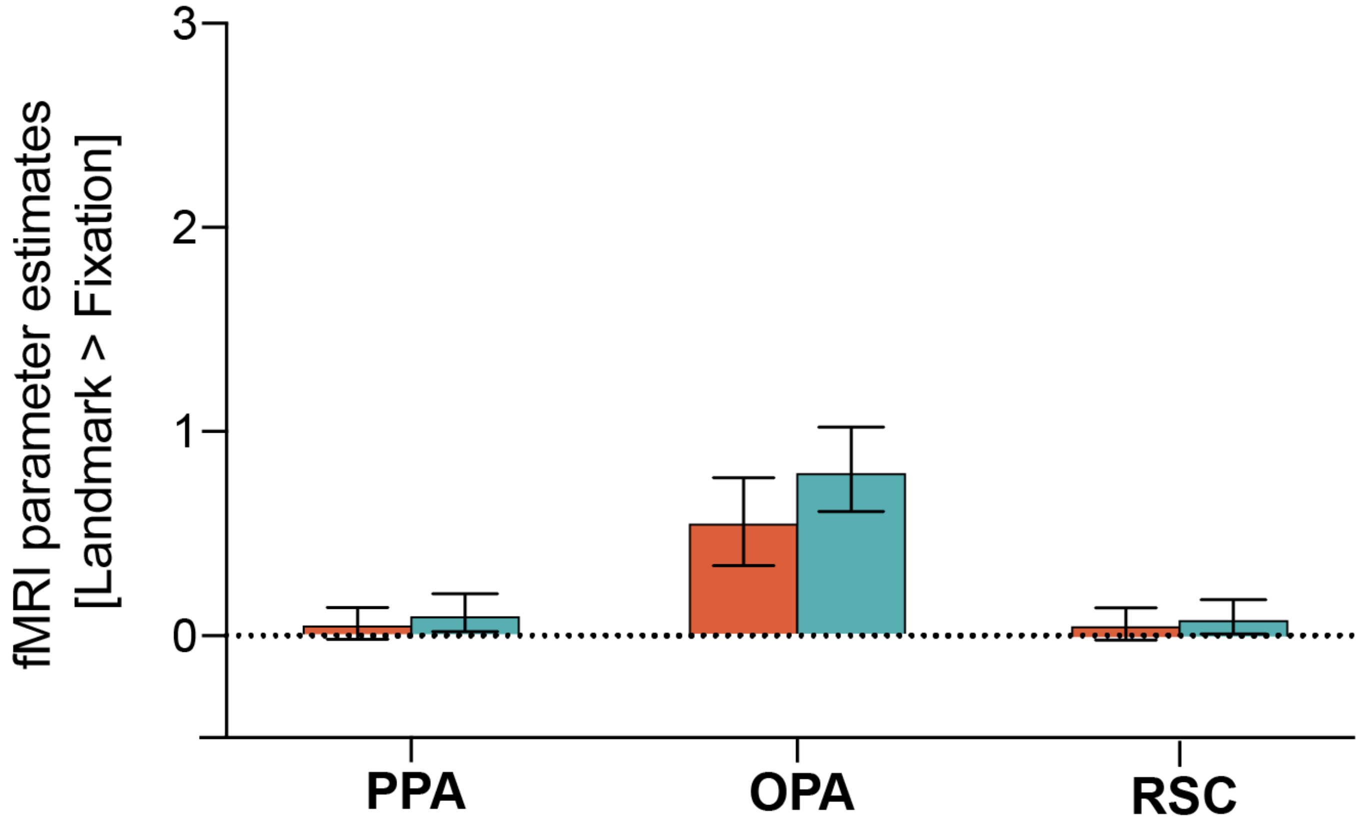


We confirmed that low-level visual processing (e.g., fixation behaviour) was not driving the increased OPA activity.

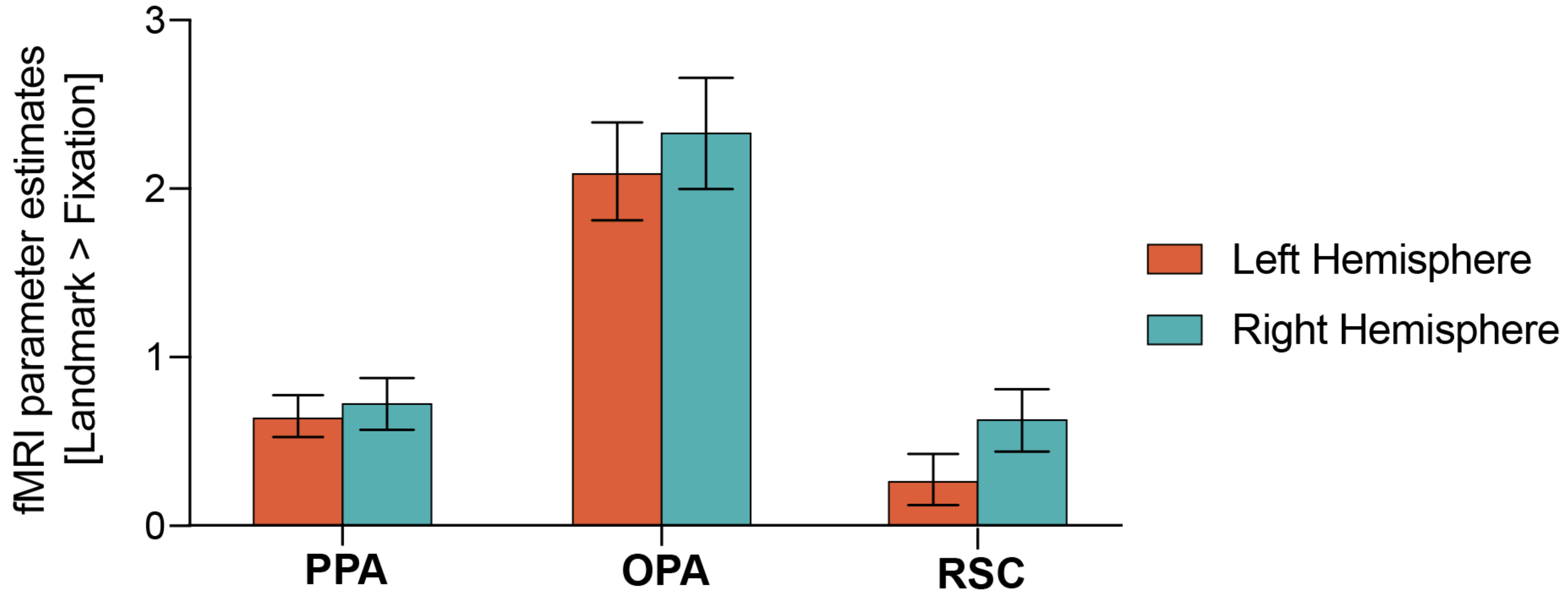
Study 2

Neuroimaging results

Young adults



Older adults



Study 3

Visual field asymmetries

Properties	LVF	UVF
Shape of visual field	Larger extent (70-80°) (Fortenbaugh et al., 2015)	Smaller extent (50-60°) (Fortenbaugh et al., 2015)
Stereopsis	Crossed disparities – near targets (Previc et al., 1995)	Uncrossed disparities – far targets (Previc et al., 1995)
Motion perception	Advantage for the LVF (Lakha & Humphreys, 2005; Amanedo et al., 2007; Zito et al., 2016)	
Attention	Greater spatial resolution (He et al., 1996, 97)	Greater spatial attention (Previc & Blume, 1993; Erel et al., 2019)
Spatial vision	More sensitive in low-to-moderate frequency range (Lundh et al., 1983; Murray et al., 1983)	More sensitive in high-frequency range (Lundh et al., 1983; Murray et al., 1983)
Perception	More global – stereomotion (Previc, 1990; Christman, 1993; Zito et al., 2016)	More local - object perception (Previc, 1990; Christman, 1993, Beer et al., 1996; Zito et al., 2016)
Visual search	Advantage for the UVF (Previc & Naegele, 2001; Pflugshaupt et al., 2009)	
Spatial judgments	Egocentric (Sdoia et al., 2004; Zhou et al., 2017)	Allocentric (Sdoia et al., 2004; Zhou et al., 2017)

Study 3

Neuropsychological profiles

Variables	Young adults 11 M / 14 F Mean (±SD)	Older adults 8 M / 12 F Mean (±SD)
MMSE	29.2 (± 1.1)	28.2 (± 1.5)
3D Mental rotation	15.9 (± 5.7)	8.5 (± 5.3)
Corsi forward	6.3 (± 1.1)	4.5 (± 0.8)
Corsi Backward	6.0 (± 1.2)	4.5 (± 0.8)
Perspective taking	23.8 (± 19.1)	51.2 (± 28.2)

Study 3

Results

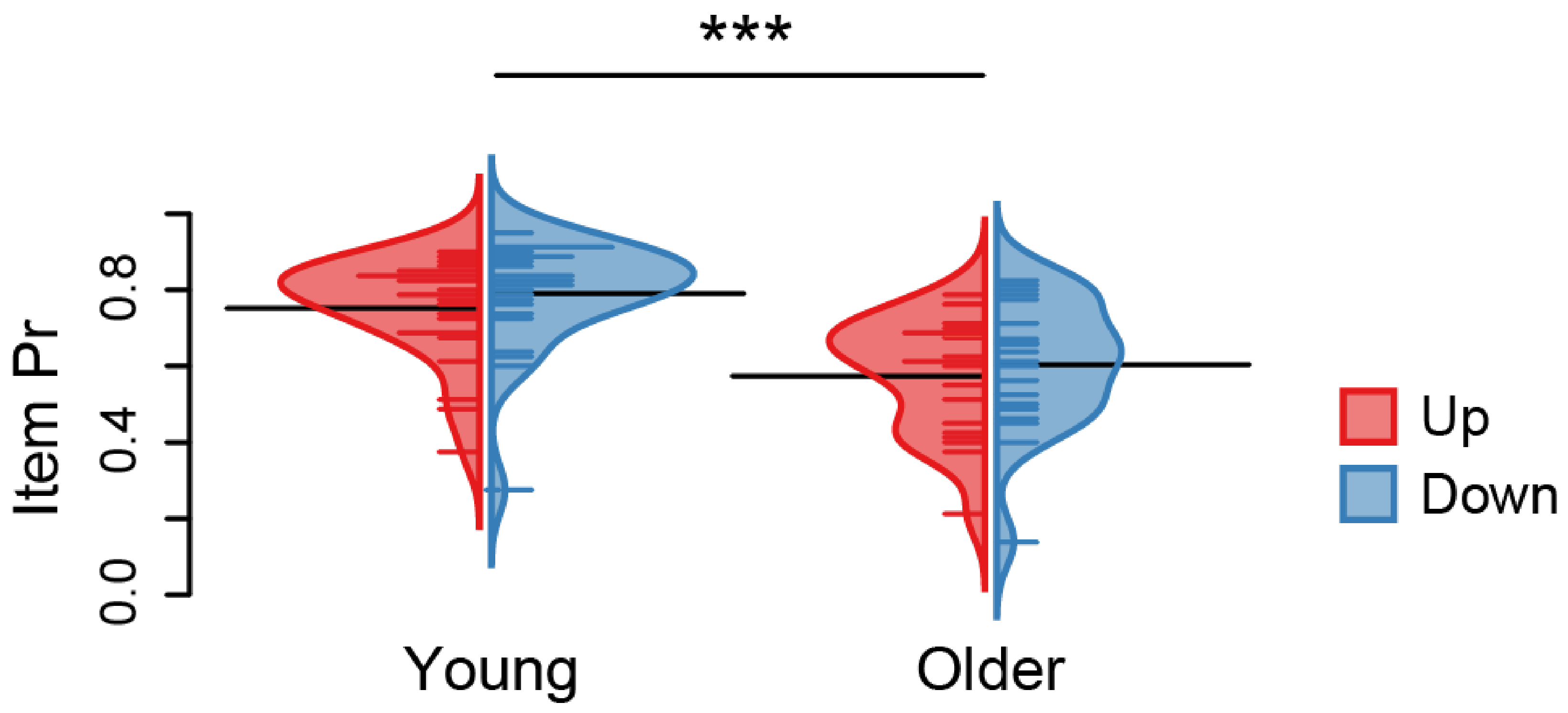
Group	Hit Rate (M ± SD)	False alarm Rate (M ± SD)	Correct rejection Rate (M ± SD)
Young (n = 25)	81.5% ± 14.6%	4.4% ± 3.6%	93.3% ± 5.1%
Older (n = 20)	69.1% ± 17.3%	10.2% ± 9.0%	82.1% ± 17.4%

