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Functional activity and connectivity during ideation in professional product design engineers

專業產品設計工程師構思過程中的功能活動與連接性

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Author Introduction

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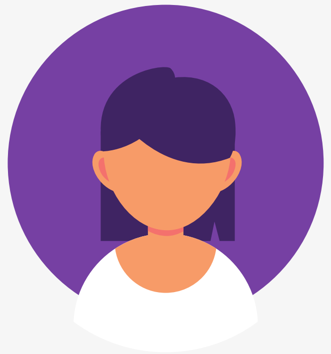

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Context

Products that reduce household food waste

- What does the product look like?
- How do users use it?
- What are its functions?
- Is this product innovative and feasible enough?

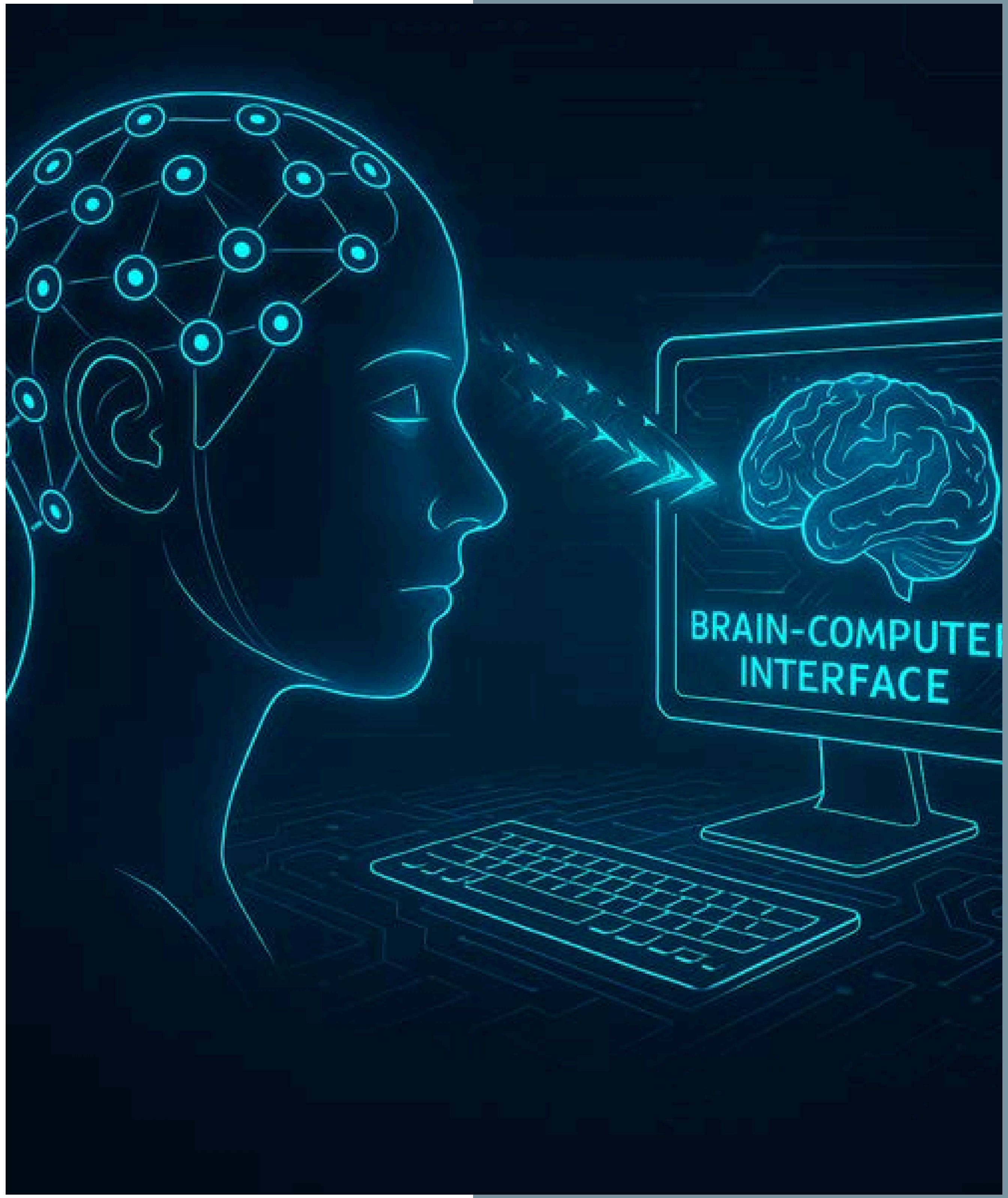
Background

What is ideation in product design engineering?

- Ideation involves generating ideas for new products that meet functional requirements.
- It is a process of producing candidate ideas in order to progressively refine a final design that can be manufactured.

The importance of studying brain activity:

- It helps to develop cognitive theories that explain and predict designer behavior.
- It also supports the development of brain-computer interface (BCI) tools for product design engineering practice, such as providing neurofeedback to sustain effective ideation performance, or enabling seamless realization of imagination in digital environments.



Background：Key Concepts and Brain Networks

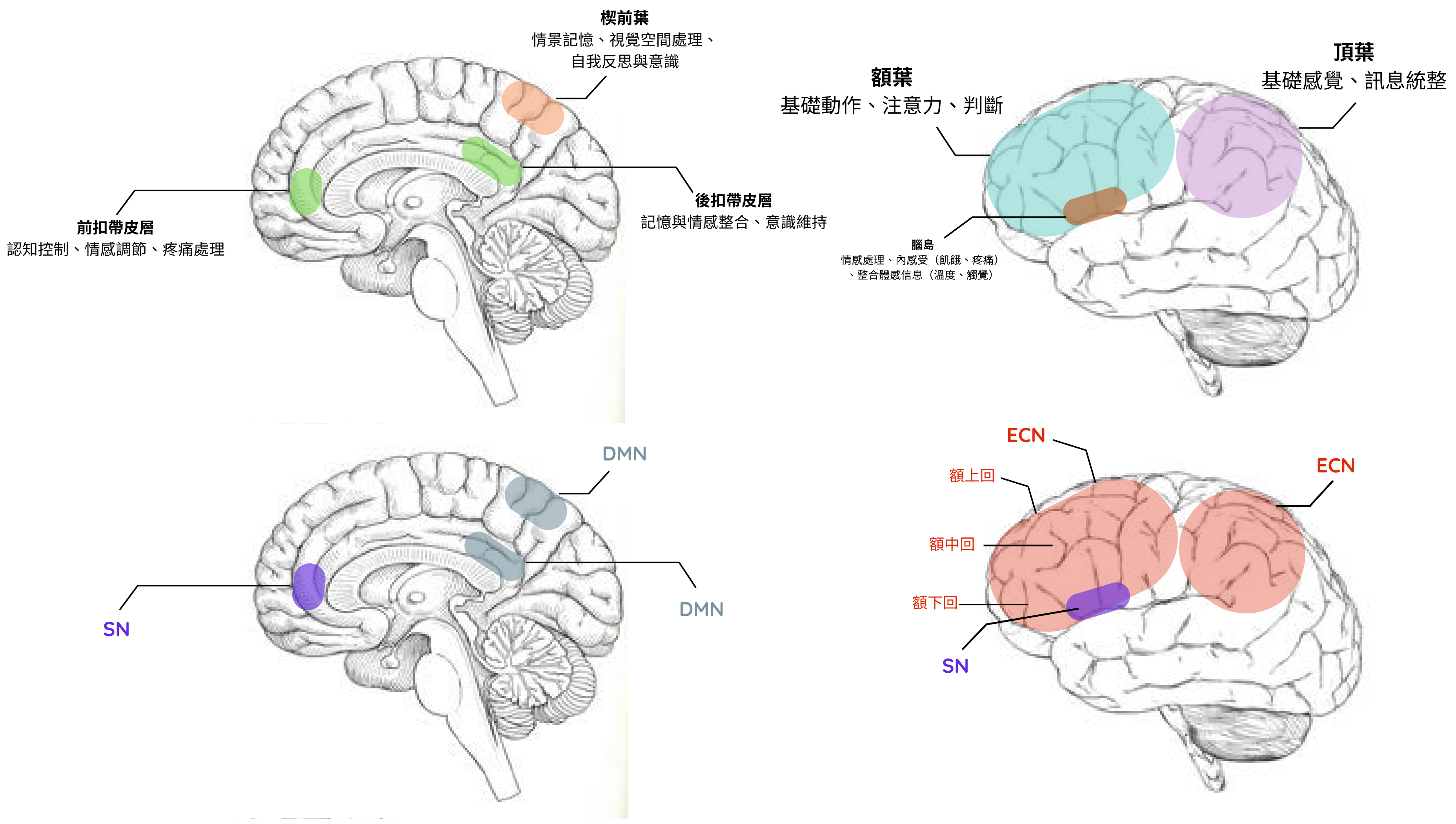
Functional Connectivity：

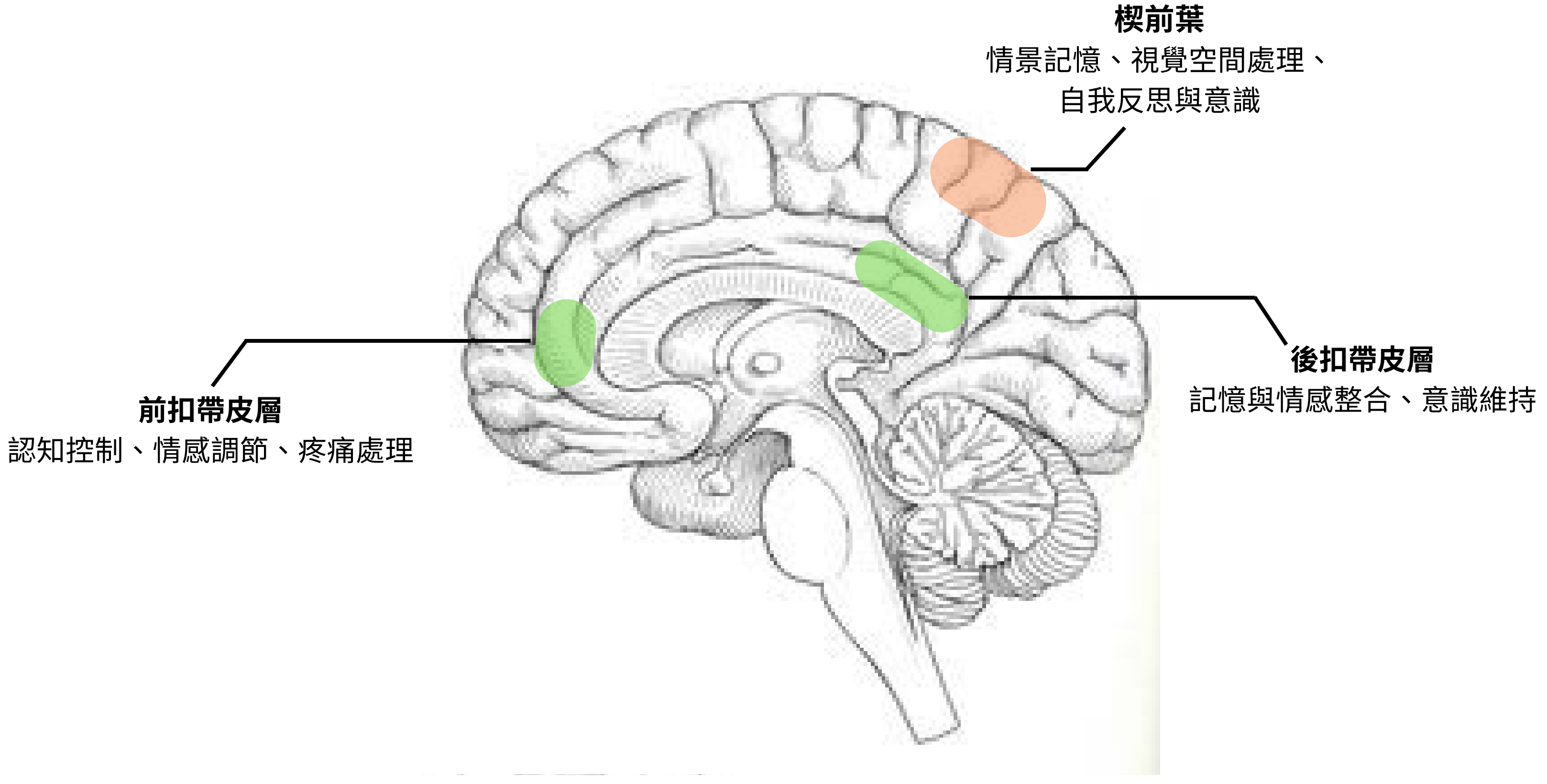
- Describes how strongly different brain regions are connected during activity.
- Even at rest, some regions consistently show strong, reliable correlations → part of larger brain networks.

Creative Cognition & Brain Networks

Generating novel and useful ideas involves three major brain networks:

1. Default Mode Network (DMN)
    - Supports spontaneous, associative thought
    - Involves mental simulation, memory, perspective-taking
2. Executive Control Network (ECN)
    - Supports top-down, analytical thinking
    - Involves evaluation, decision-making
3. Salience Network (SN)
    - Detects task-relevant stimuli
    - Acts as a gate between DMN & ECN

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自我反思與意識
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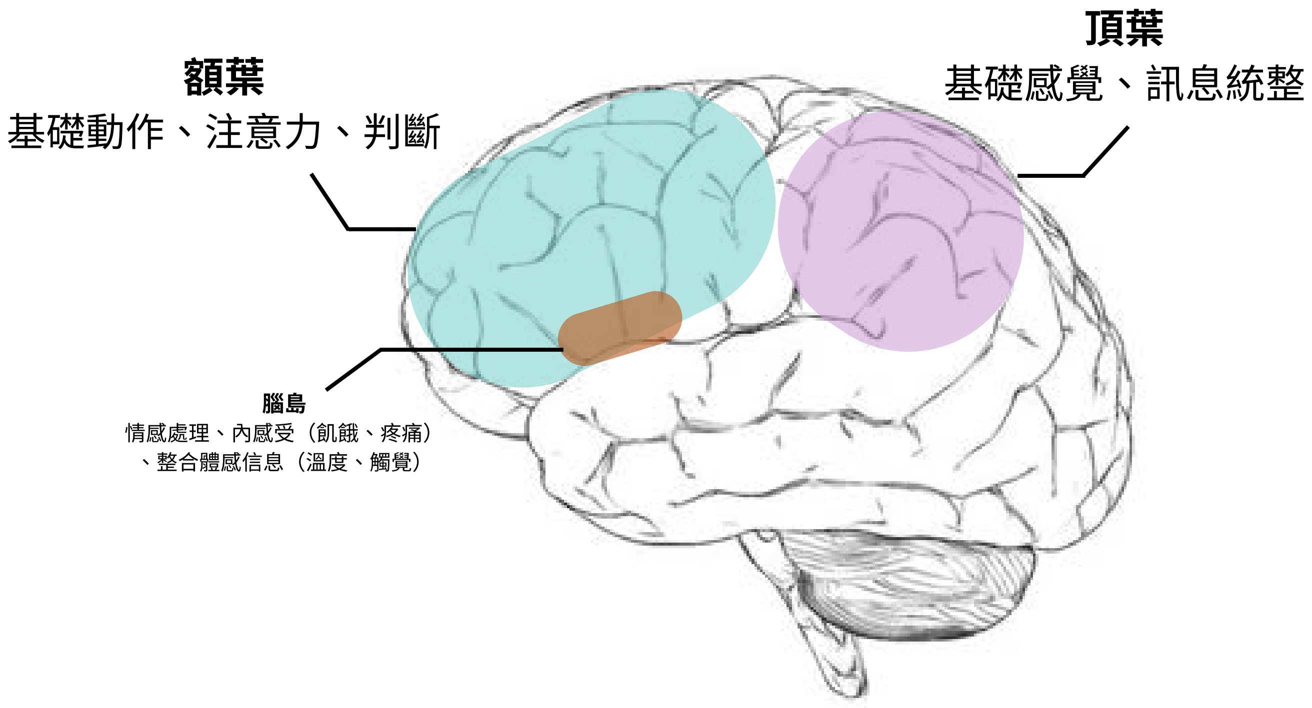
後扣帶皮層
記憶與情感整合、意識維持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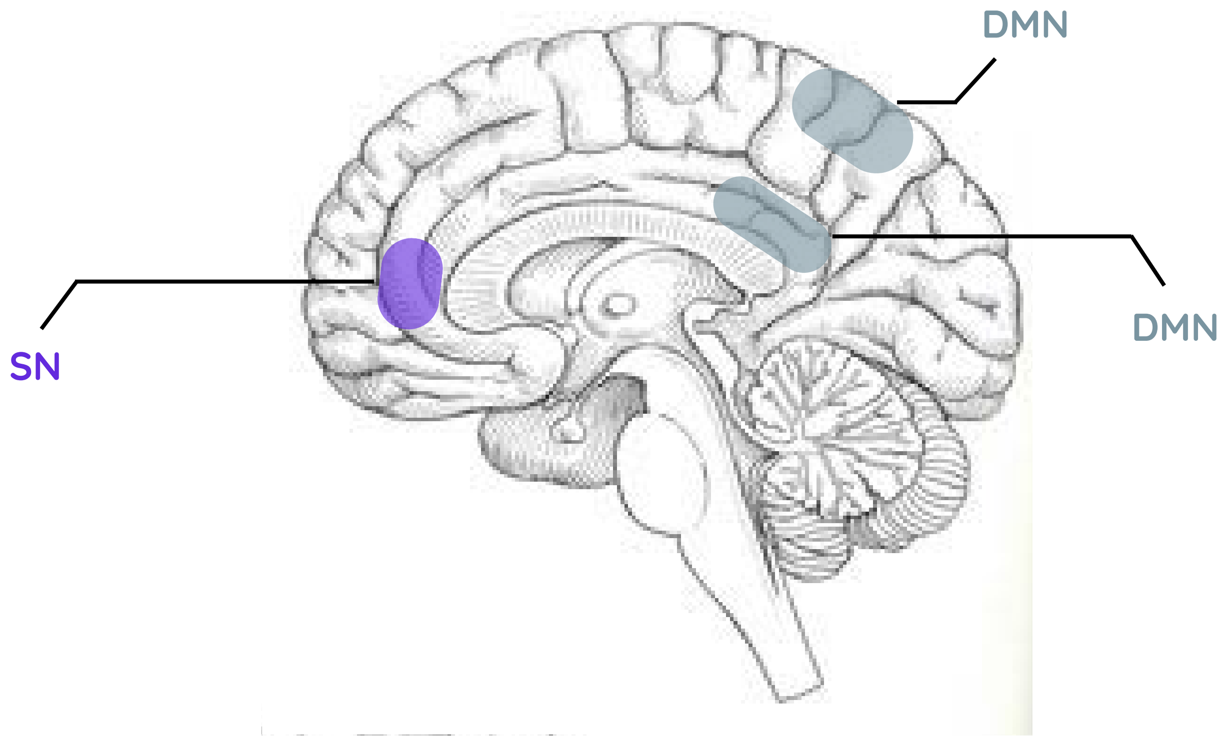
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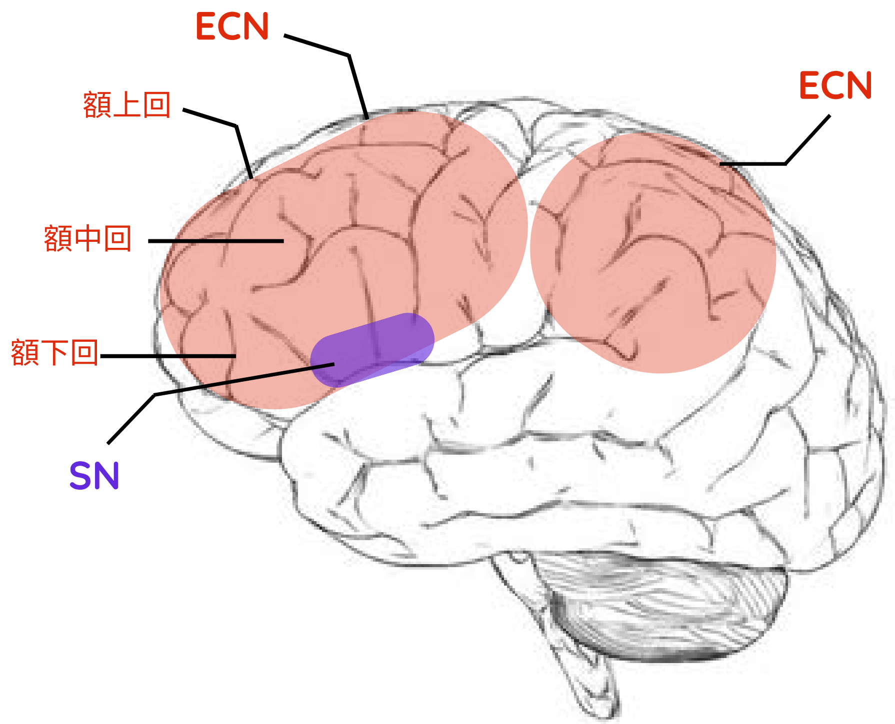
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Research objectives and methods