Study 3

Standard *Pr* results

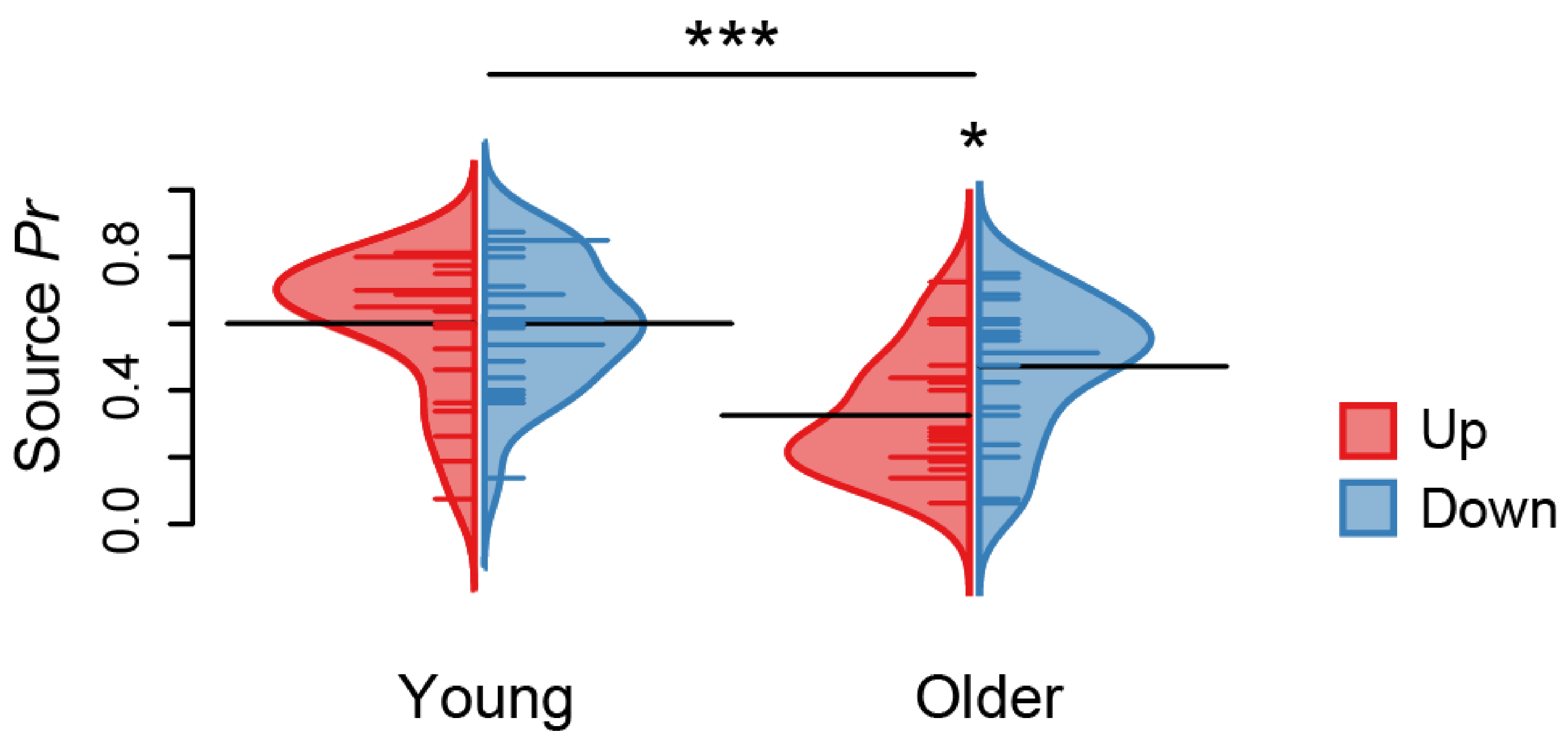
ITEM MEMORY

Standard *Pr* analysis



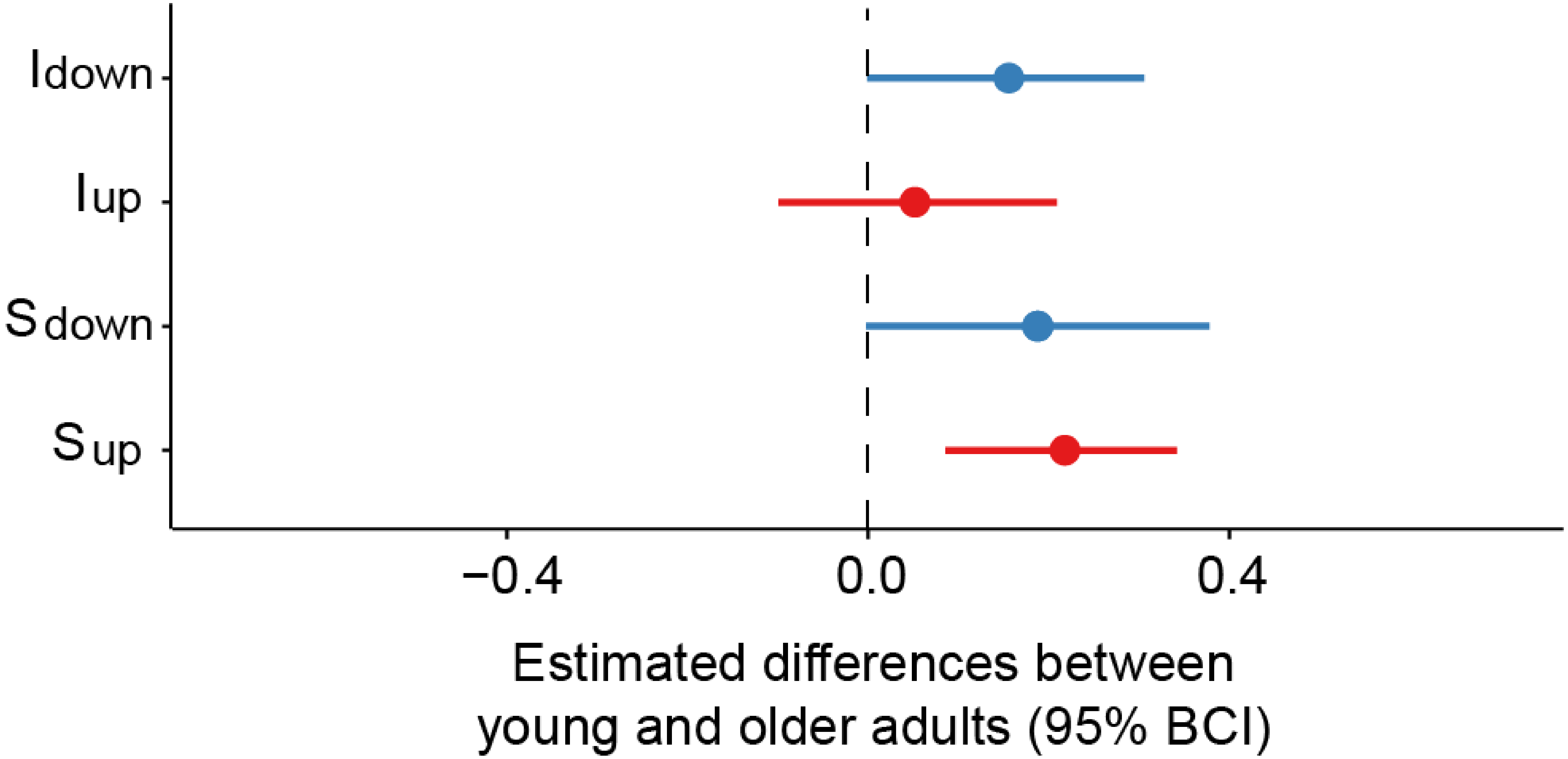
SPATIAL MEMORY

Standard *Pr* analysis



Study 3

MPT results



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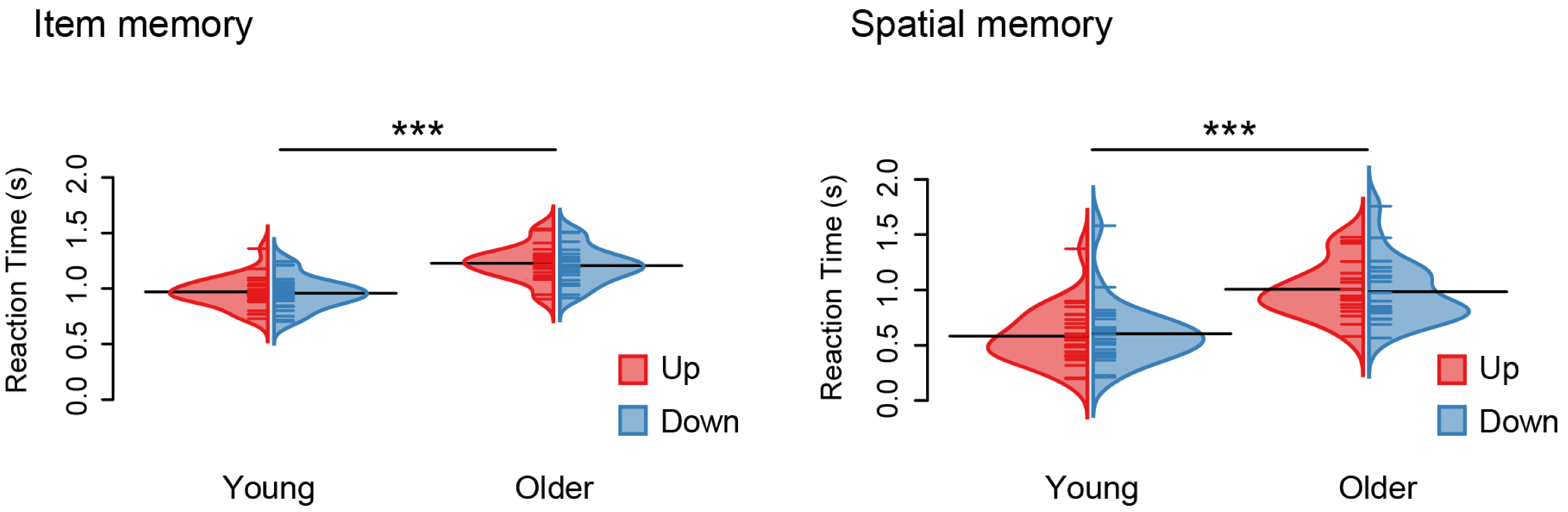
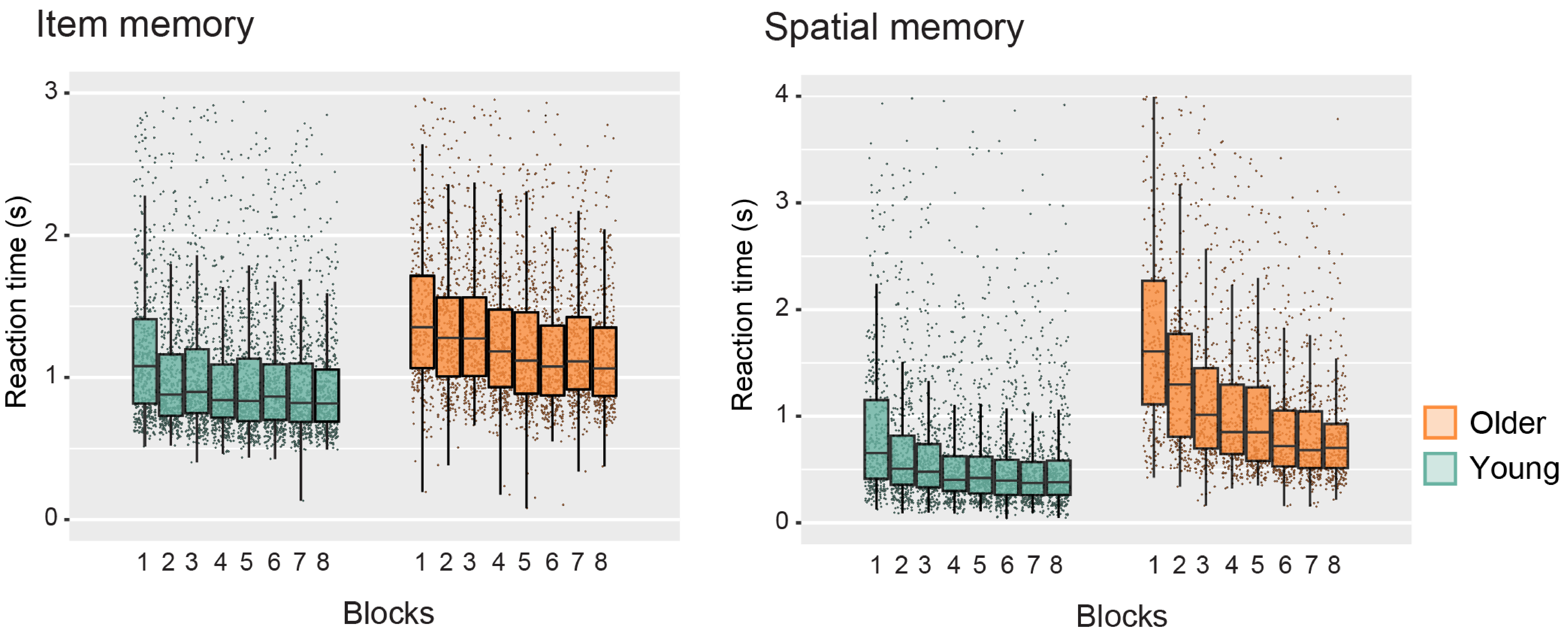
Study 3