Objective:

- To explore functional activity and connectivity in professional product design engineers during the ideation process using functional magnetic resonance imaging (fMRI),
- with a particular focus on how different brain regions functionally interact.

Participants

- 32 professional product design engineers (final sample n=30), right-handed, no history of neurological impairment.
- At least 2 years of professional experience (mean = 9.95 years).

Study Design

Event-related fMRI design with four conditions:

- Design Ideation
- Working Memory (2-back task)
- Visuospatial Processing (Mental rotation task)
- Baseline (Rest)

Experimental Procedure

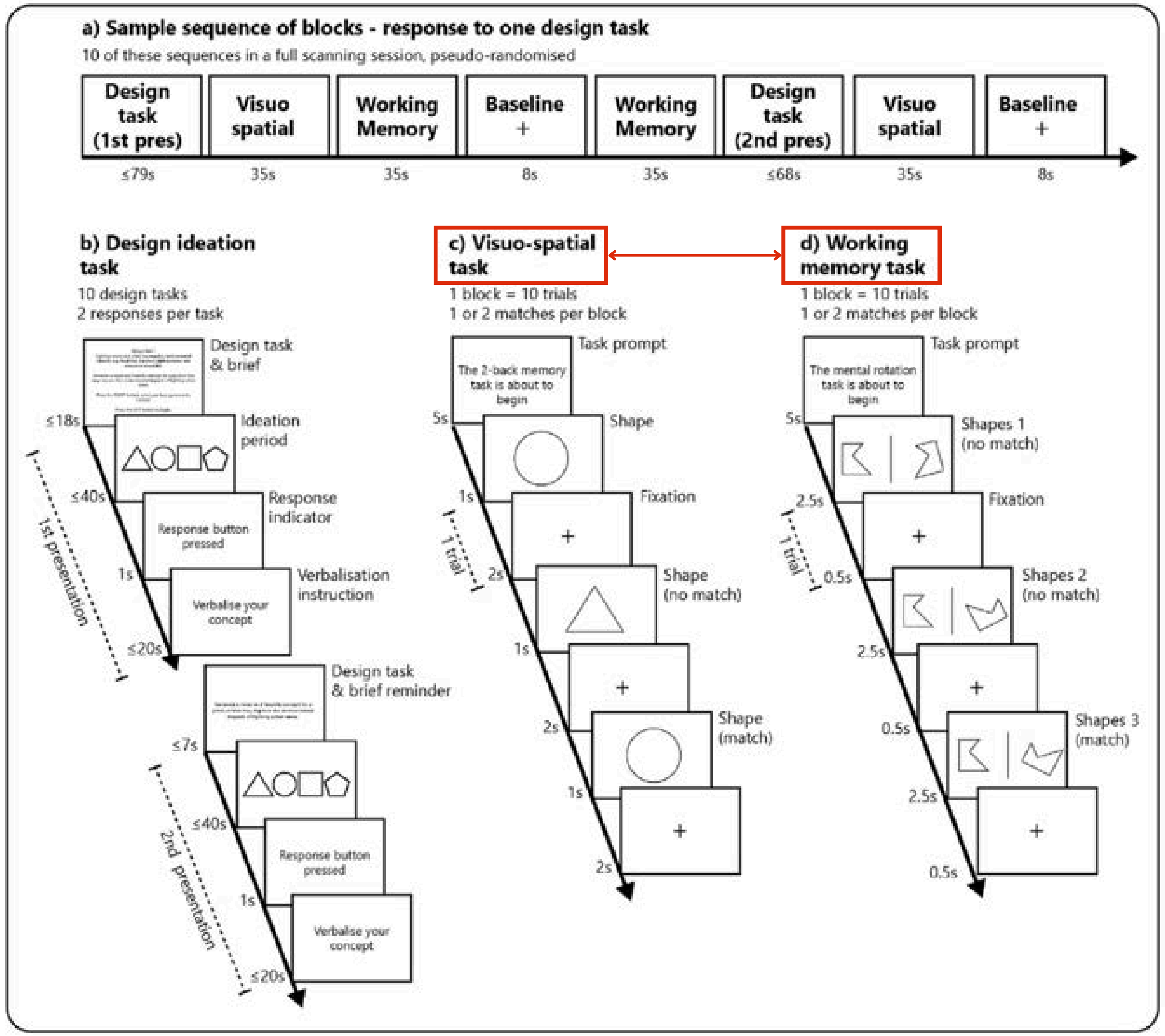


Figure 1 Illustrated procedures for each of the four tasks

Study Design

Table 1 Design briefs used in the design ideation task

#	*Design brief*
1	The use of mains water in gardening is often limited in summer due to low rainfall and droughts. Generate concepts for novel and feasible products that may reduce the mains water consumption associated with gardening.
2	Domestic food waste is a serious problem due to global food shortages and socio-economic imbalances. Generate concepts for novel and feasible products that may reduce unnecessary food wastage in the home.
3	Pets can become lonely or stressed when left alone for extended periods of time. Generate concepts for novel and feasible products that can improve the quality of life for pets who are left home alone for extended periods
4	Camping is a popular activity but can have negative environmental impacts through disruption to wildlife; litter and pollution of water sources. Generate concepts for novel and feasible products that reduce the negative impacts of camping.
5	Chores such as cooking and cleaning may be difficult for wheelchair users due to space and height limitations. Generate concepts for novel and feasible products that may facilitate domestic chores for wheelchair users.
6	Rain and wind make it difficult for pedestrians to keep dry and pose dangers e.g. slipping; falling trees. Generate concepts for novel and feasible products to reduce the discomfort and danger of poor weather for pedestrians.
7	Leaving personal belongings unattended while working in cafes may expose them to the risk of theft. Generate concepts for novel and feasible products that allow belongings to be secured in a public workspace for short periods.
8	Sitting in the same position for long periods may be harmful to health. Generate concepts for novel and feasible products that may facilitate physical exercise whilst completing activities in a seated position in the home and office.
9	Working while travelling may be noisy; full of distractions; and physically uncomfortable. Generate concepts for novel and feasible products that may reduce the difficulties associated with on the go working.
10	Dog excrement on pavements is unsightly and unhygienic but its disposal may be unpleasant and unhygienic for dog owners. Generate concepts for novel and feasible products that may improve dog excrement disposal for dog owners.

*Design briefs were adapted from Hay et al. (2019a) by adding 'novel and feasible' except for task 3 which is new.

Analysis Process

1. fMRI Data Collection and Preprocessing

- Siemens 3T MRI used to scan brain activity during ideation.
- Preprocessing steps (aligning and cleaning the data):
    - Spatial realignment (correcting for head movement across time)
    - Slice timing correction (aligning slices acquired at different times)
    - Normalization and smoothing (mapping each participant's brain to a standard MNI template and smoothing for comparison)
    - High-pass filtering (128s) to remove low-frequency noise

2. Standard Contrast Analysis (GLM and t-contrast)

- General Linear Model (GLM) used to model each participant's brain data.
- Main contrasts:
    - Ideation > Baseline (rest) → Identify brain regions more active during ideation than rest
    - Ideation > Working Memory
    - Ideation > Visuospatial Processing
- Conjunction contrast to isolate ideation-specific activity (excluding working memory and visuospatial effects).
- All results thresholded at FWE $p < 0.05$.

Analysis Process

3.Psychophysiological Interaction (PPI) Analysis

- Concept of PPI:
  - It’s not just about identifying which brain regions are active ("what lights up"), but also which regions are "talking" to each other during ideation.
  - Think of it like teamwork: The left prefrontal cortex isn’t working alone; it’s working with areas like the right prefrontal cortex and the cerebellum.
- How it works:
  - Identify ROIs (seed regions) → Brain areas showing strong activation during ideation (from contrast analysis).
  - Examine which other brain regions "light up together" (co-activate) with these seeds during ideation.
  - Use conjunction contrasts to ensure these connections are specific to ideation, not just due to working memory or visuospatial processes.

Examples of design concepts

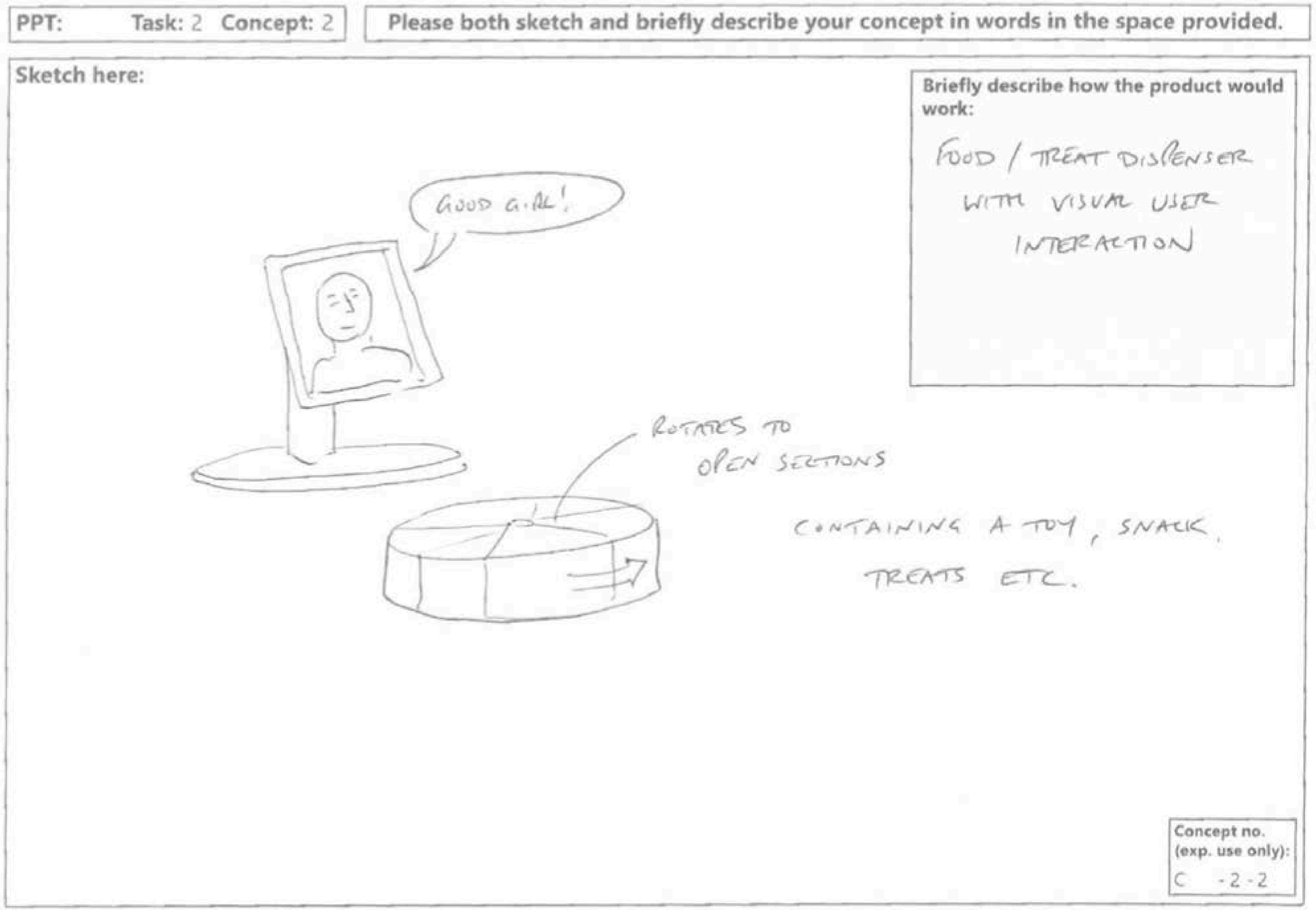
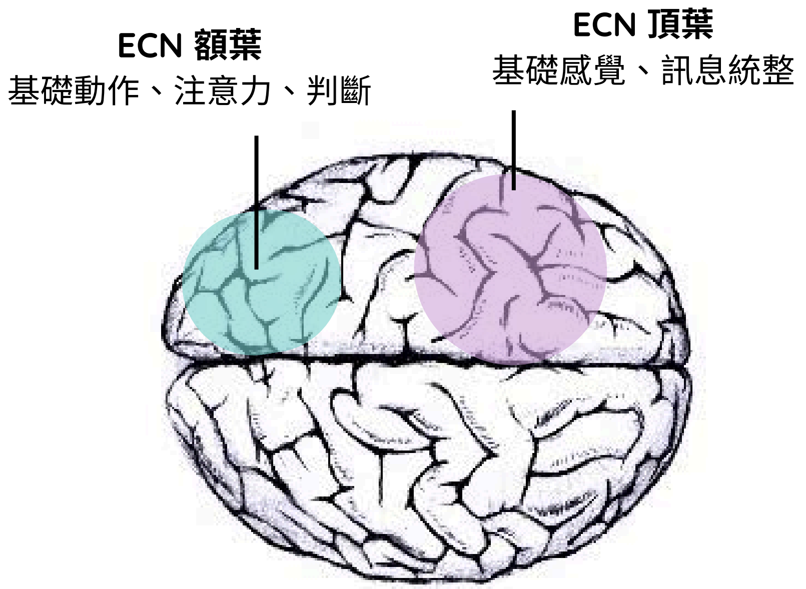
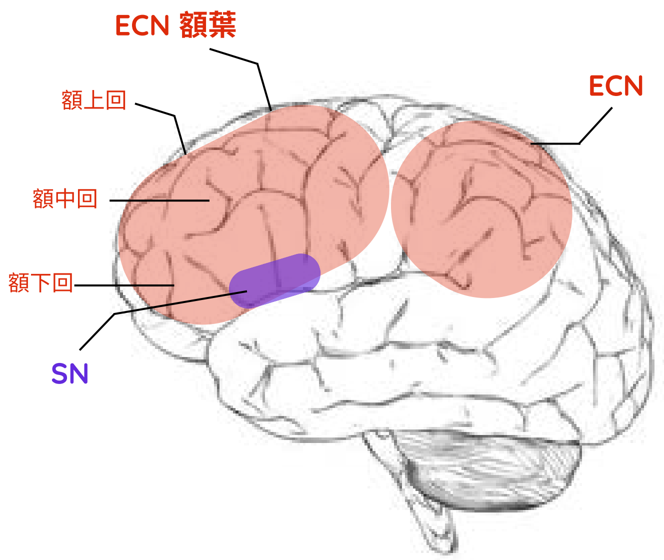


Figure 2 An example of a design concept produced by one of the designers. Participants were asked to "Generate concepts for novel and feasible products that can improve the quality of life for pets who are left home alone for extended periods"

Functional activity results (Ideation vs. Baseline)