Reaction time results



Study 3

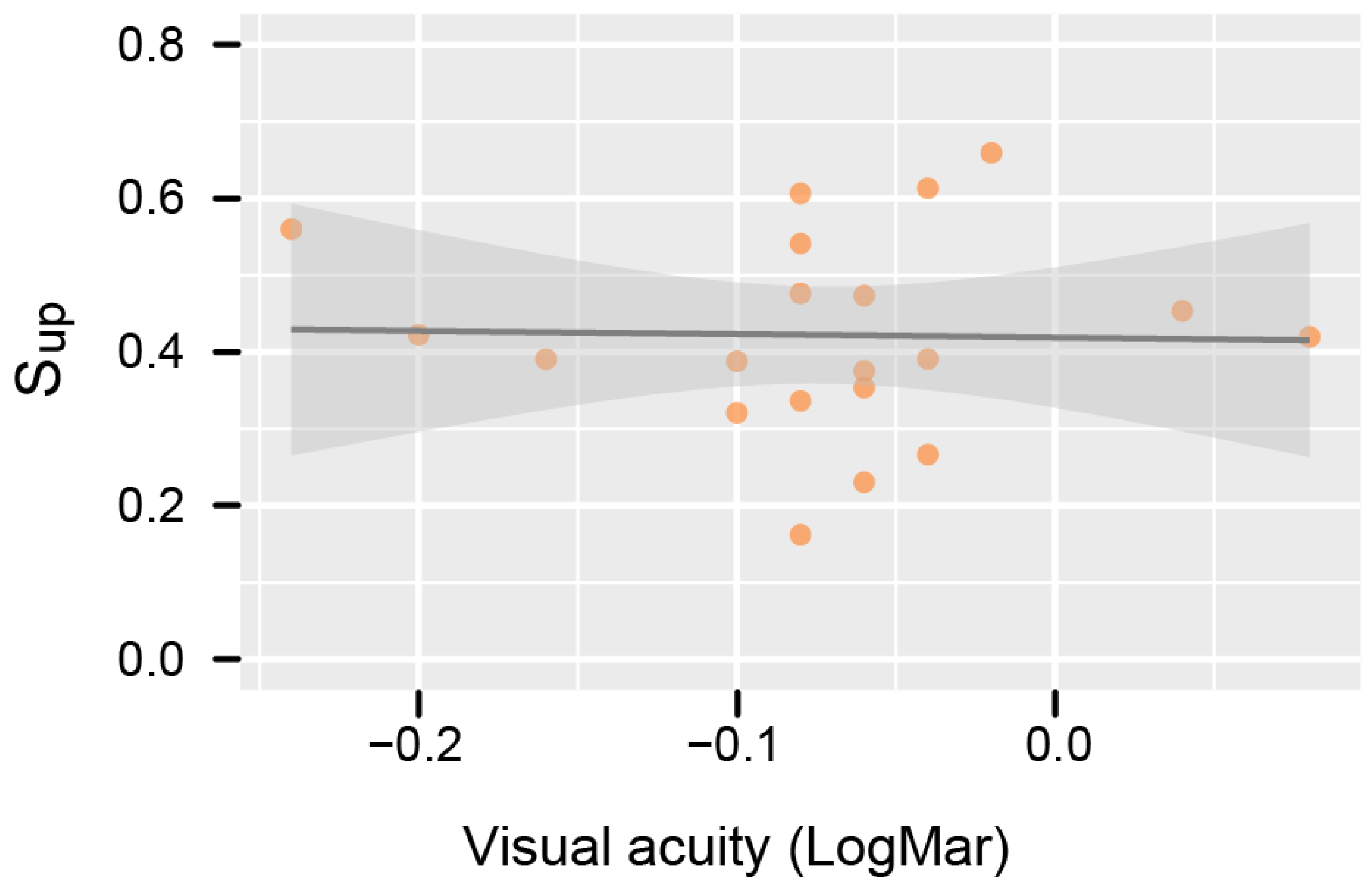
Reaction time results



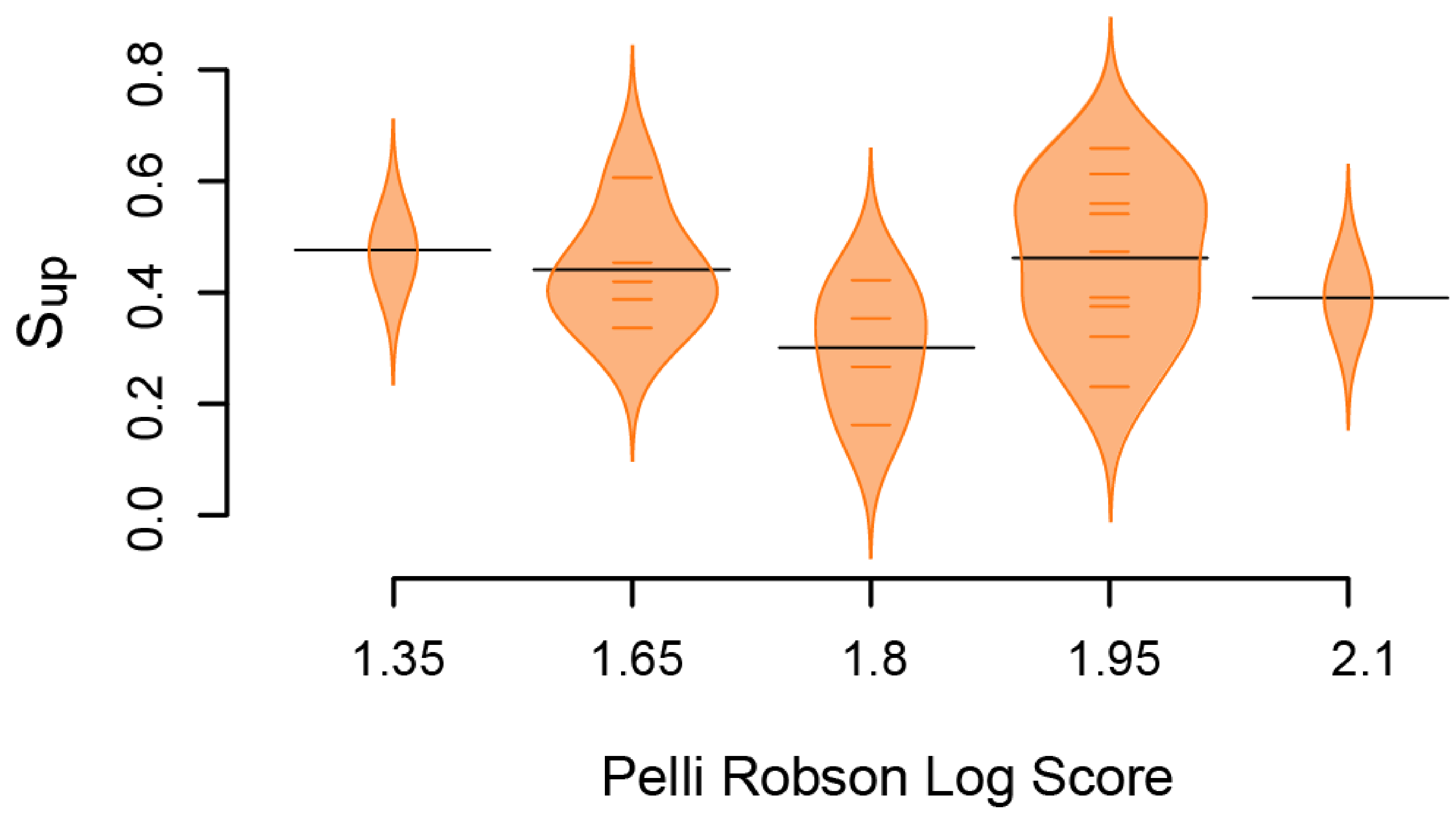
Study 3

Visual measures results

Visual acuity

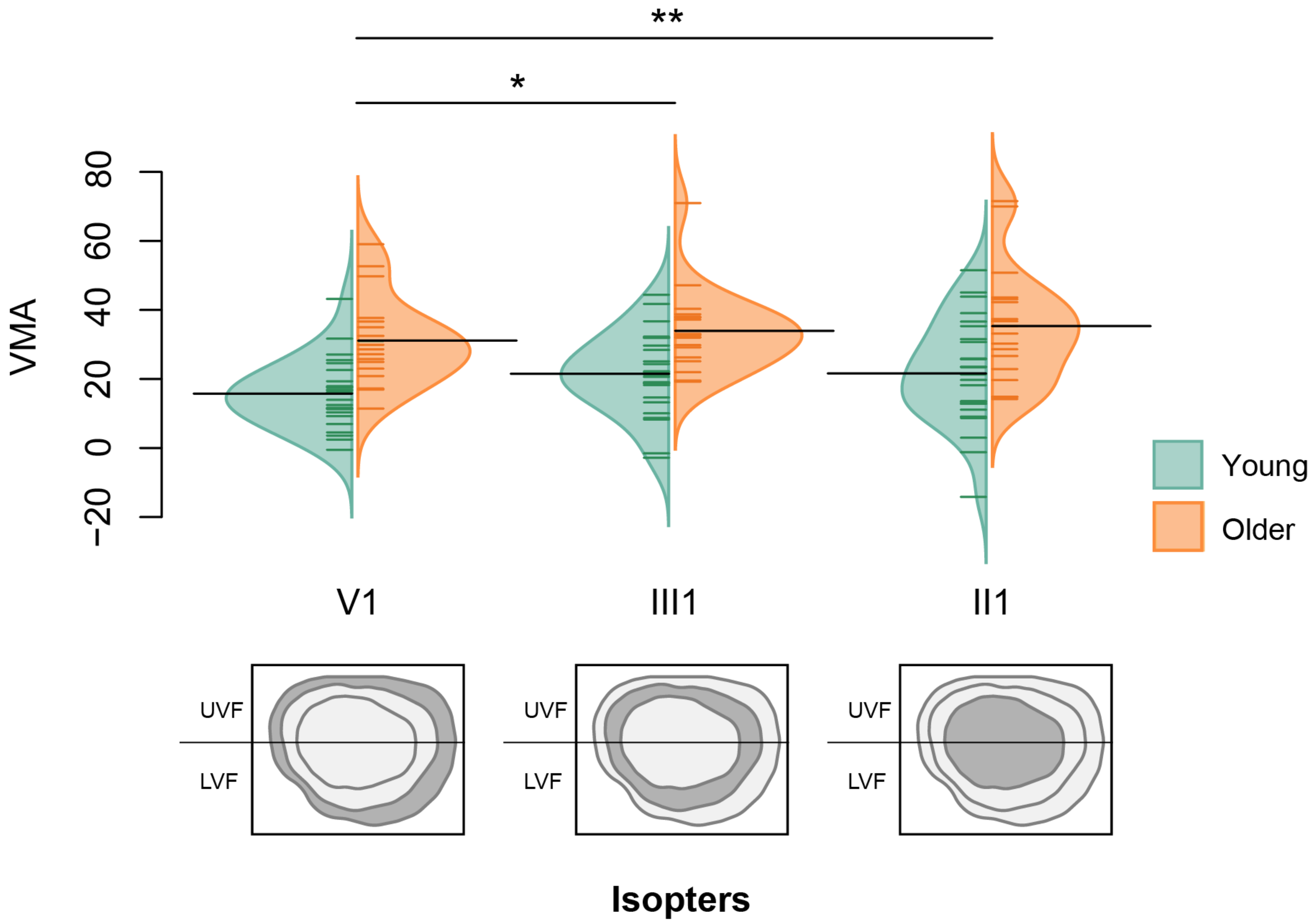


Contrast sensitivity



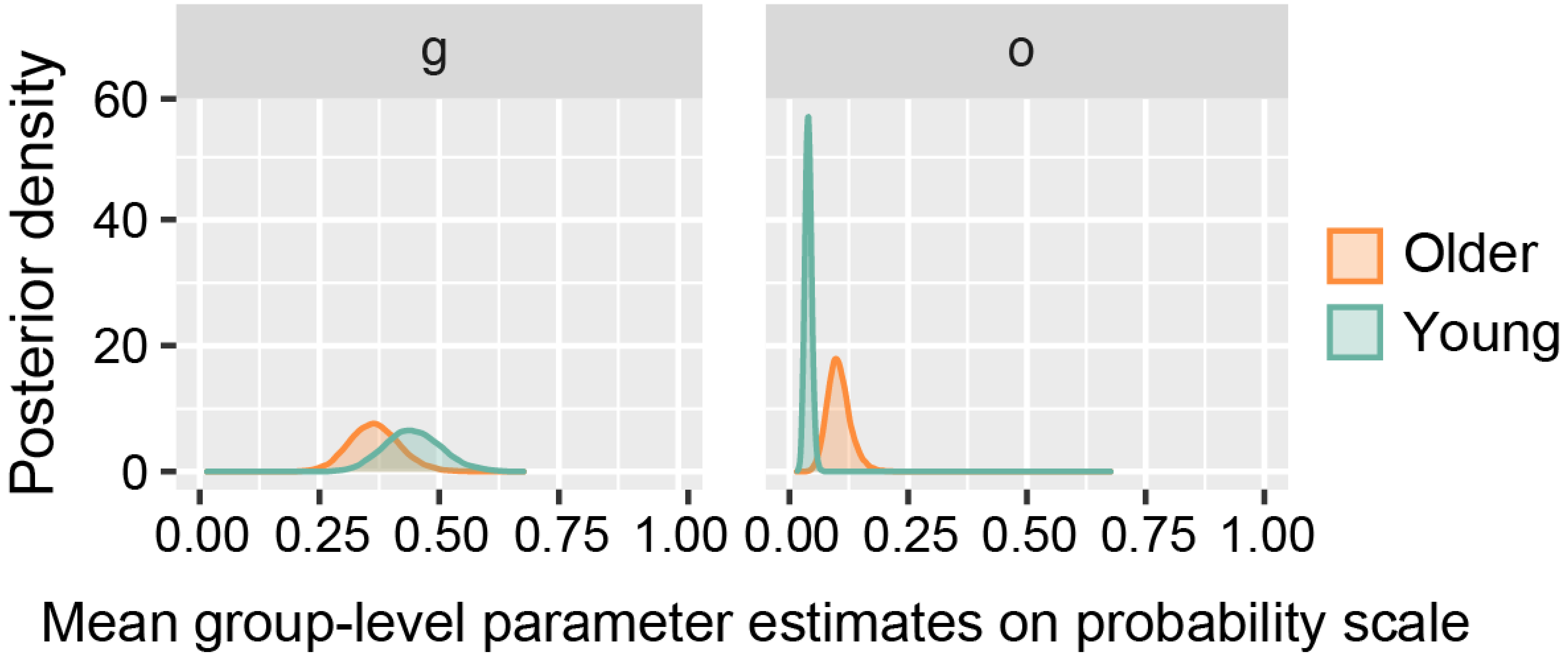
Study 3

Visual field results



Study 3

Visual field results

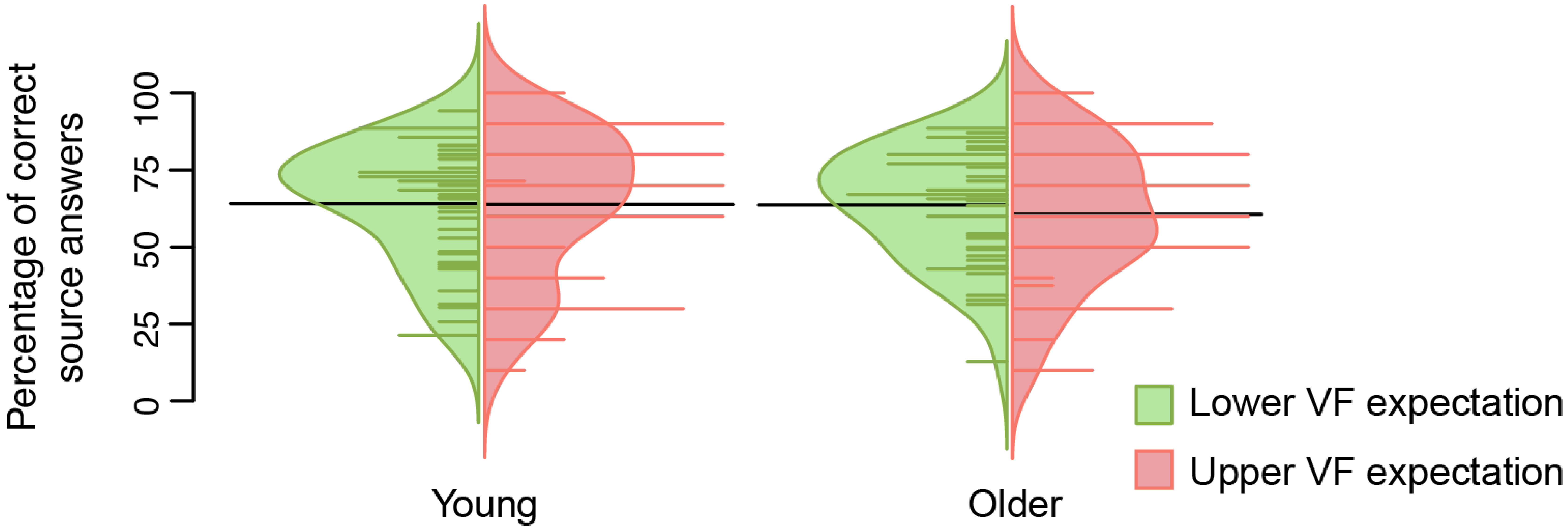


Older adults' probability of guessing that an item is old is lower than young adults'.

No age-related difference in the probability of guessing that an item is situated in the UVF.

Study 3

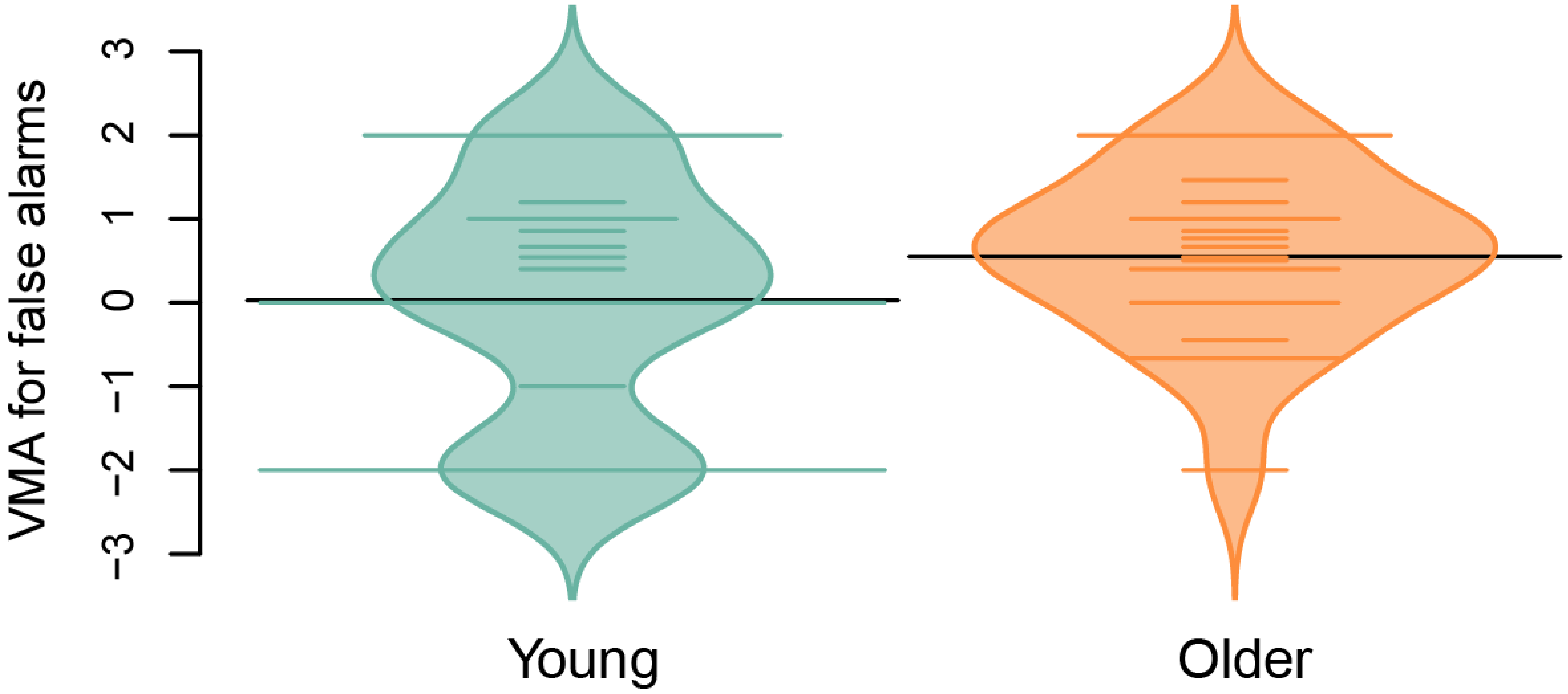
Visual field expectation results



No effects of pre-exposure on spatial memory performance in young and older adults.