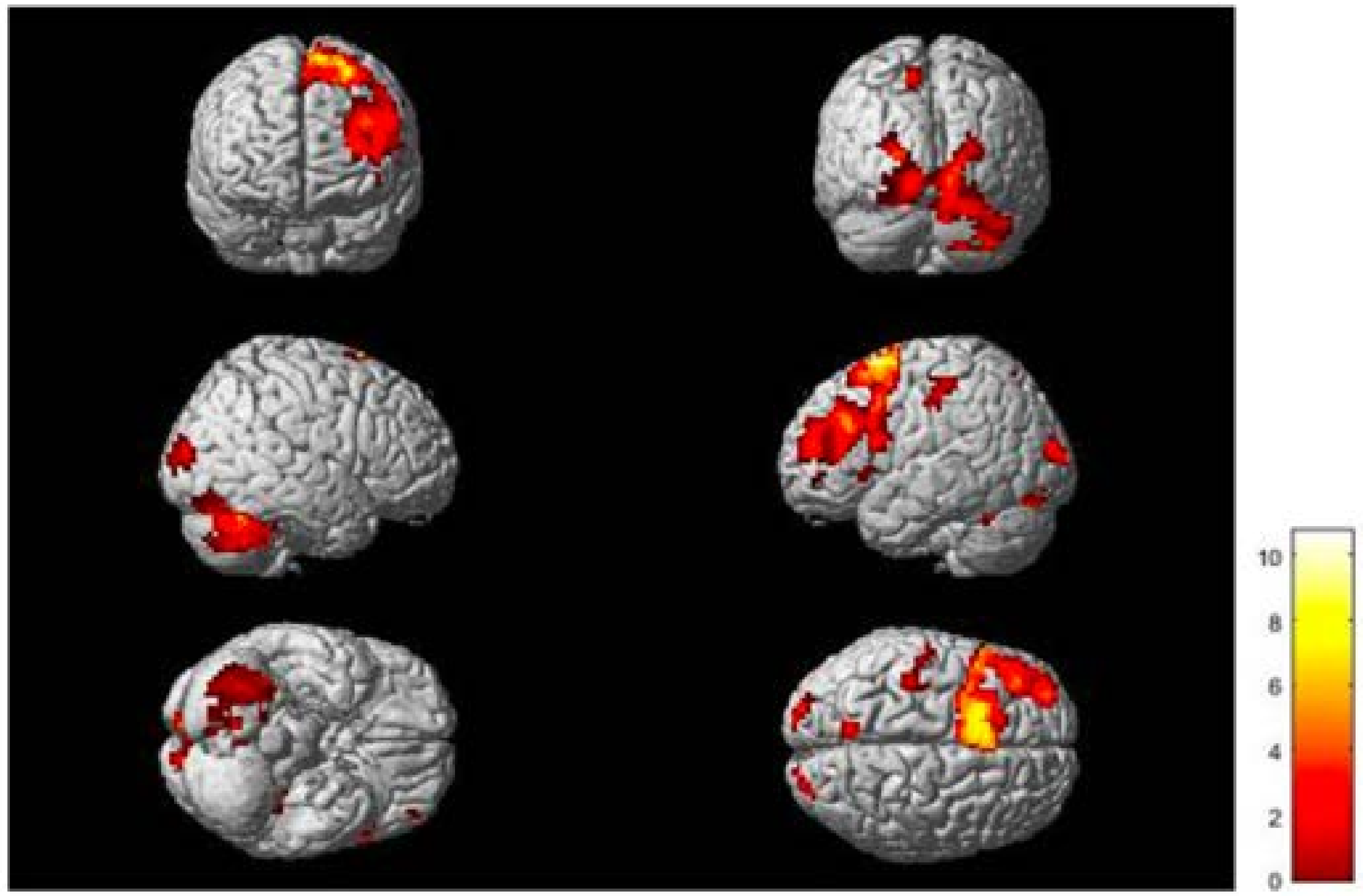


Figure 3 Regions showing significantly higher activation during ideation compared with baseline. Colours indicate effect size (t-value).

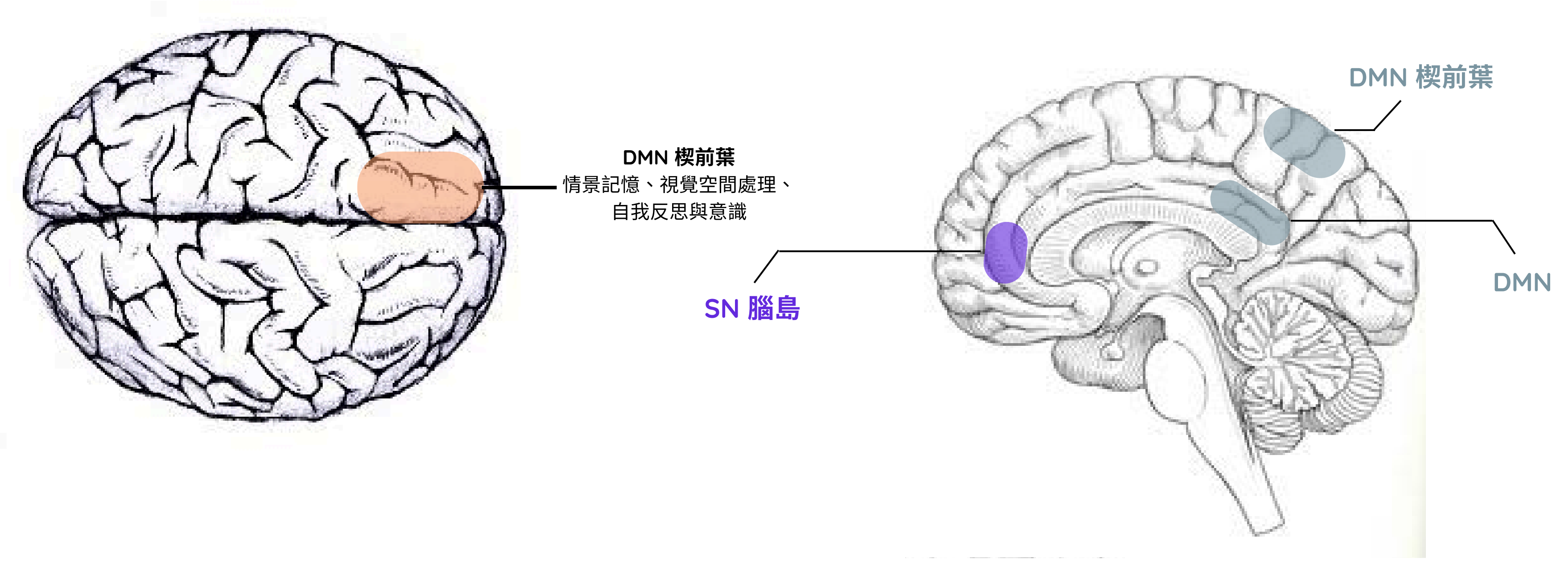
Table 2 Regions showing significant activation during ideation versus baseline (MNI coordinates)

Cluster size	*P value (FWE corrected)*	*P Value (uncorrected)*	*SPM(Z)*	*x*	*y*	*z (mm)*	*Area*
1410	<0.001	<0.001	6.76	−54	17	32	Left inferior frontal gyrus
			6.55	−21	11	68	Left superior frontal gyrus
			6.37	−9	5	65	Left supplementary motor area
1883	<0.001	<0.001	6.71	33	−55	−28	Right cerebellum
			6.64	15	−85	−10	Right lingual gyrus
			6.55	15	−97	2	Right calcarine
79	<0.001	<0.001	5.61	18	2	23	Right caudate
67	<0.001	<0.001	5.53	33	−55	8	
			5.3	36	−40	−1	
			5.06	30	−64	2	Right lingual gyrus
90	<0.001	<0.001	5.52	−39	−31	53	Left postcentral gyrus
			5.2	−57	−19	41	Left supramarginal gyrus
			4.86	−42	−25	41	Left inferior parietal lobule
14	0.001	0.028	5.47	−27	−25	−4	
41	<0.001	0.001	5.36	−9	−67	53	Left precuneus
15	0.001	0.023	5.2	−54	17	2	Left inferior frontal gyrus
49	<0.001	<0.001	5.1	−18	5	20	Left caudate
			4.97	−18	−1	5	Left pallidum
			4.91	−18	11	5	Left putamen
10	0.003	0.057	5.07	−42	−37	−7	
16	0.001	0.02	5.05	27	−37	20	
			4.83	30	−34	5	
20	0.001	0.011	5.05	−33	−52	−28	Left cerebellum
7	0.005	0.104	5.01	−33	−34	−22	Left fusiform
23	<0.001	0.007	4.98	−30	−58	26	
			4.91	−33	−52	20	
6	0.007	0.13	4.81	−45	50	−7	Left middle frontal gyrus
7	0.005	0.104	4.76	−24	−64	8	Left calcarine
3	0.014	0.277	4.68	−3	−34	−4	
1	0.027	0.539	4.67	15	2	5	
1	0.027	0.539	4.67	24	−28	−1	
1	0.027	0.539	4.64	30	−43	14	
3	0.014	0.277	4.63	15	−4	2	
1	0.027	0.539	4.63	−18	−49	11	Left precuneus
2	0.019	0.375	4.63	12	−61	5	Right lingual gyrus
1	0.027	0.539	4.62	24	−70	11	Right calcarine
1	0.027	0.539	4.61	−30	26	−1	Left insula

Functional Activity Results (Ideation vs. Controls)

Table 3 Regions showing significant activation during ideation versus working memory and visuospatial processing (MNI coordinates)

Cluster size	*P value (FWE corrected)*	*P Value (uncorrected)*	*SPM(Z)*	*x*	*y*	*z (mm)*	*Area*
401	<0.001	<0.001	6.86	−42	−61	26	Left angular gyrus
			6.8	−45	−67	35	Left angular gyrus
			6.24	−18	−49	11	Left precuneus
689	<0.001	<0.001	6.79	−27	20	62	Left middle frontal gyrus
			6.54	−24	29	53	Left middle frontal gyrus
			6.43	−21	44	32	Left superior frontal gyrus
239	<0.001	<0.001	6.59	42	−67	−37	Right cerebellum
			6.56	33	−76	−37	Right cerebellum
21	0.001	0.019	5.77	48	−64	29	Right angular gyrus
38	<0.001	0.003	5.75	27	−52	14	
15	0.002	0.042	5.48	−39	−34	−7	
46	<0.001	0.001	5.41	−12	−58	−13	Left cerebellum
			4.64	−15	−43	−10	Left lingual gyrus
8	0.006	0.123	5.22	−33	35	−7	Left inferior frontal gyrus
17	0.002	0.031	5.08	−27	−34	−13	Left parahippocampal gyrus
2	0.022	0.436	4.99	−3	56	−13	Left medial frontal gyrus
1	0.03	0.593	4.75	45	−10	17	Right rolandic operculum
4	0.014	0.268	4.65	−36	−22	53	Left postcentral gyrus
1	0.03	0.593	4.56	12	56	23	Right superior frontal gyrus
2	0.022	0.436	4.56	18	53	26	Right superior frontal gyrus
1	0.03	0.593	4.56	−48	−13	−22	Left middle temporal gyrus
2	0.022	0.436	4.55	15	11	20	Right caudate



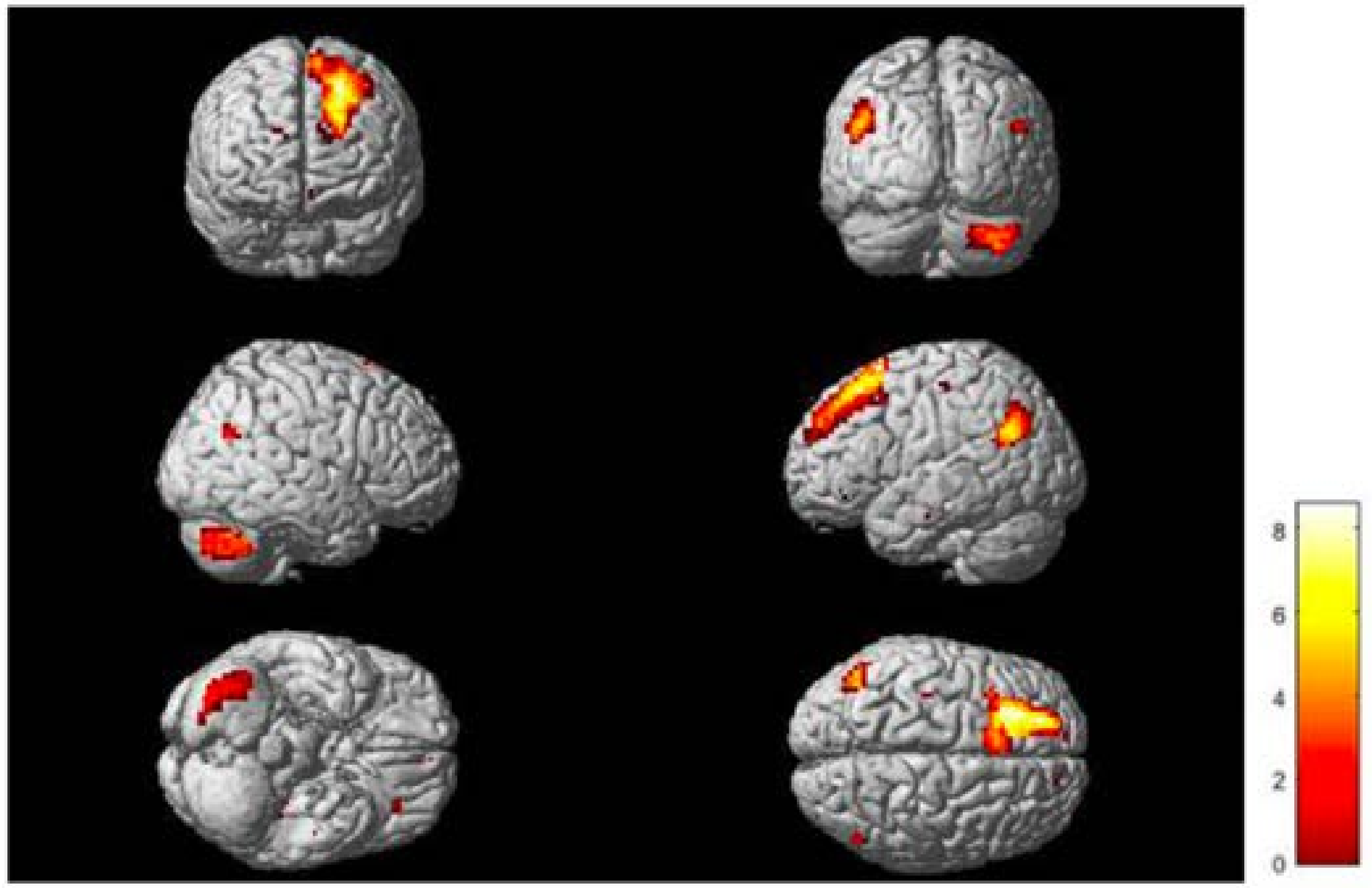


Figure 4 Regions showing significantly higher activity during ideation compared with both working memory and visuospatial processing

PPI analysis results

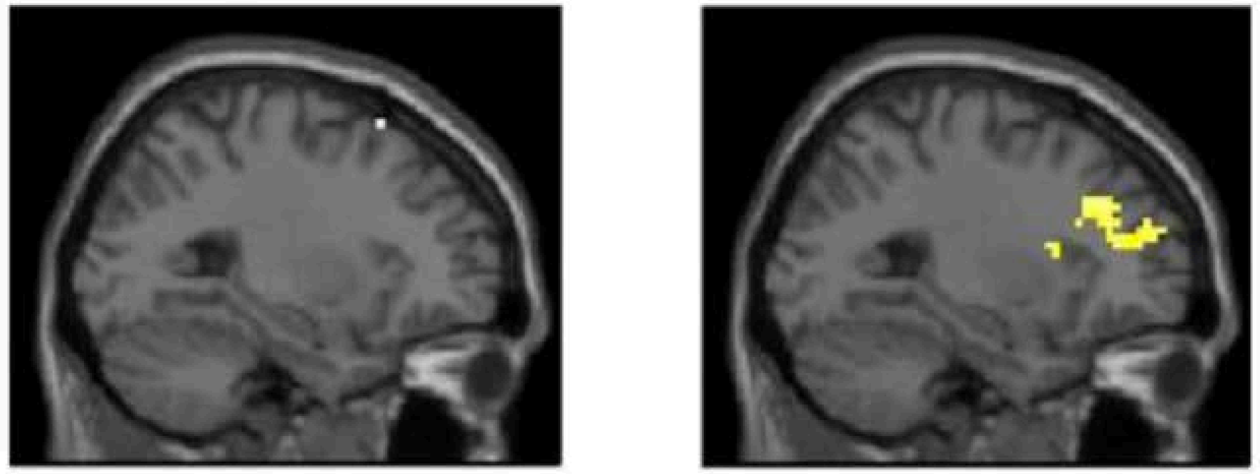
Table 4 Results of PPI analysis: regions showing significantly greater functional connectivity with ROI during ideation, as compared with working memory and visuospatial processing (MNI coordinates)

ROI: Left middle frontal gyrus (L.MFG, −27, 20,62)

Cluster size	P value (FWE corrected)	P Value (uncorrected)	SPM(Z)	x	y	z (mm)	Area
1	0.028	0.548	4.64	−27	20	62	Left middle frontal gyrus