Study 3

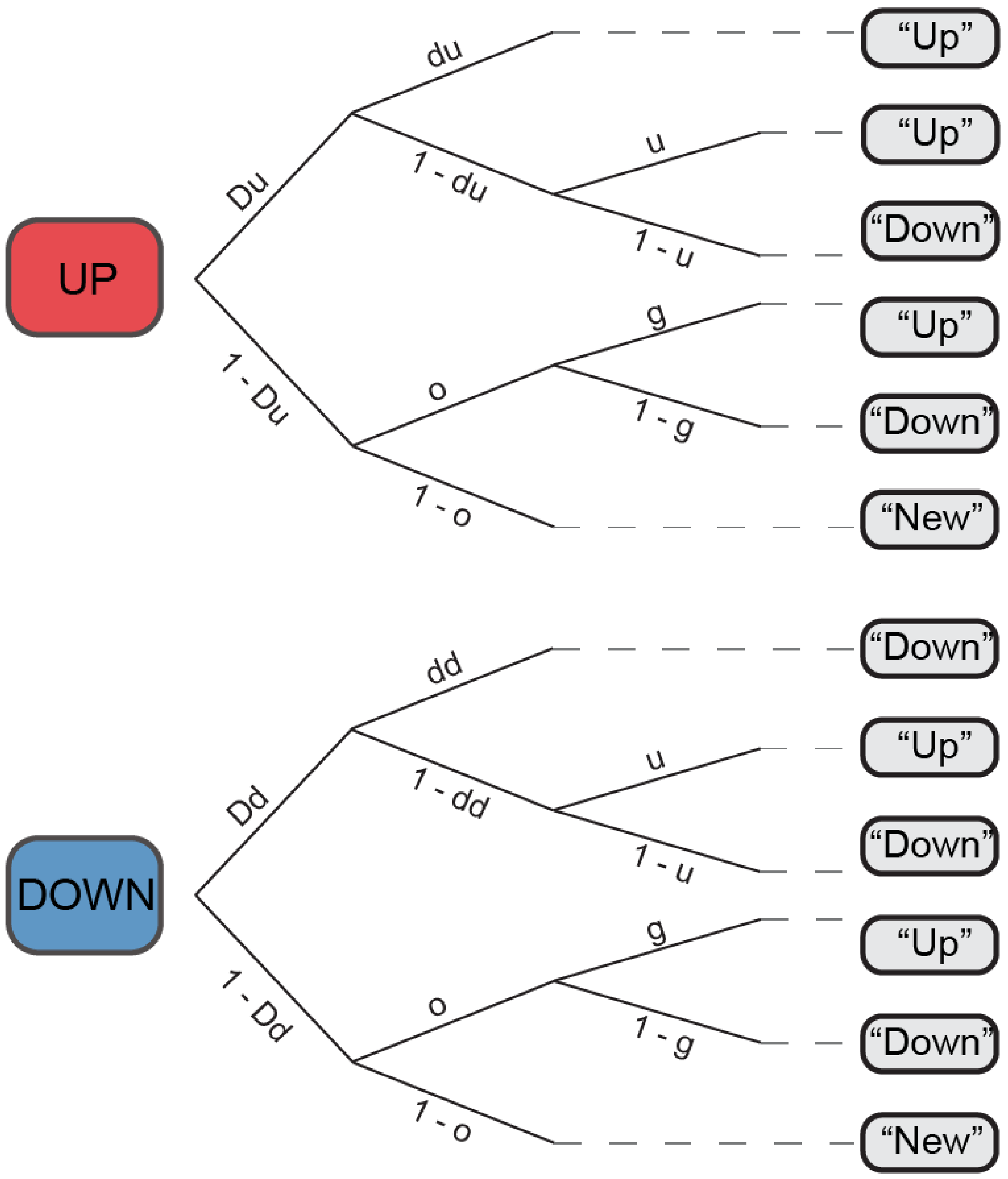
False alarm results

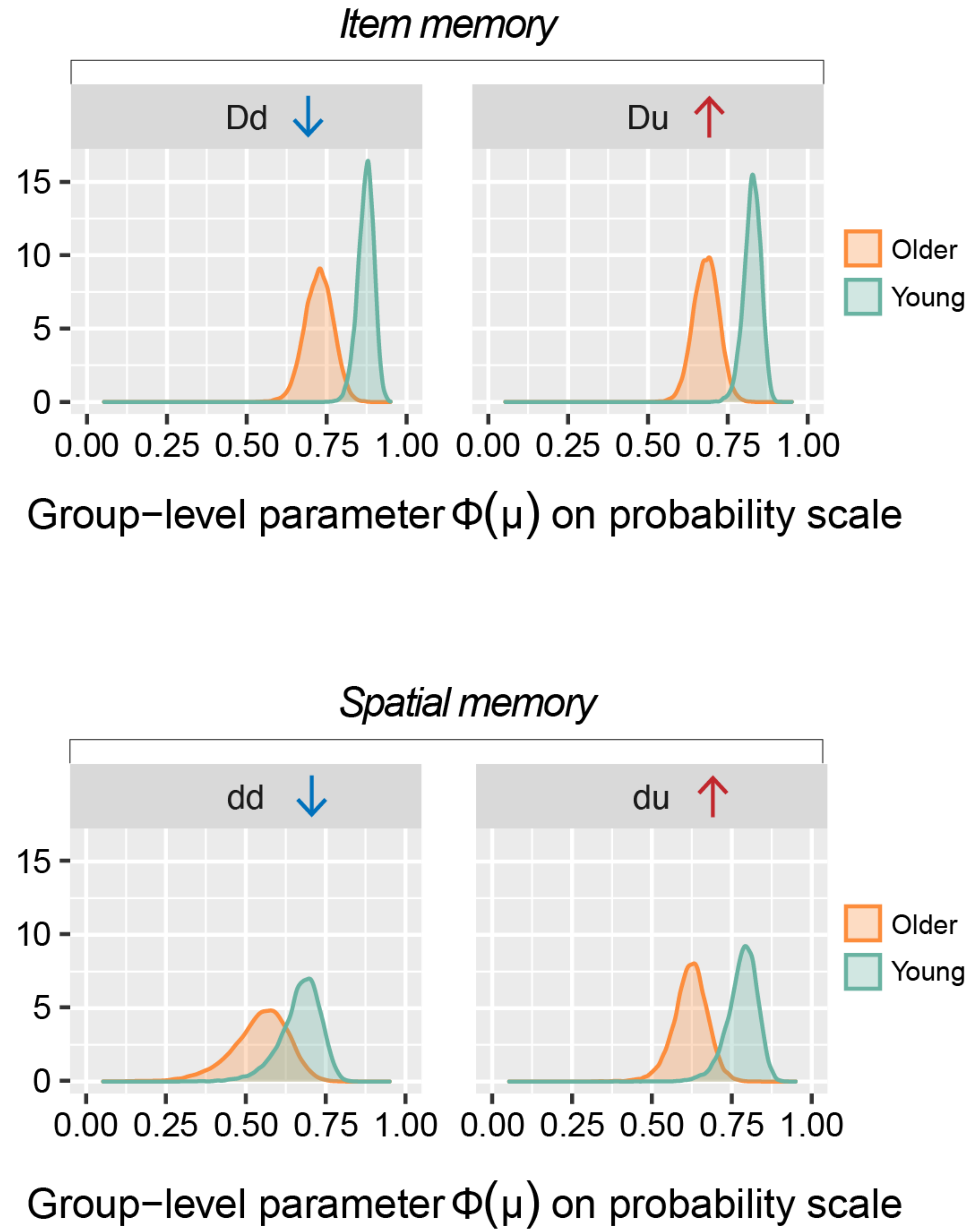


False alarms were not biased for the lower visual field in neither young nor older adults.

Study 3

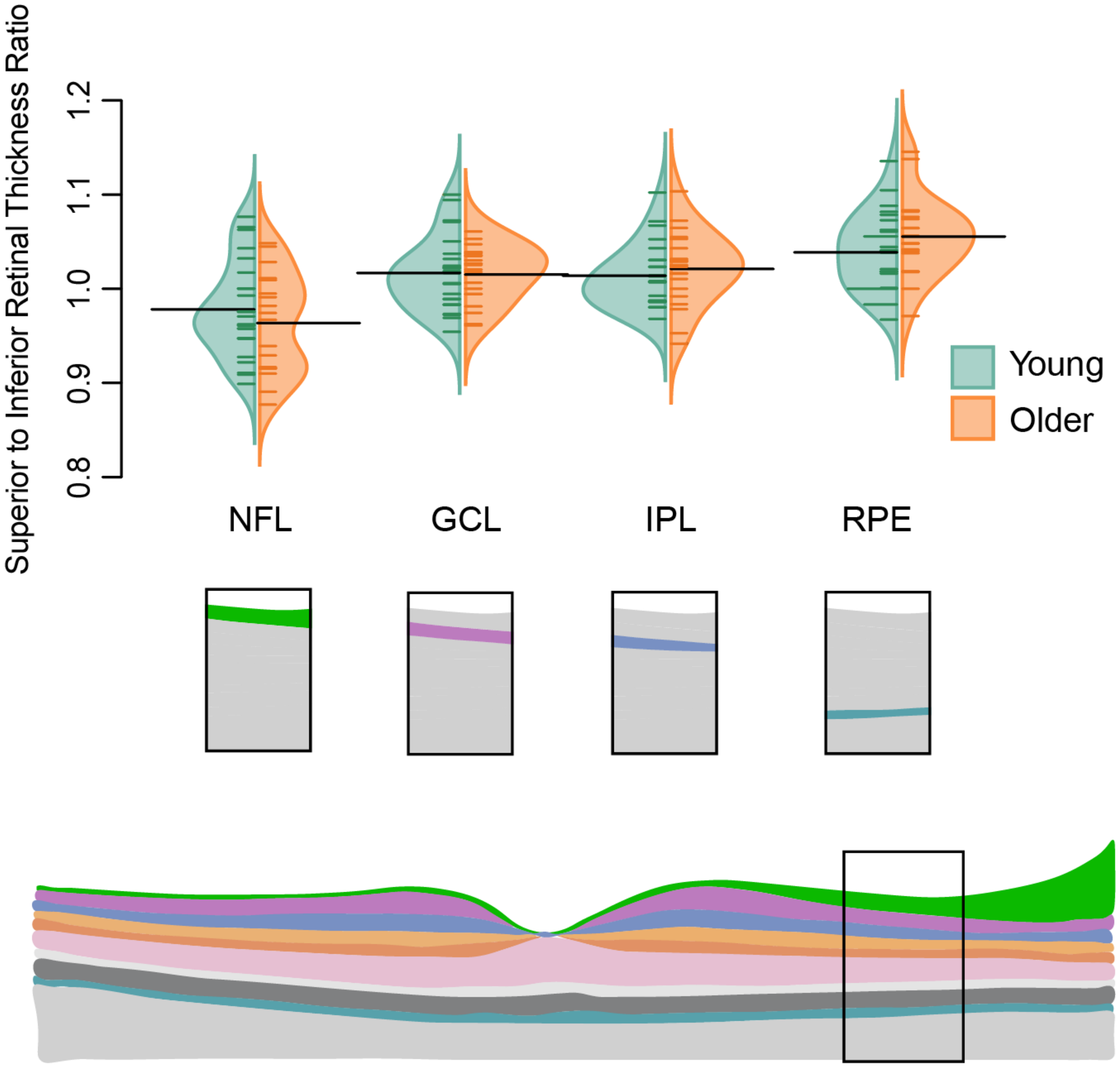
Item-Source results





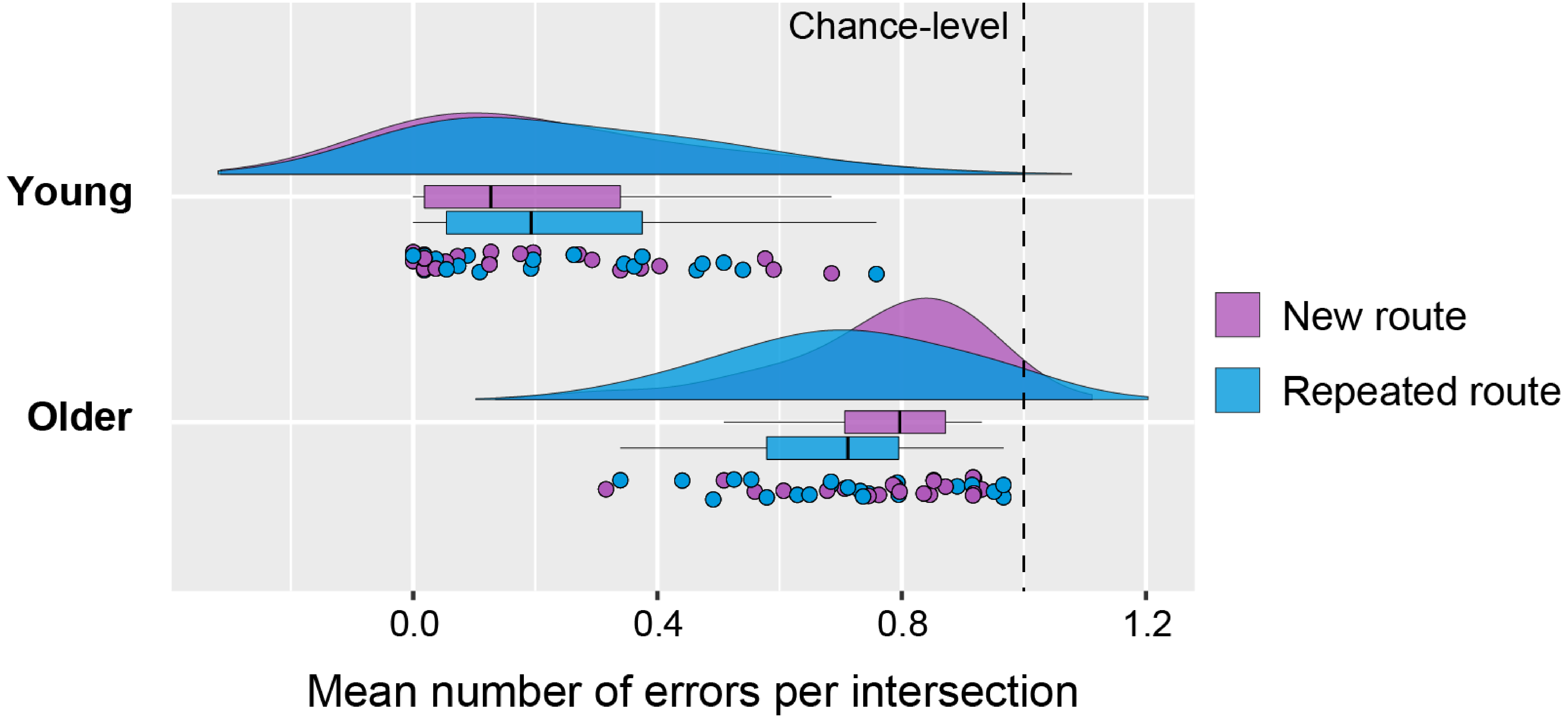
Complementary Study

OCT results



Study 4

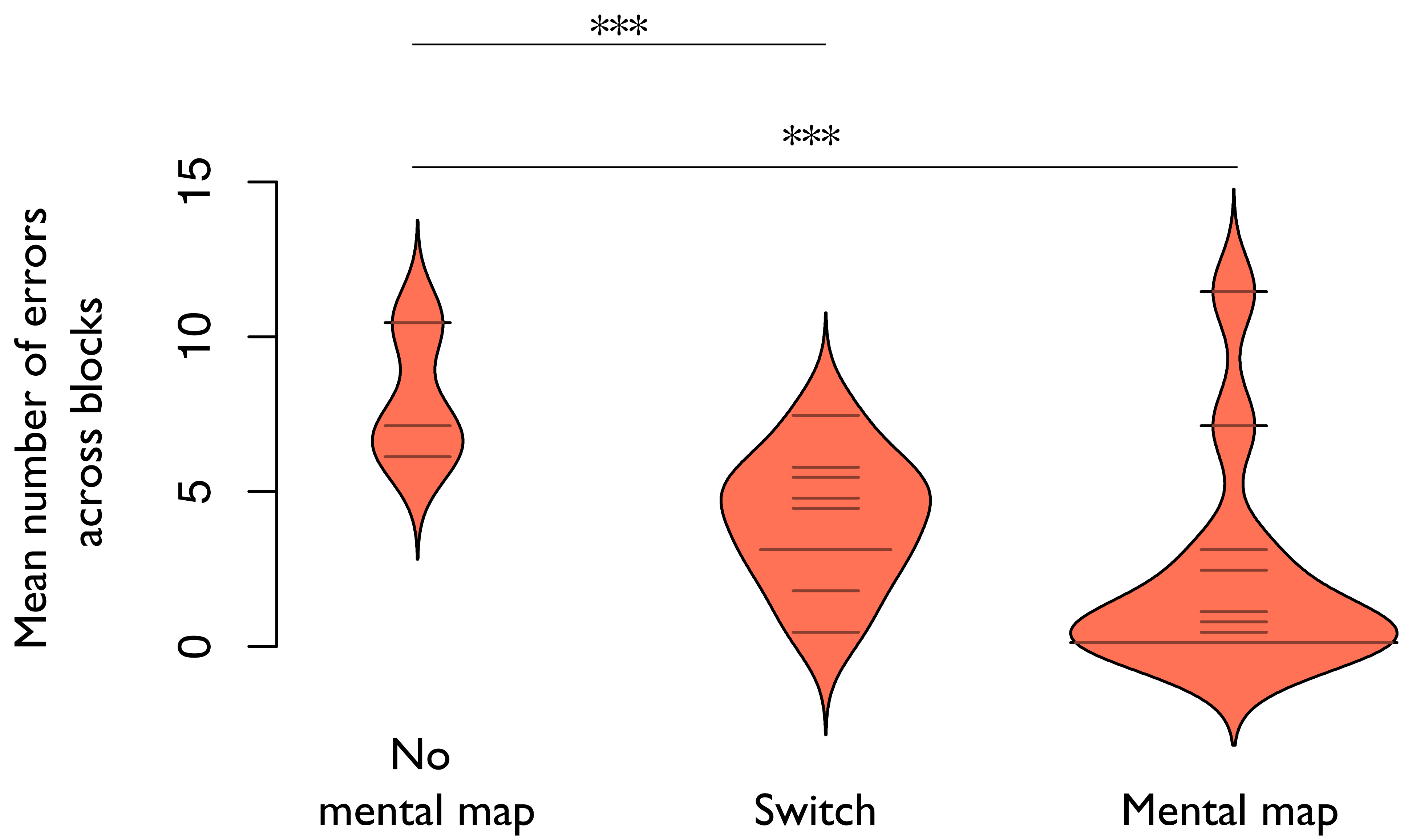
Behavioural results



Older adults make less errors on repeated routes than on new routes.