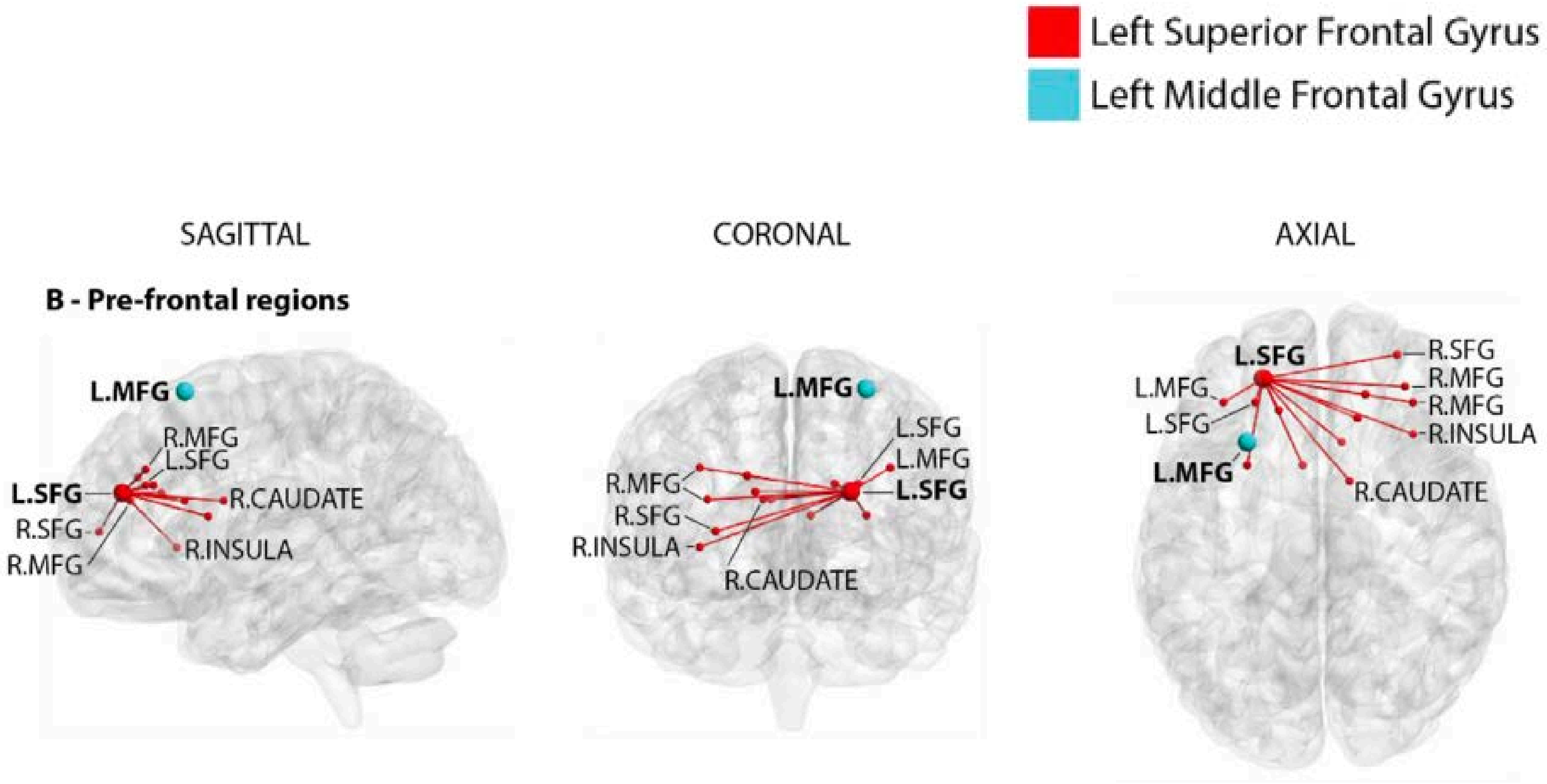
ROI: Left superior frontal gyrus (L.SFG, -21, 44, 23)

Cluster size	P value (FWE corrected)	P Value (uncorrected)	SPM(Z)	x	y	z (mm)	Area
282	<0.001	<0.001	5.77	−36	35	32	Left middle frontal gyrus
			5.44	−15	32	26	
			5.34	−24	35	26	Left superior frontal gyrus
8	0.005	0.098	5.36	12	5	20	Right caudate
77	<0.001	<0.001	5.22	33	41	20	Right middle frontal gyrus
			4.88	36	35	32	Right middle frontal gyrus
			4.64	30	53	8	Right superior frontal gyrus
39	<0.001	0.001	5.18	18	38	29	
			4.74	15	29	23	
5	0.009	0.183	4.94	−27	11	14	
1	0.028	0.559	4.65	9	20	20	
2	0.02	0.398	4.62	−6	11	14	
1	0.028	0.559	4.55	36	23	2	Right insula



a) Left Middle Frontal Gyrus

b) Left Superior Frontal Gyrus



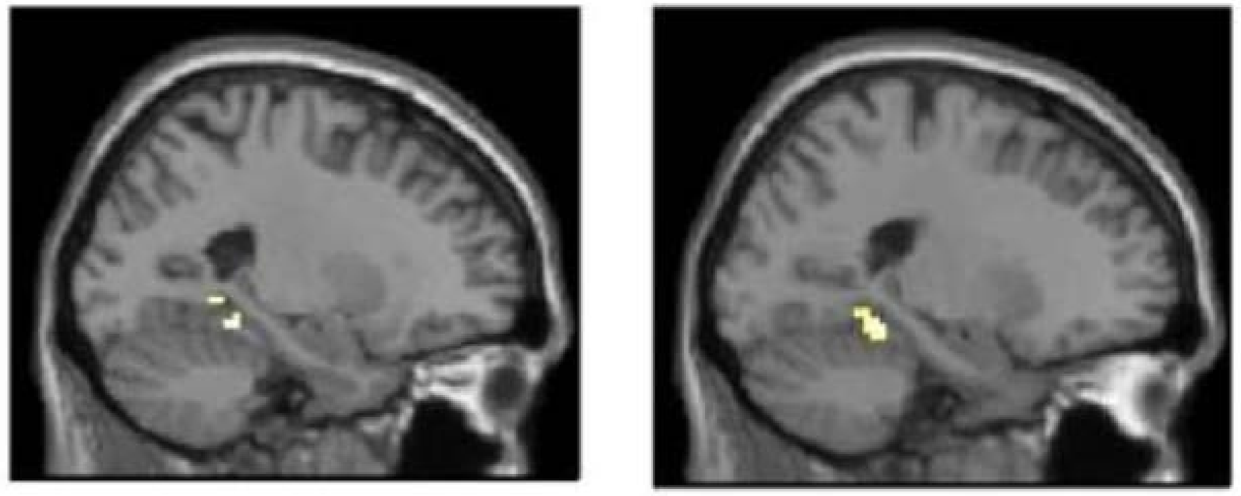
PPI analysis results

ROI: Left angular gyrus (L.AG, -42, -61, 26)

Cluster size	P value (FWE corrected)	P Value (uncorrected)	SPM(Z)	x	y	z (mm)	Area
20	0.001	0.016	5.18	−24	−40	−13	Left fusiform gyrus
			5.38	−18	−46	−4	Left lingual gyrus

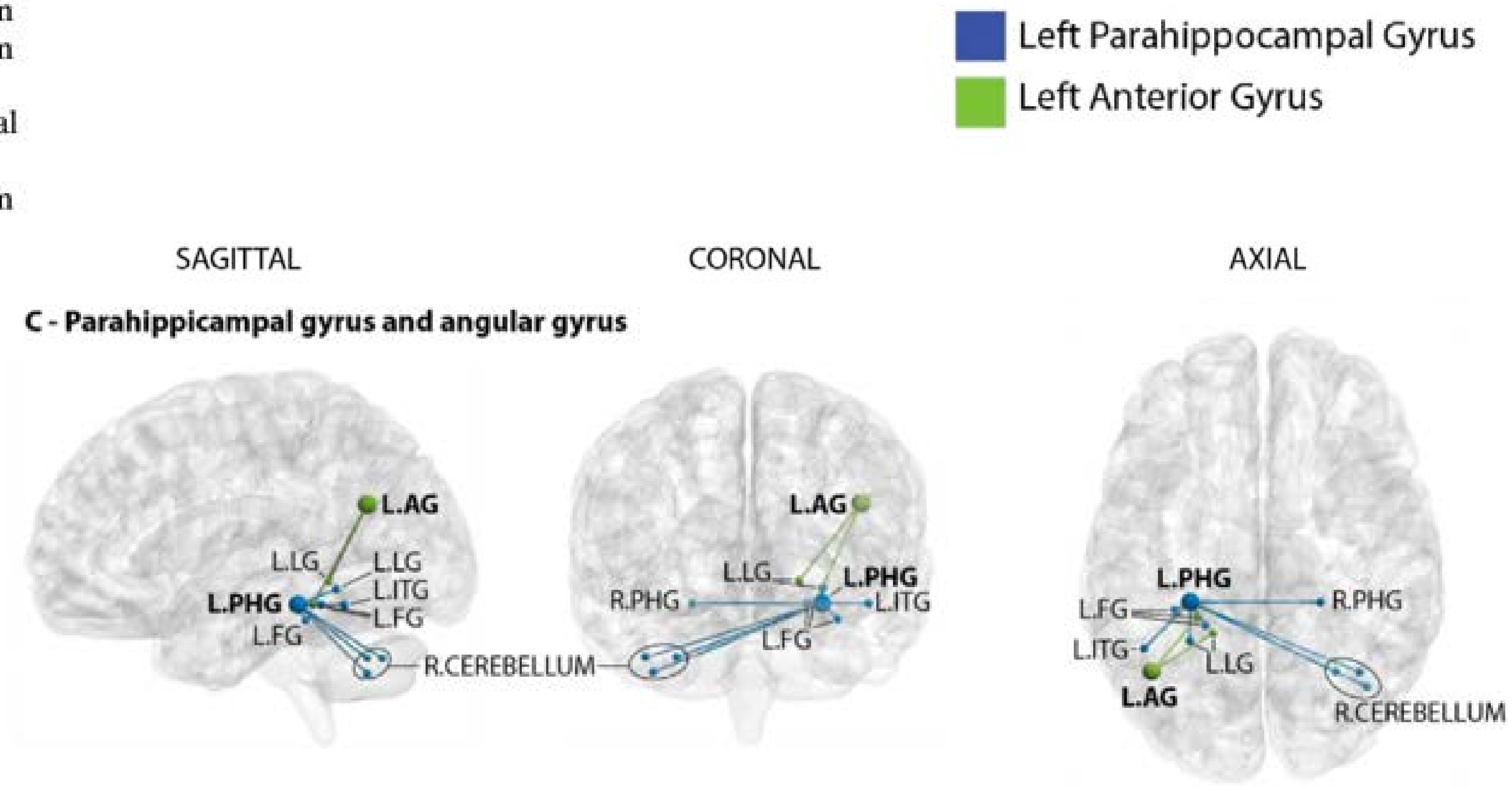
ROI: Left parahippocampal gyrus (L.PHG, -27, -34, -13)