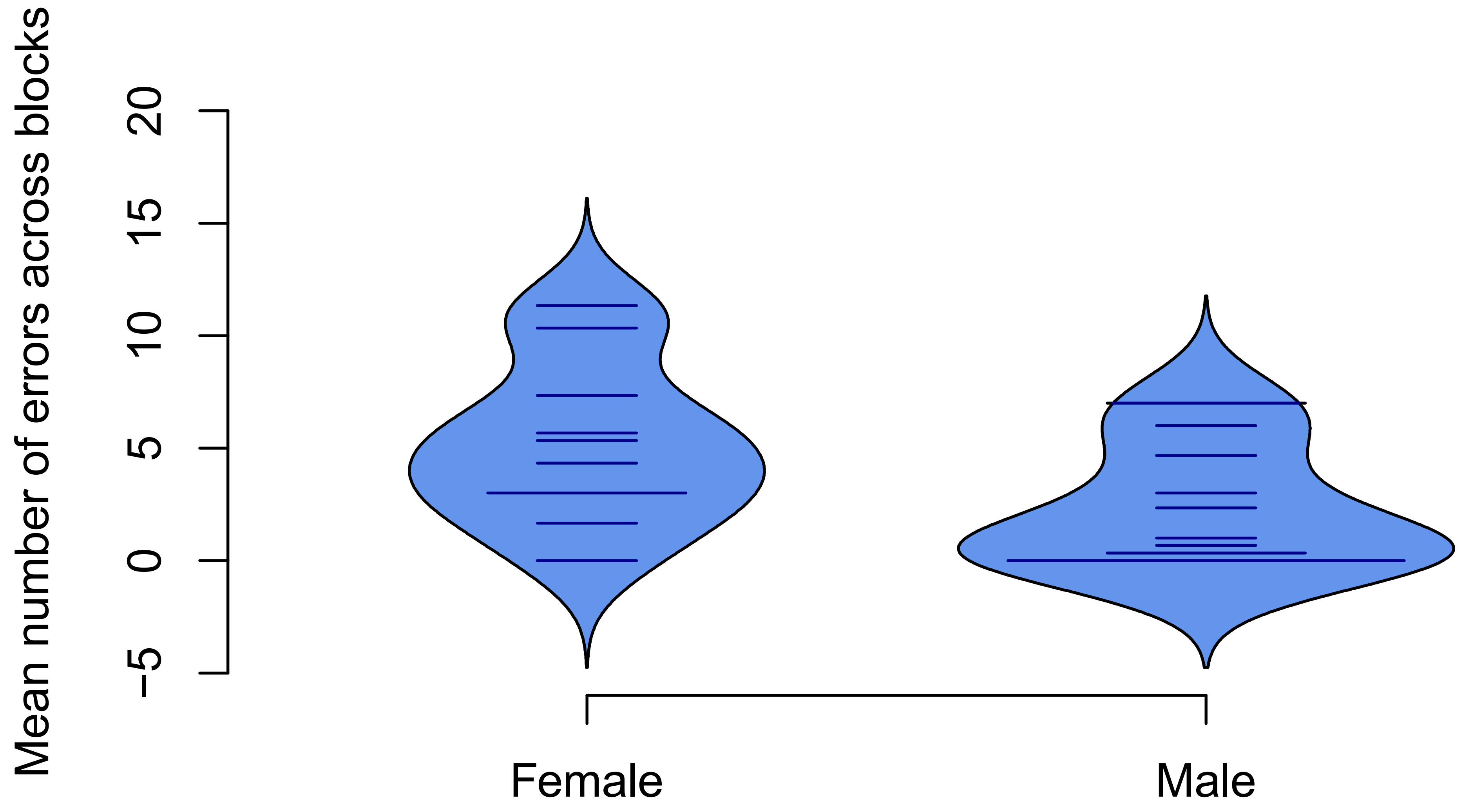
Study 4

Behavioural results



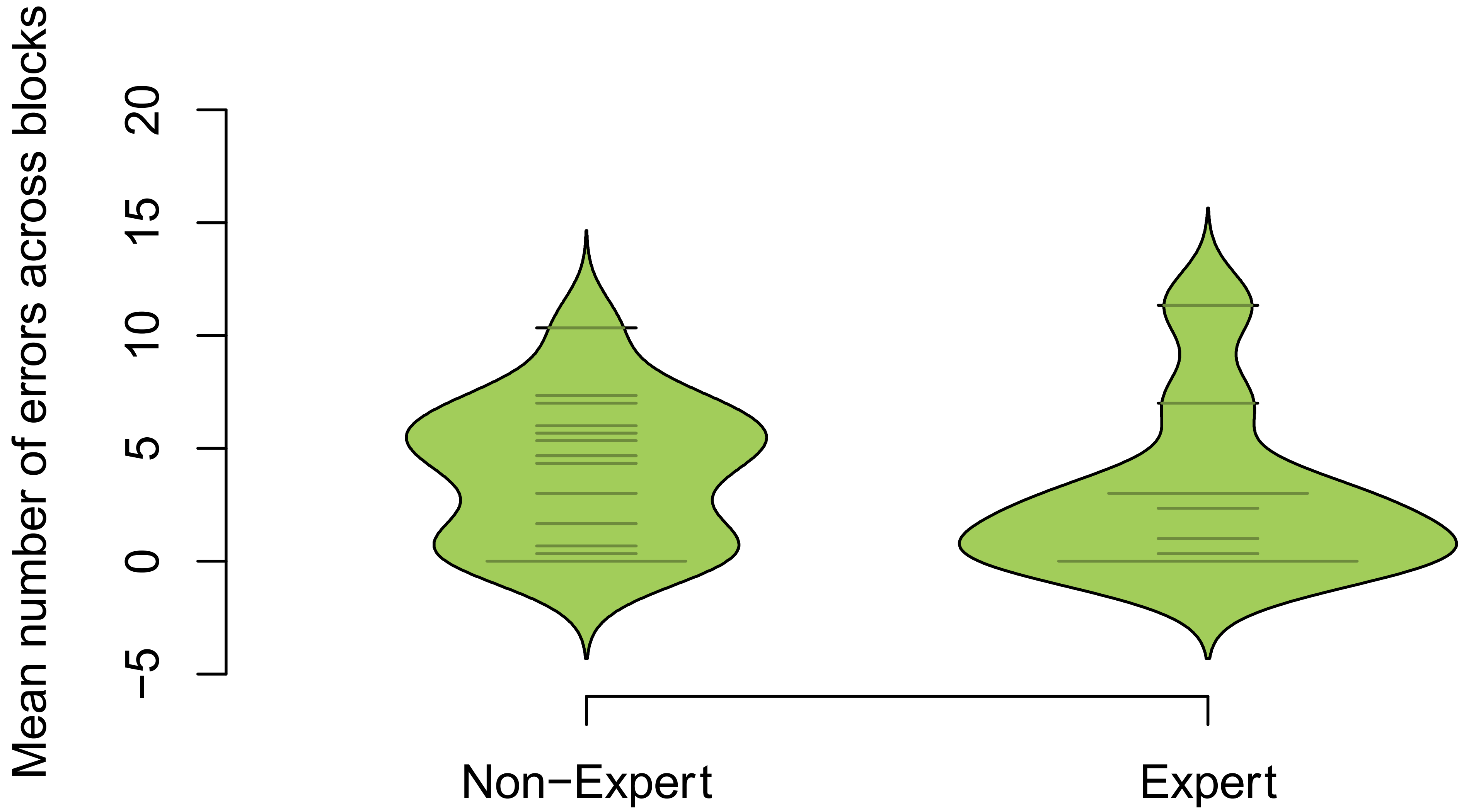
Study 4

Behavioural results



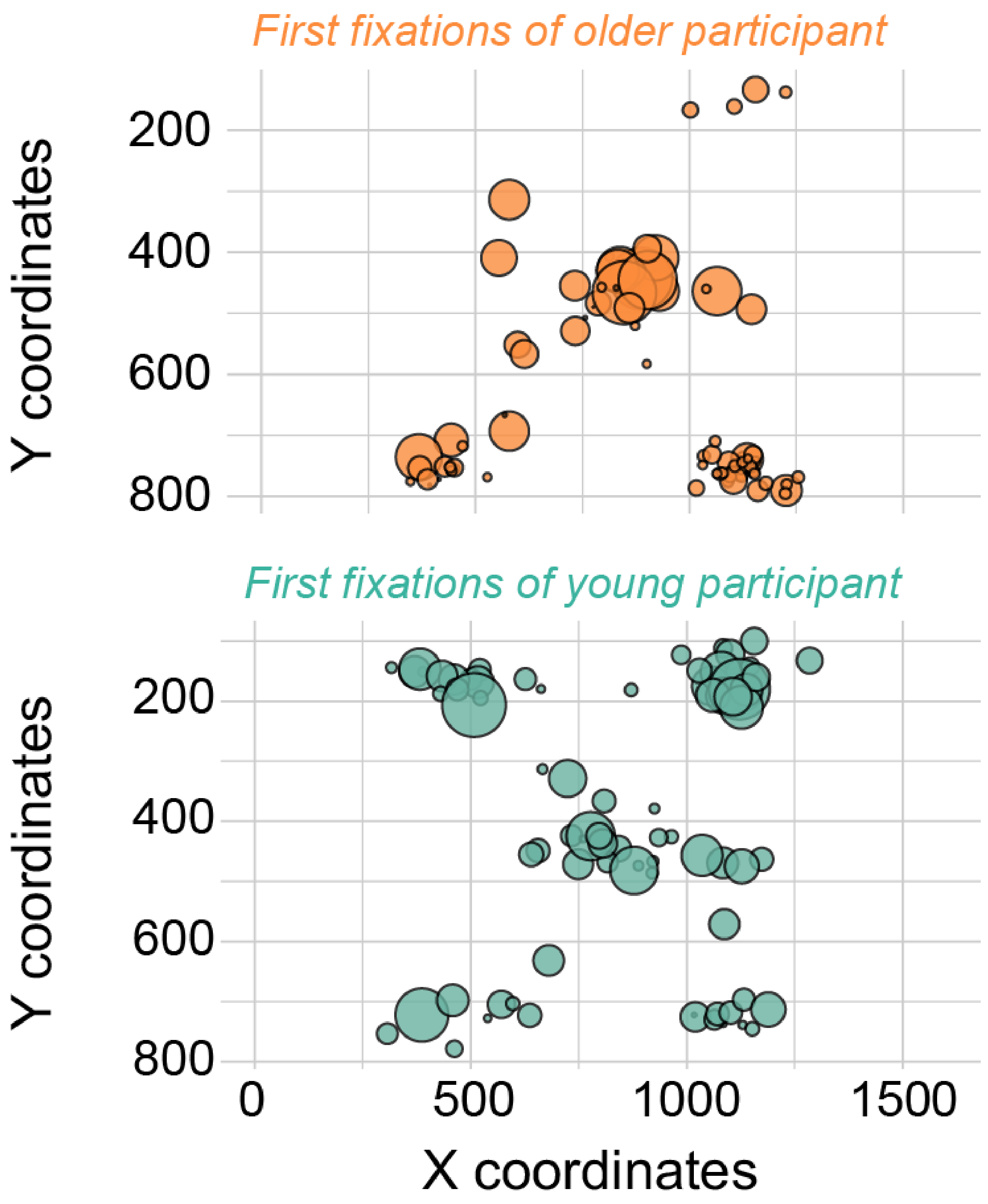
Study 4

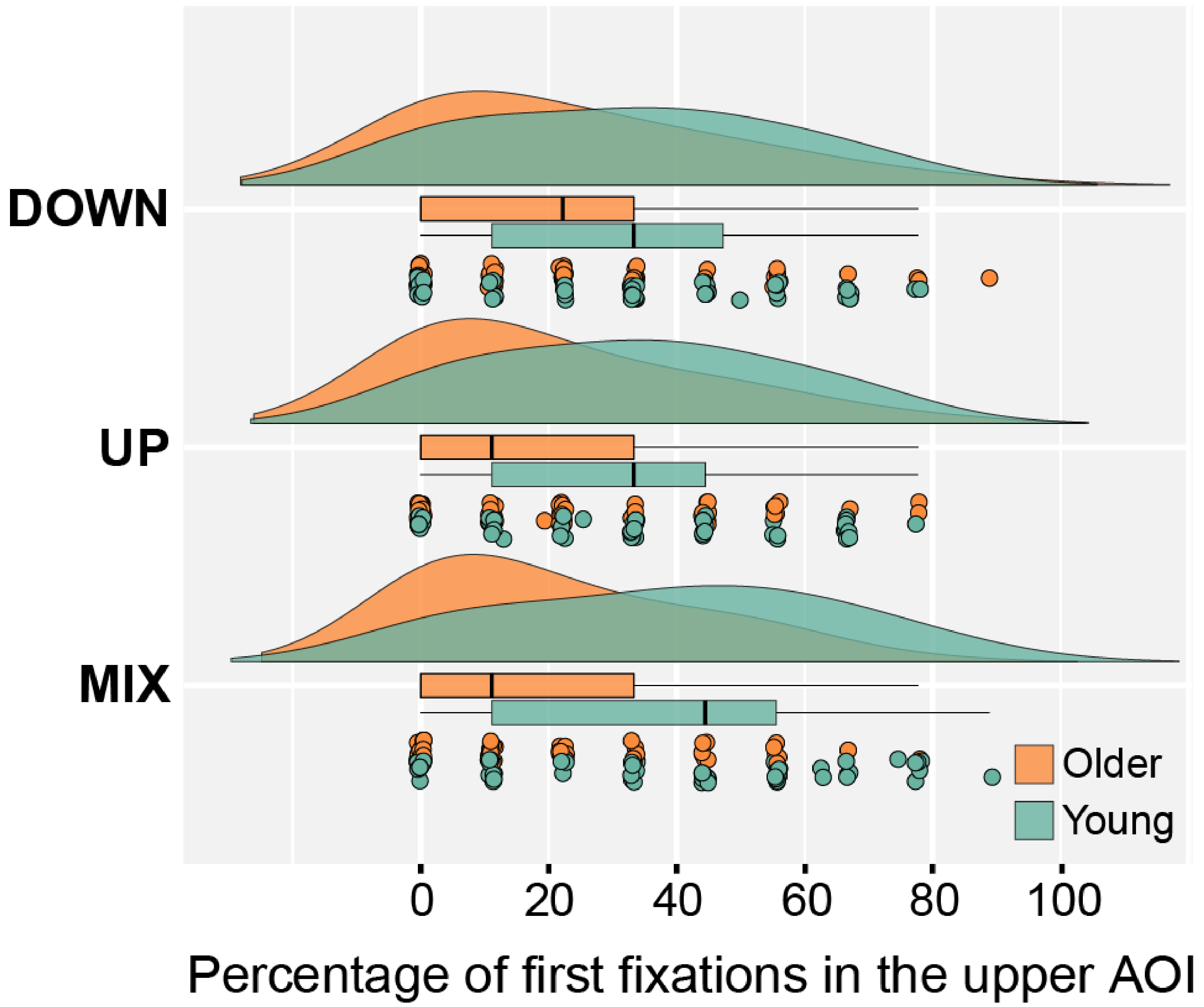
Behavioural results



Study 4

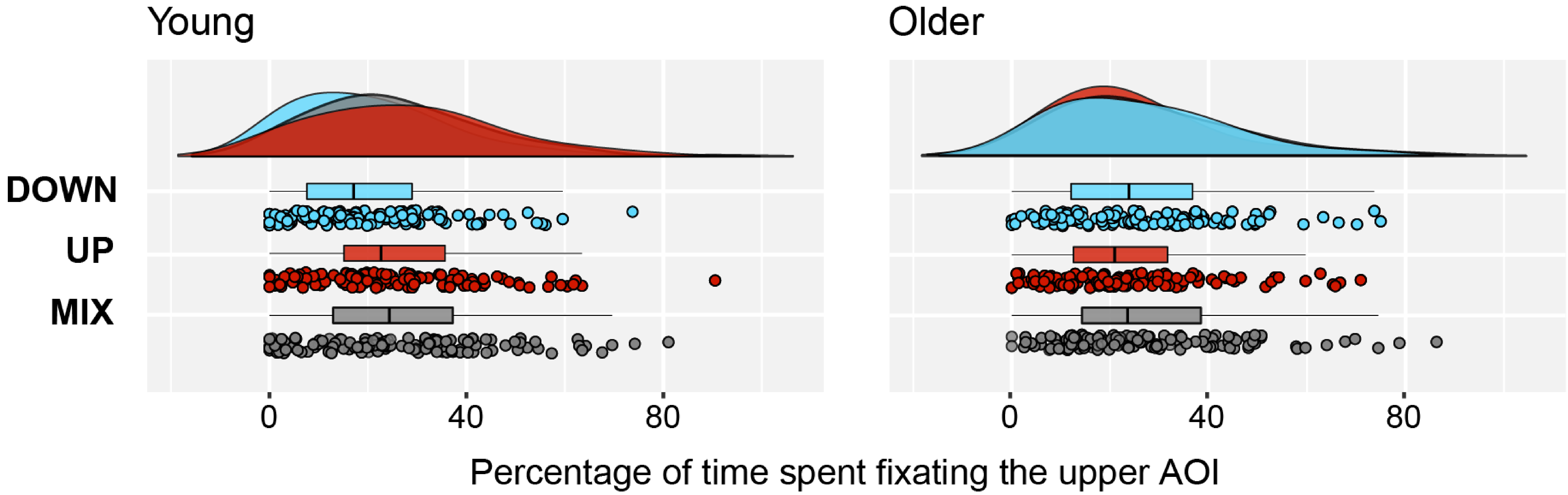
Eye tracking results





Study 4

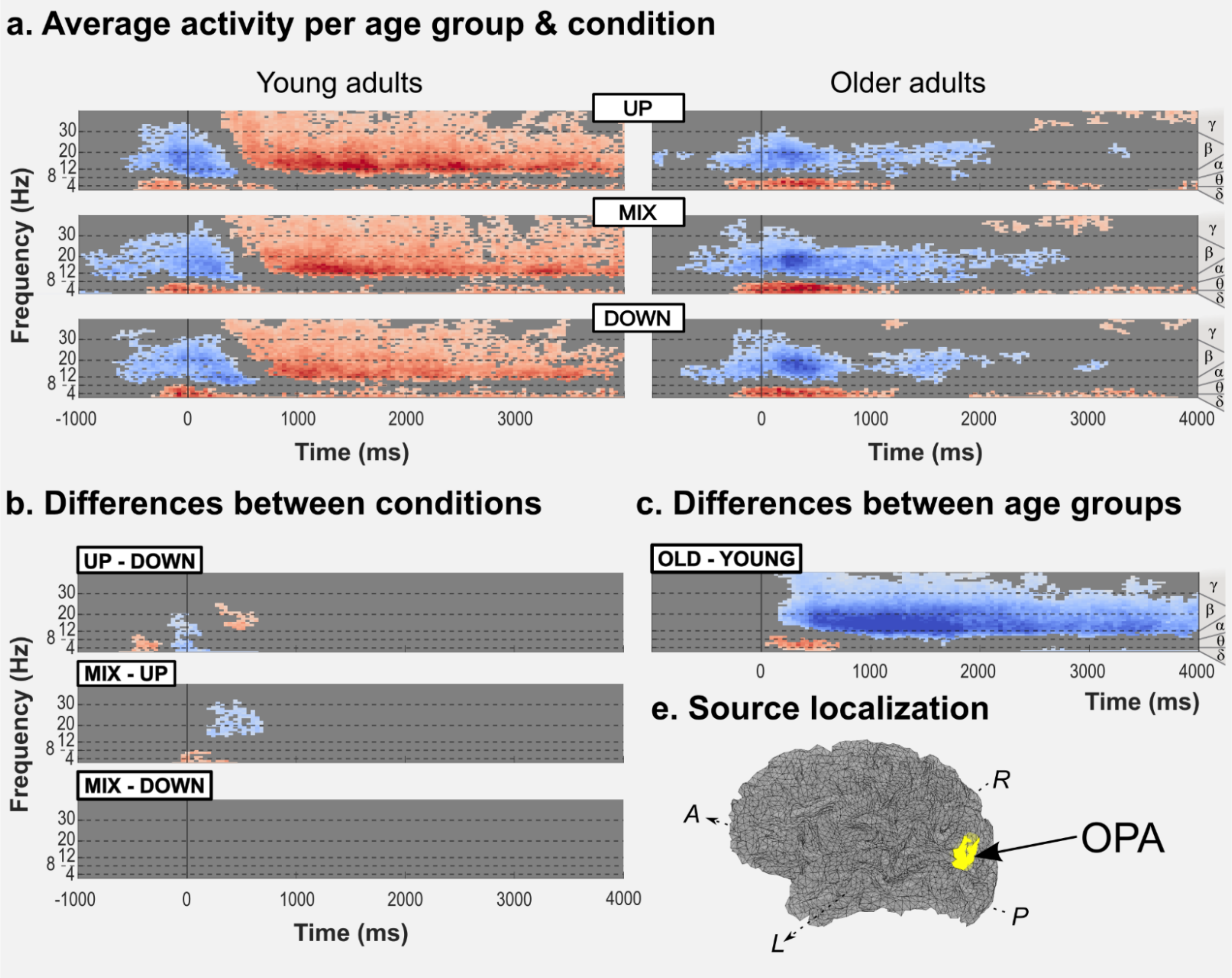
Eye tracking results



Young adults modulate their gaze patterns to the upper AOI according to the condition.

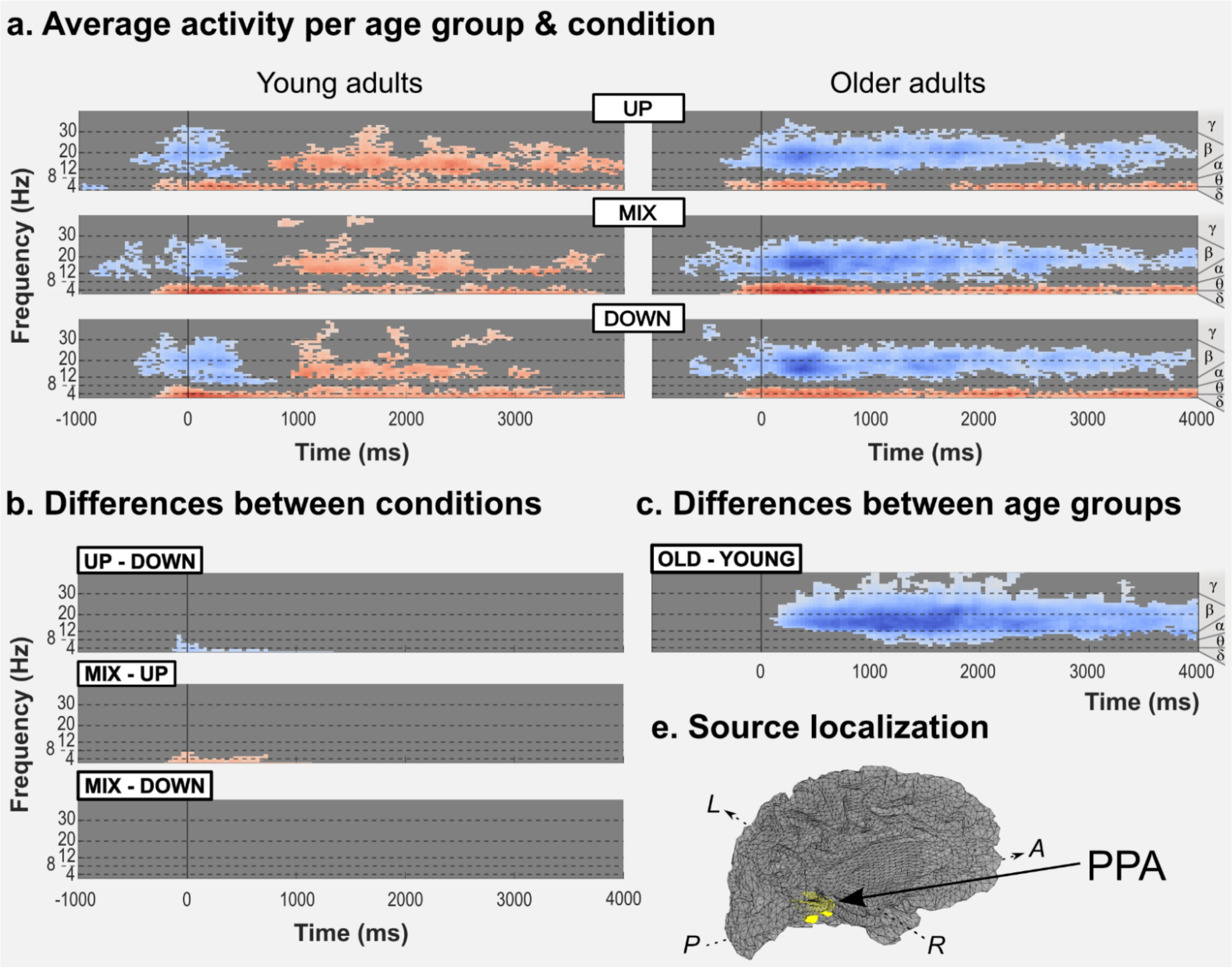
Study 4

EEG results



Study 4

EEG results



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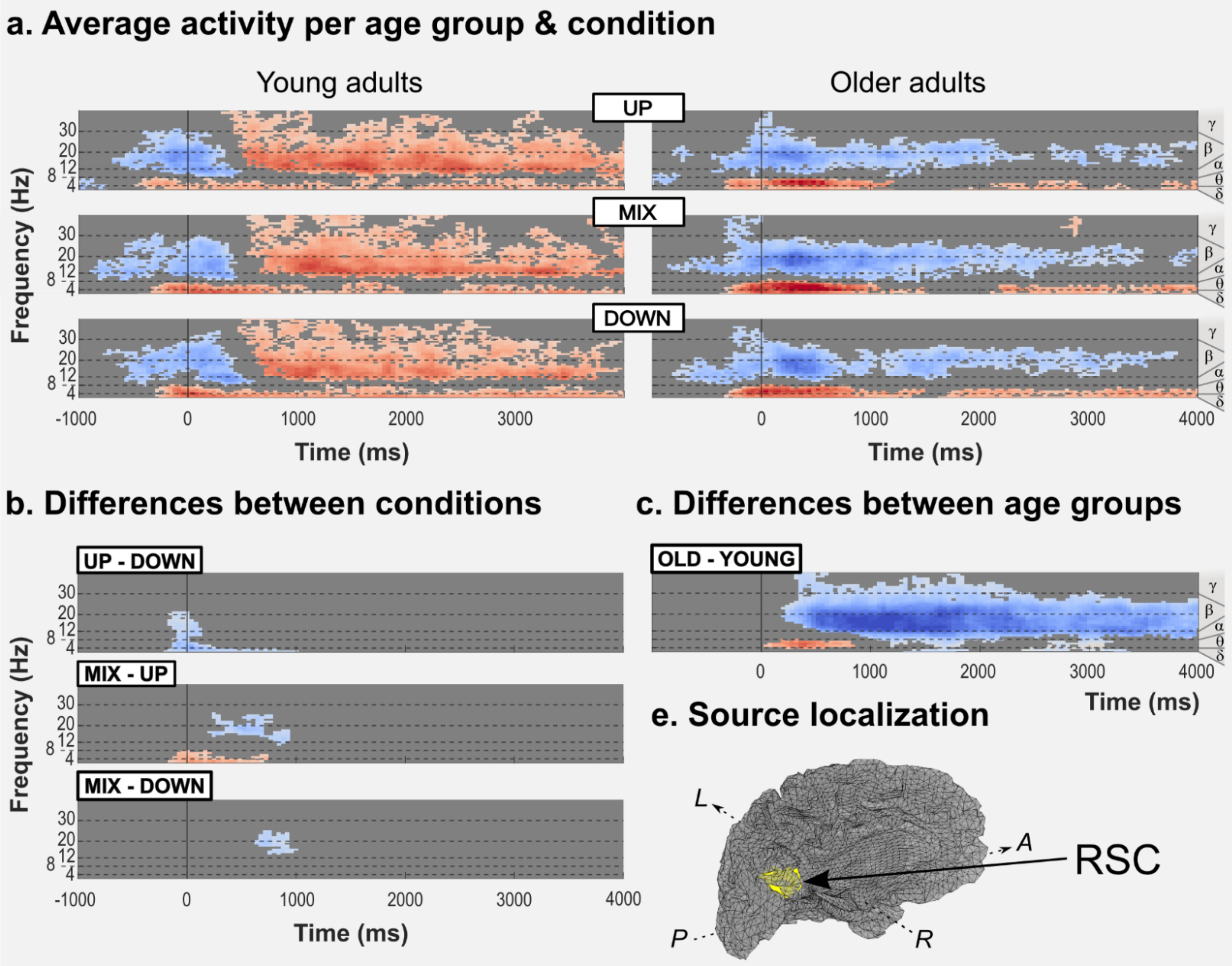
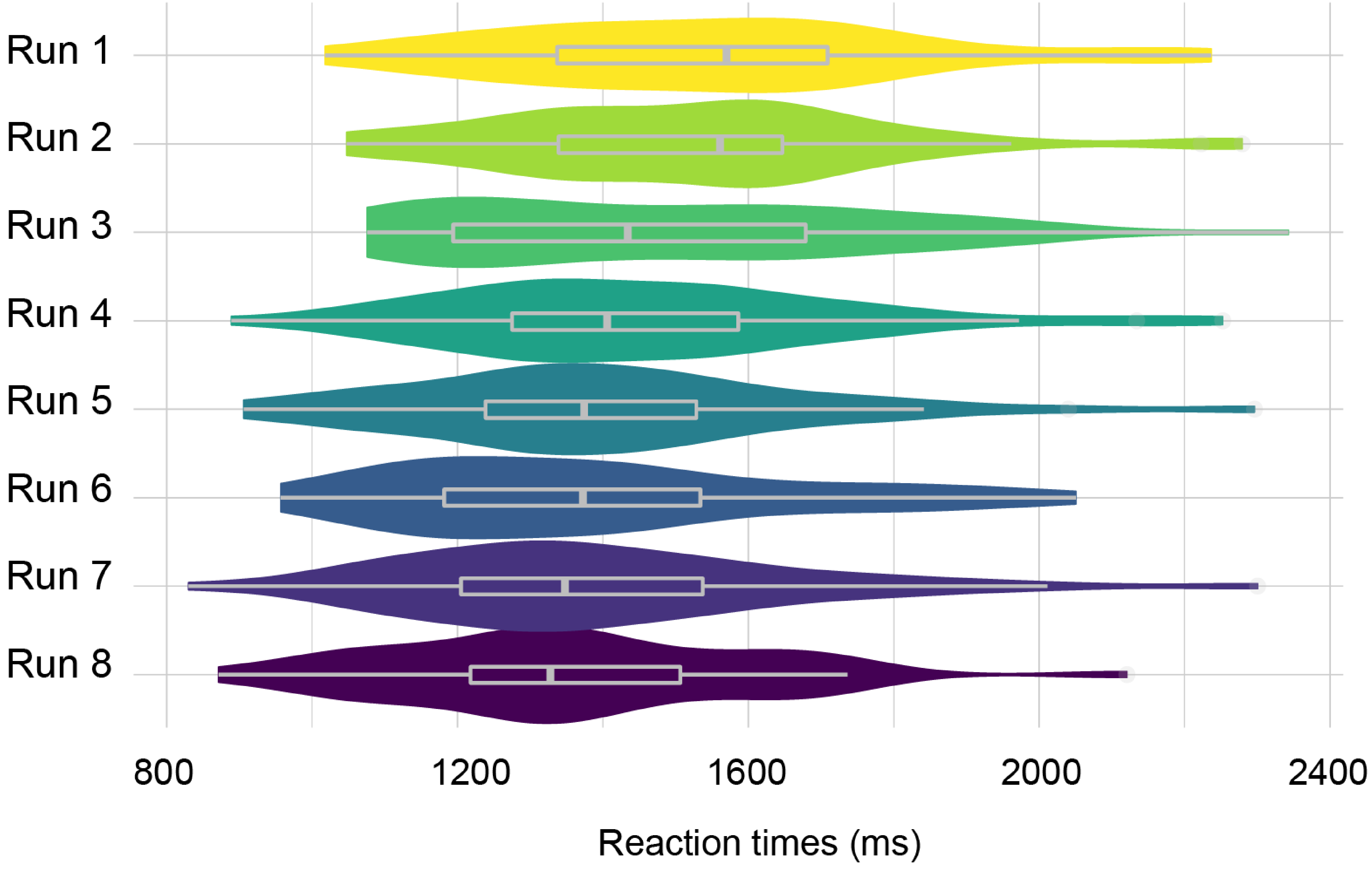
EEG results



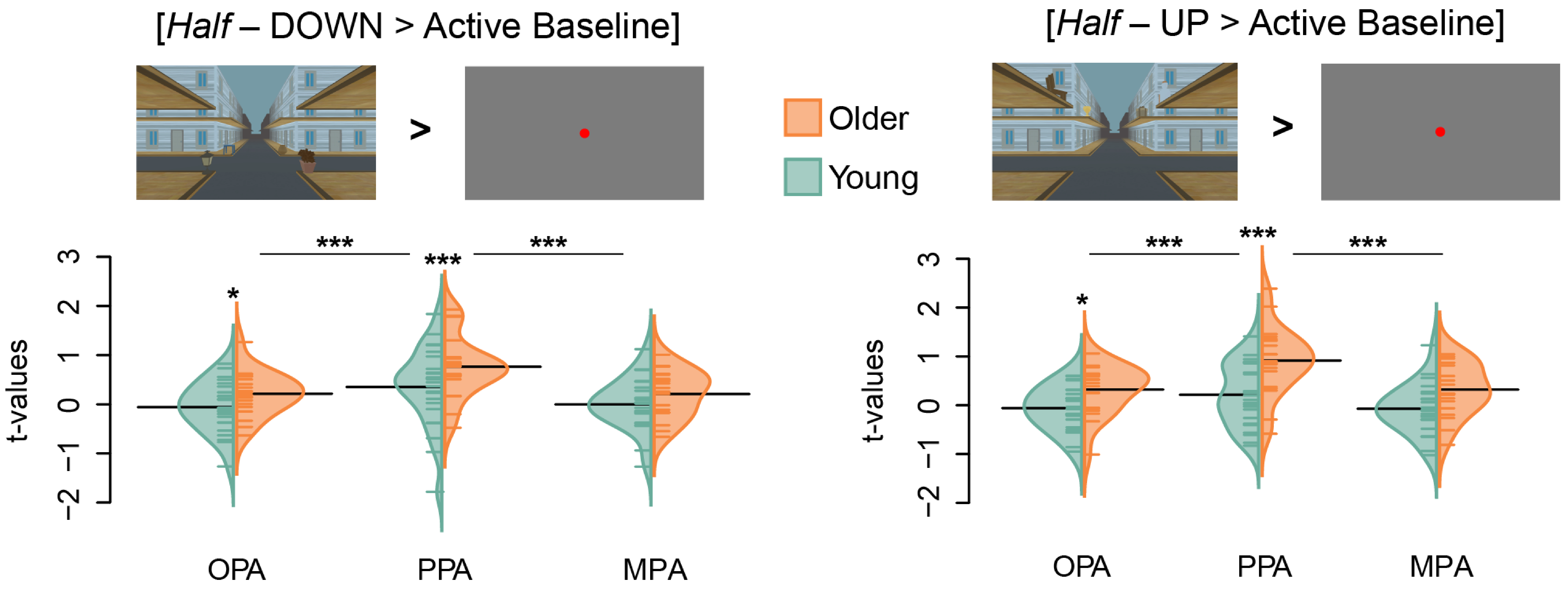
Study 5

Behavioural results



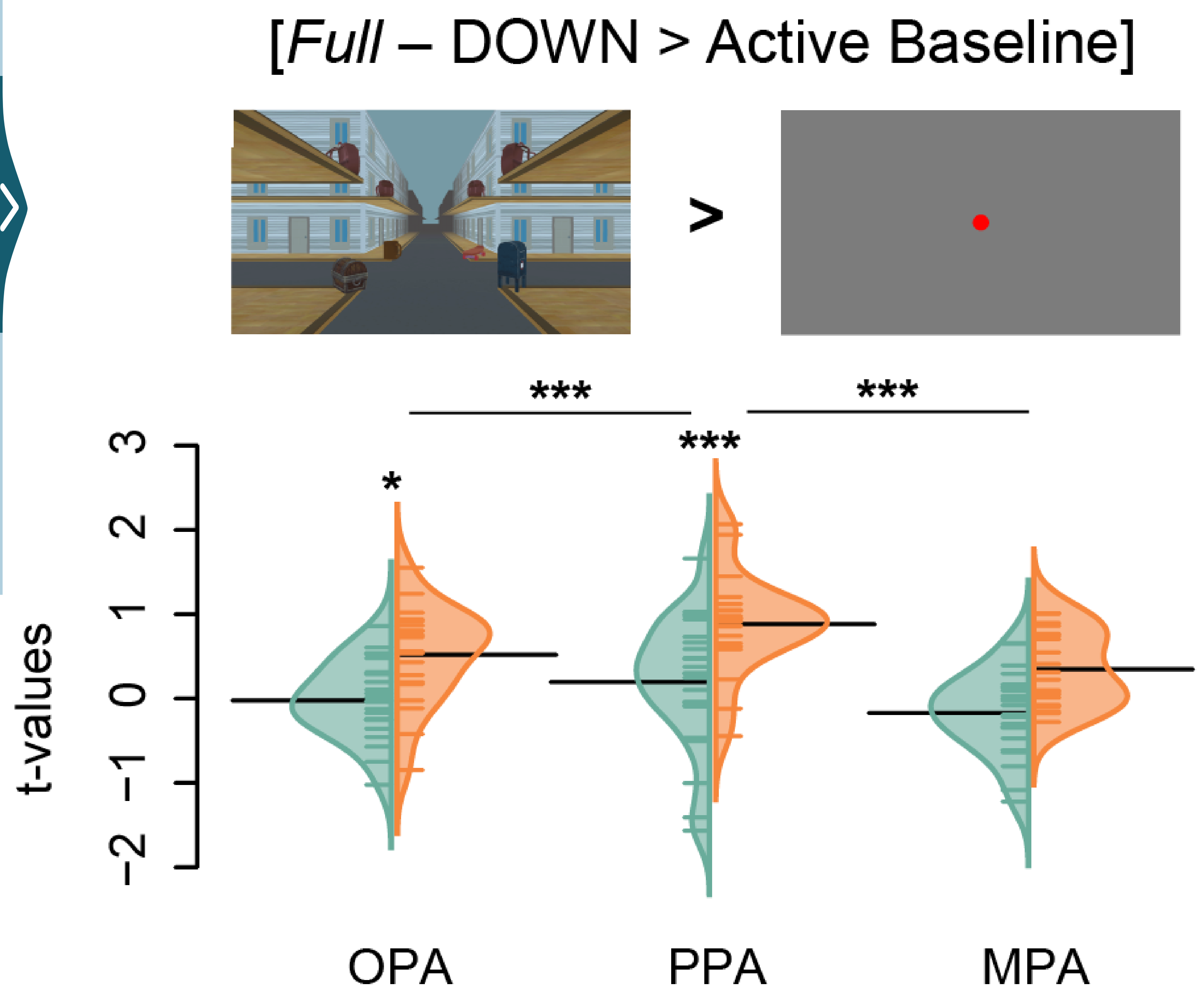
Study 5

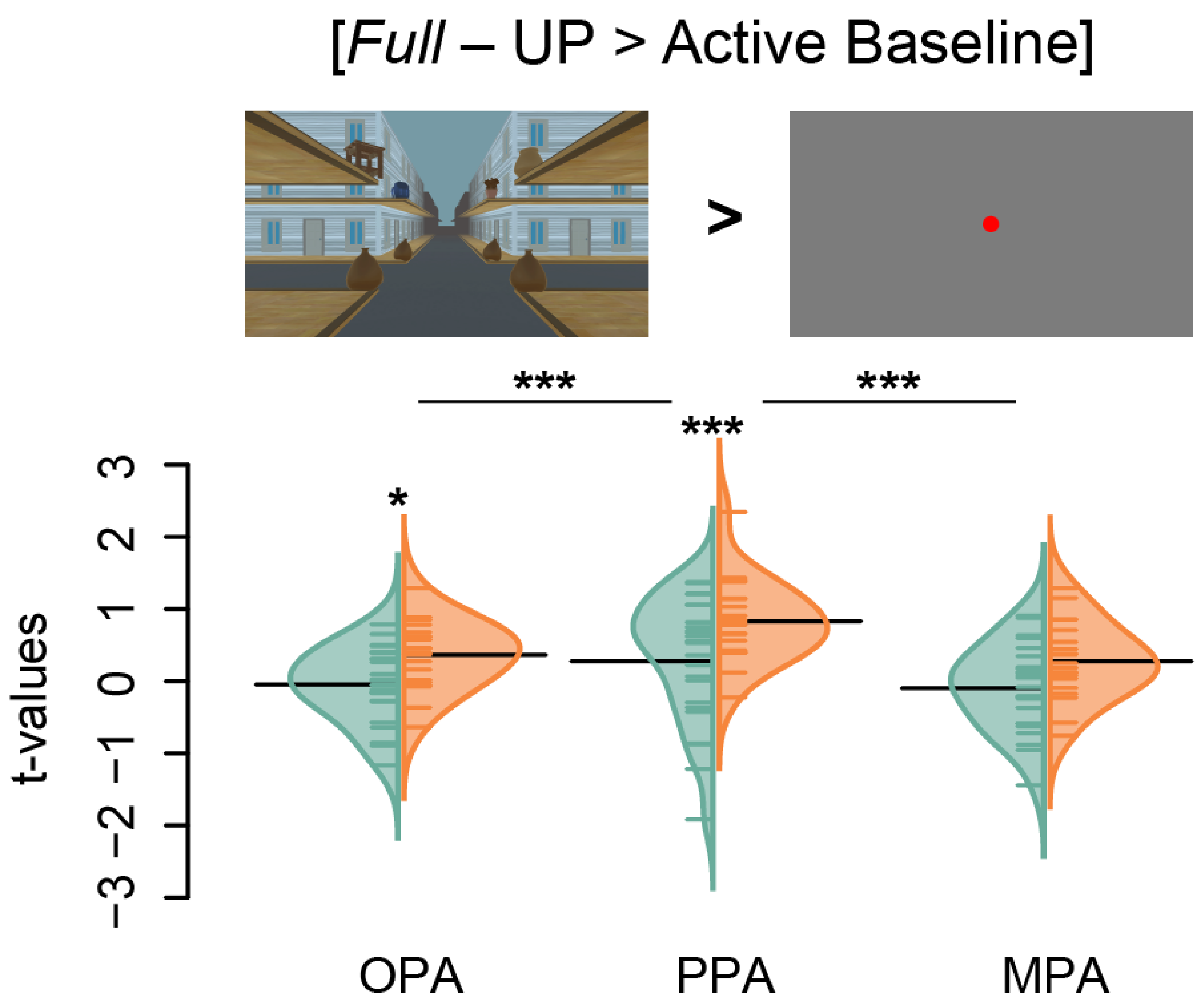
Neuroimaging results



Study 5

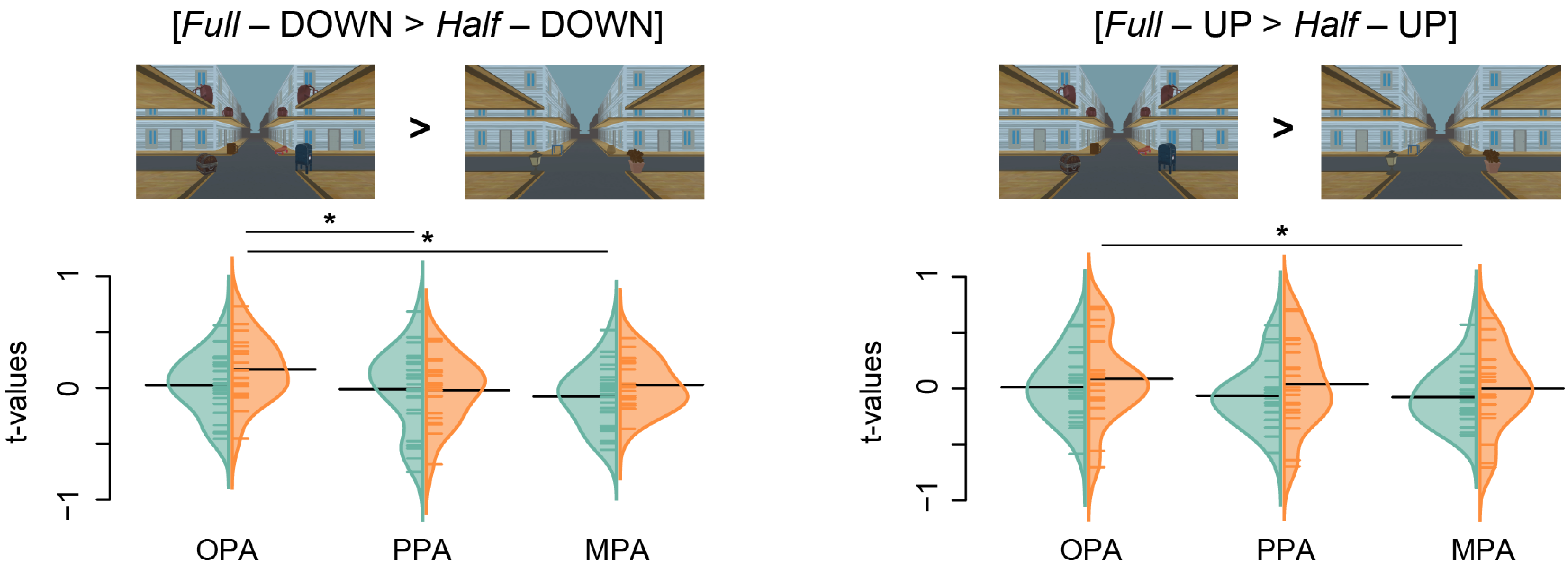
Neuroimaging results





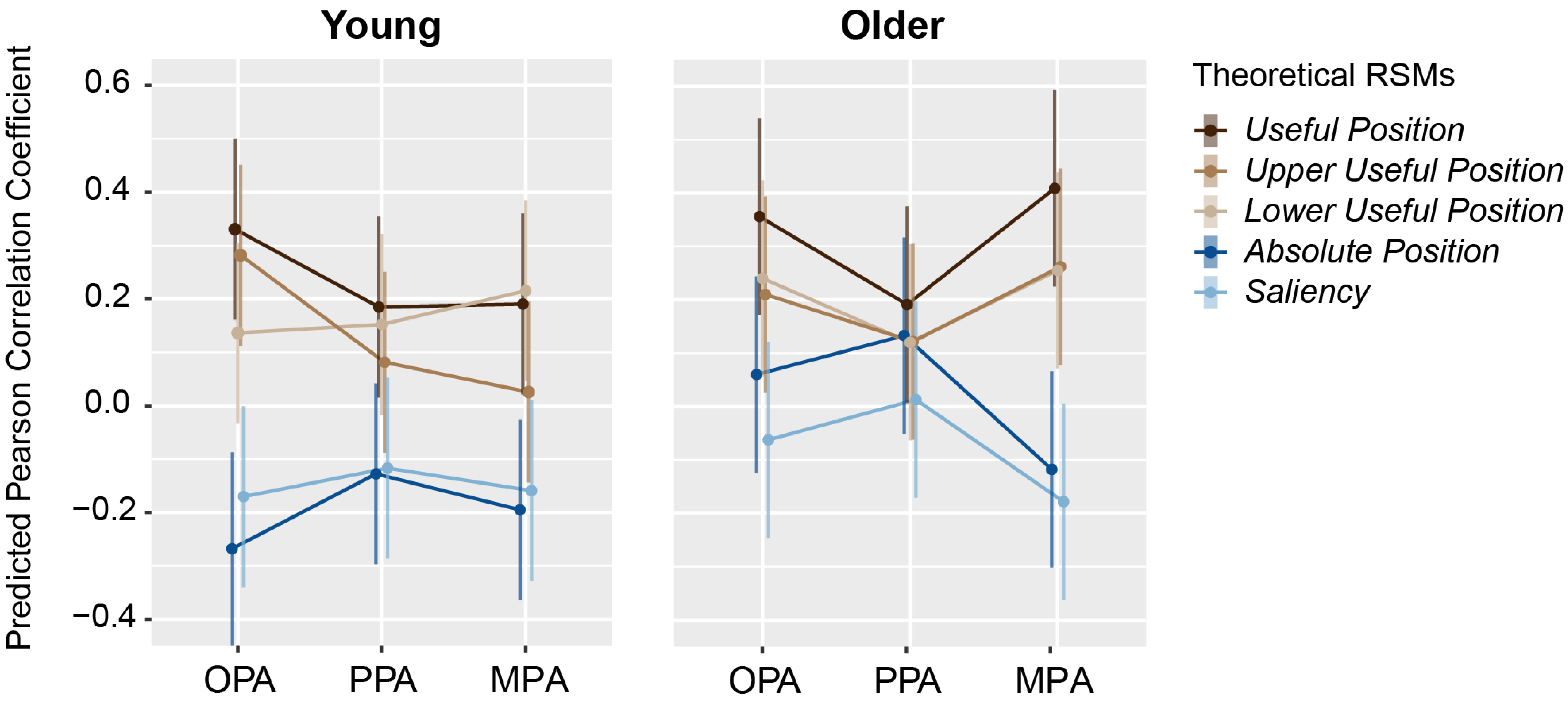
Study 5

Neuroimaging results



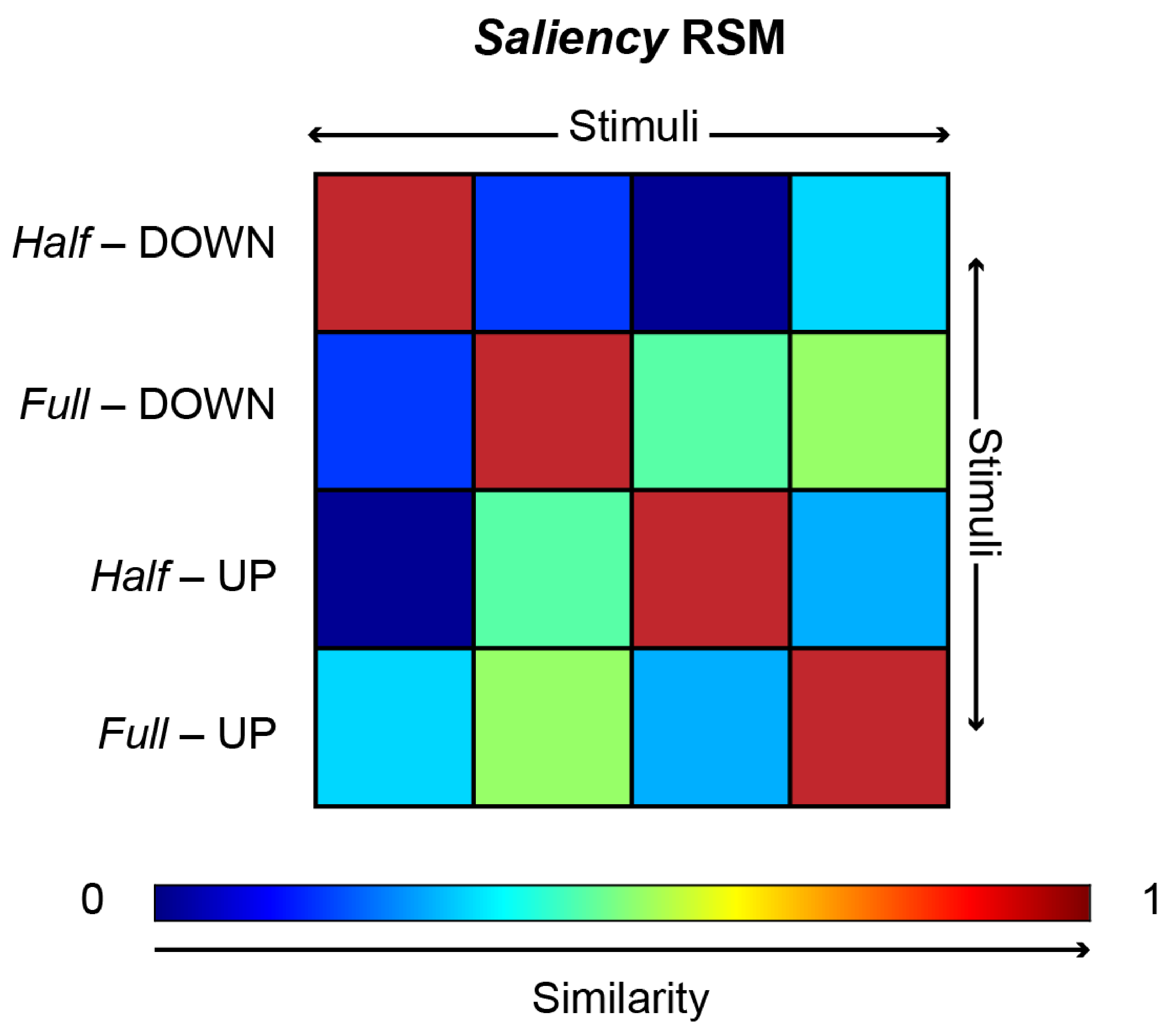
Study 5

Neuroimaging results



Study 5

Neuroimaging results



Study 5

Neuroimaging results

	OPA	PPA	MPA
Absolute Position > Useful Position	t(266) = -2.23 *p* = 0.62	t(266) = -0.44 *p* = 1.00	t(266) = -4.02 *p* = 0.0066
Absolute Position > Upper Useful Position	t(266) = -1.15 *p* = 1.00	t(266) = 0.086 *p* = 1.00	t(266) = -2.90 *p* = 0.20
Absolute Position > Lower Useful Position	t(266) = -1.38 *p* = 0.99	t(266) = 0.098 *p* = 1.00	t(266) = -2.84 *p* = 0.23
Absolute Position > Saliency	t(266) = 0.93 *p* = 1.00	t(266) = 0.92 *p* = 1.00	t(266) = 0.46 *p* = 1.00
Useful Position > Upper Useful Position	t(266) = 1.11 *p* = 1.00	t(266) = 0.53 *p* = 1.00	t(266) = 1.12 *p* = 1.00
Useful Position > Lower Useful Position	t(266) = 0.88 *p* = 1.00	t(266) = 0.54 *p* = 1.00	t(266) = 1.17 *p* = 1.00
Useful Position > Saliency	t(266) = 3.19 *p* = 0.098	t(266) = 1.36 *p* = 0.99	t(266) = 4.48 *p* = 0.0011
Upper Useful Position > Lower Useful Position	t(266) = -0.23 *p* = 1.00	t(266) = 0.012 *p* = 1.00	t(266) = 0.053 *p* = 1.00
Upper Useful Position > Saliency	t(266) = 2.08 *p* = 0.75	t(266) = 0.83 *p* = 1.00	t(266) = 3.36 *p* = 0.061
Lower Useful Position > Saliency	t(266) = 2.31 *p* = 0.58	t(266) = 0.82 *p* = 1.00	t(266) = 3.31 *p* = 0.071

Results from post-hoc tests of the linear mixed models looking at theoretical RSMs in **young** adults.

Study 5

Neuroimaging results

	OPA	PPA	MPA
Absolute Position > Useful Position	t(266) = -2.23 p = 0.62	t(266) = -0.44 p = 1.00	t(266) = -4.02 p = 0.0066
Absolute Position > Upper Useful Position	t(266) = -1.15 p = 1.00	t(266) = 0.086 p = 1.00	t(266) = -2.90 p = 0.20
Absolute Position > Lower Useful Position	t(266) = -1.38 p = 0.99	t(266) = 0.098 p = 1.00	t(266) = -2.84 p = 0.23
Absolute Position > Saliency	t(266) = 0.93 p = 1.00	t(266) = 0.92 p = 1.00	t(266) = 0.46 p = 1.00
Useful Position > Upper Useful Position	t(266) = 1.11 p = 1.00	t(266) = 0.53 p = 1.00	t(266) = 1.12 p = 1.00
Useful Position > Lower Useful Position	t(266) = 0.88 p = 1.00	t(266) = 0.54 p = 1.00	t(266) = 1.17 p = 1.00
Useful Position > Saliency	t(266) = 3.19 p = 0.098	t(266) = 1.36 p = 0.99	t(266) = 4.48 p = 0.0011
Upper Useful Position > Lower Useful Position	t(266) = -0.23 p = 1.00	t(266) = 0.012 p = 1.00	t(266) = 0.053 p = 1.00
Upper Useful Position > Saliency	t(266) = 2.08 p = 0.75	t(266) = 0.83 p = 1.00	t(266) = 3.36 p = 0.061
Lower Useful Position > Saliency	t(266) = 2.31 p = 0.58	t(266) = 0.82 p = 1.00	t(266) = 3.31 p = 0.071

Results from post-hoc tests of the linear mixed models looking at theoretical RSMs in **older** adults.

Study 5

Neuroimaging results

	F-test	*p*-value	ES [95%-CI]
Half - DOWN x *Full* - DOWN **vs.** *Half* - UP x *Half* - DOWN	$F(1, 778) = 12.26$	$p < 0.001$	0.016 [0.0030, 0.037]
Half - DOWN x *Full* - DOWN **vs.** *Half* - DOWN x *Full* - UP	$F(1, 778) = 35.16$	$p < 0.001$	0.043 [0.020, 0.074]
Half - DOWN x *Full* - DOWN **vs.** *Half* - UP x *Full* - DOWN	$F(1, 778) = 29.60$	$p < 0.001$	0.037 [0.015, 0.066]
Half - DOWN x *Full* - DOWN **vs.** *Full* - UP x *Full* - DOWN	$F(1, 778) = 21.44$	$p < 0.001$	0.027 [0.0090, 0.053]
Half - DOWN x *Full* - DOWN **vs.** *Half* - UP x *Full* - UP	$F(1, 778) = 0.16$	$p = 0.69$	0.00020 [0.00, 0.0067]
Half - UP x *Full* - UP **vs.** *Half* - UP x *Half* - DOWN	$F(1, 778) = 9.66$	$p = 0.0020$	0.012 [0.0017, 0.032]
Half - UP x *Full* - UP **vs.** *Full* - UP x *Half* - DOWN	$F(1, 778) = 30.64$	$p < 0.001$	0.038 [0.016, 0.068]
Half - UP x *Full* - UP **vs.** *Half* - UP x *Full* - DOWN	$F(1, 778) = 25.47$	$p < 0.001$	0.032 [0.012, 0.060]
Half - UP x *Full* - UP **vs.** *Full* - UP x *Full* - DOWN	$F(1, 778) = 17.94$	$p < 0.001$	0.023 [0.0065, 0.047]
Full - DOWN x *Full* - UP **vs.** *Half* - DOWN x *Half* - UP	$F(1, 778) = 1.26$	$p = 0.26$	0.0016 [0.00, 0.012]

Results from post-hoc tests of the overall linear mixed model looking at the effects of pairwise comparison.