Cluster size	P value (FWE corrected)	P Value (uncorrected)	SPM(Z)	x	y	z (mm)	Area
33	<0.001	0.004	5.38	−21	−43	−13	Left fusiform gyrus
			4.82	−27	−49	−7	Left lingual gyrus
16	0.002	0.034	5.15	−45	−52	−13	Left inferior temporal gyrus
24	0.001	0.012	5.02	39	−61	−40	Right cerebellum
			4.81	30	−61	−34	Right cerebellum
2	0.022	0.428	4.74	24	−34	−13	Right parahippocampal gyrus
2	0.022	0.428	4.6	42	−67	−34	Right cerebellum
1	0.03	0.586	4.54	−33	−37	−19	Left fusiforn



c) Left Angular Gyrus

d) Left Parahippocampal Gyrus



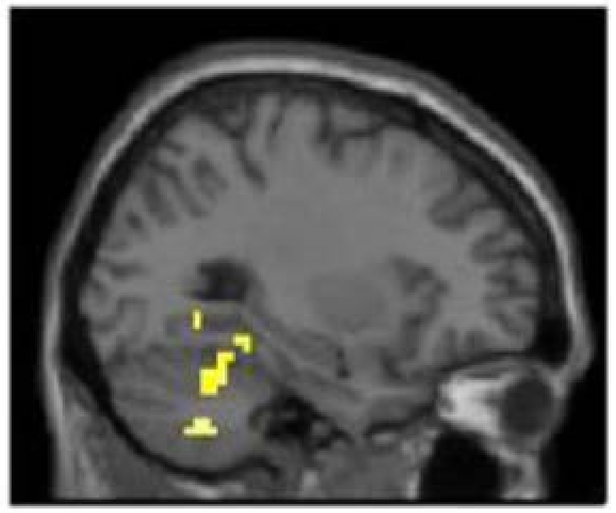
PPI analysis results

ROI: Left lingual gyrus (L.LG, -15, -43, -10)

Cluster size	P value (FWE corrected)	P Value (uncorrected)	SPM(Z)	x	y	z (mm)	Area
852	<0.001	<0.001	5.67	24	−58	−7	Right lingual gyrus
			5.6	15	−61	2	Right lingual gyrus
			5.6	21	−49	−10	Right lingual gyrus
57	<0.001	0.001	5.29	−27	−55	−46	Left cerebellum
			5.27	−48	−61	−37	Left cerebellum
			4.82	−36	−64	−40	Left cerebellum
19	0.002	0.034	5.08	3	−70	−25	Vermis
48	<0.001	0.002	4.99	39	−64	−43	Right cerebellum
			4.87	27	−61	−40	
2	0.024	0.47	4.85	15	−58	−49	Right cerebellum
3	0.019	0.372	4.63	−12	17	41	Left superior frontal gyrus
5	0.013	0.249	4.6	−36	−46	−37	Left cerebellum
1	0.031	0.621	4.57	0	−67	−46	
1	0.031	0.621	4.55	−45	−49	−31	Left cerebellum
1	0.031	0.621	4.53	30	−46	−28	Right cerebellum
1	0.031	0.621	4.51	30	29	−4	
1	0.031	0.621	4.5	−33	−40	−31	Left cerebellum

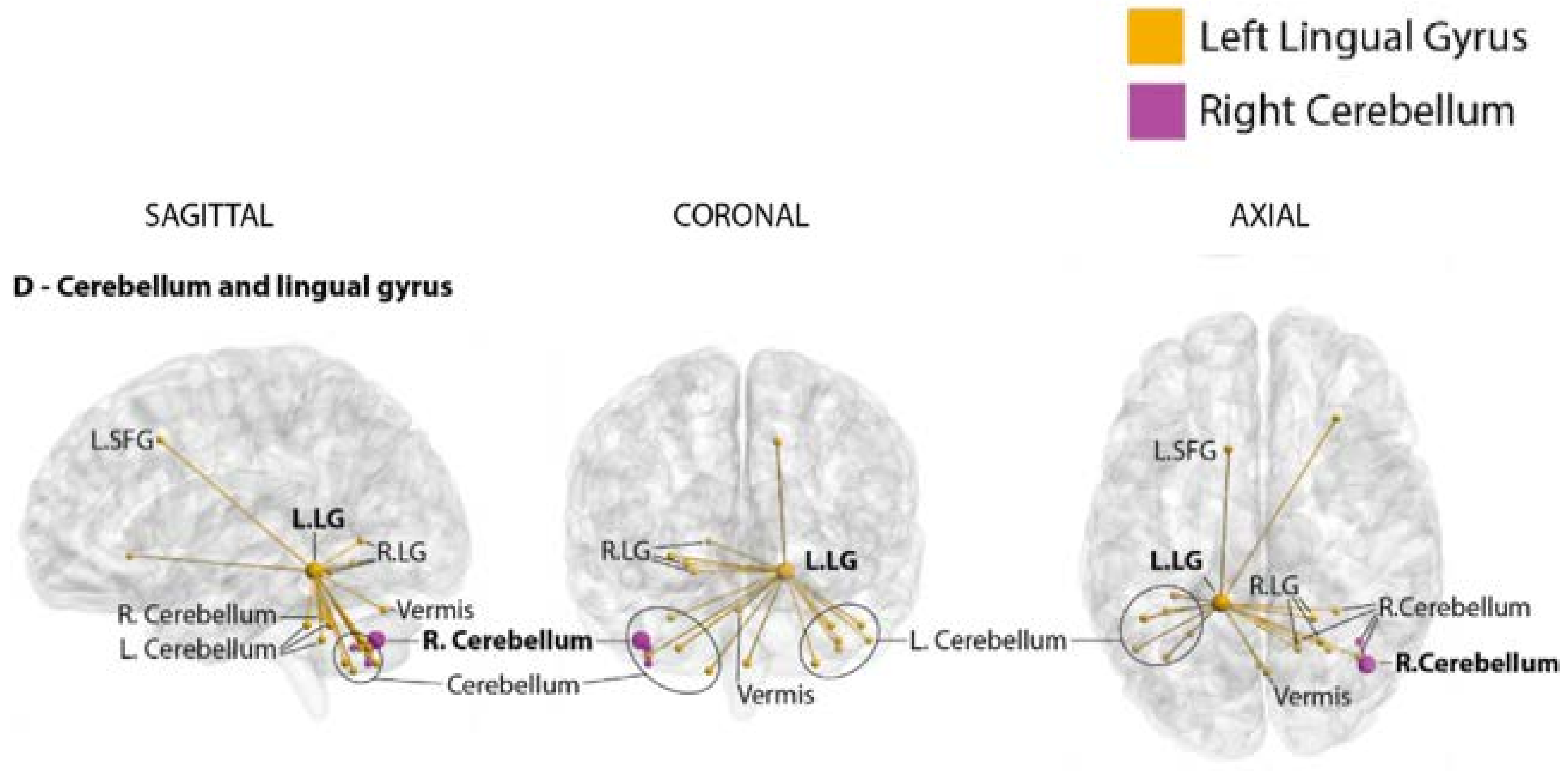
ROI: Right cerebellum (42, -67, -37)

Cluster size	P value (FWE corrected)	P Value (uncorrected)	SPM(Z)	x	y	z (mm)	Area
3	0.017	0.339	4.83	39	−64	−46	Right cerebellum
3	0.017	0.339	4.64	39	−58	−40	Right cerebellum



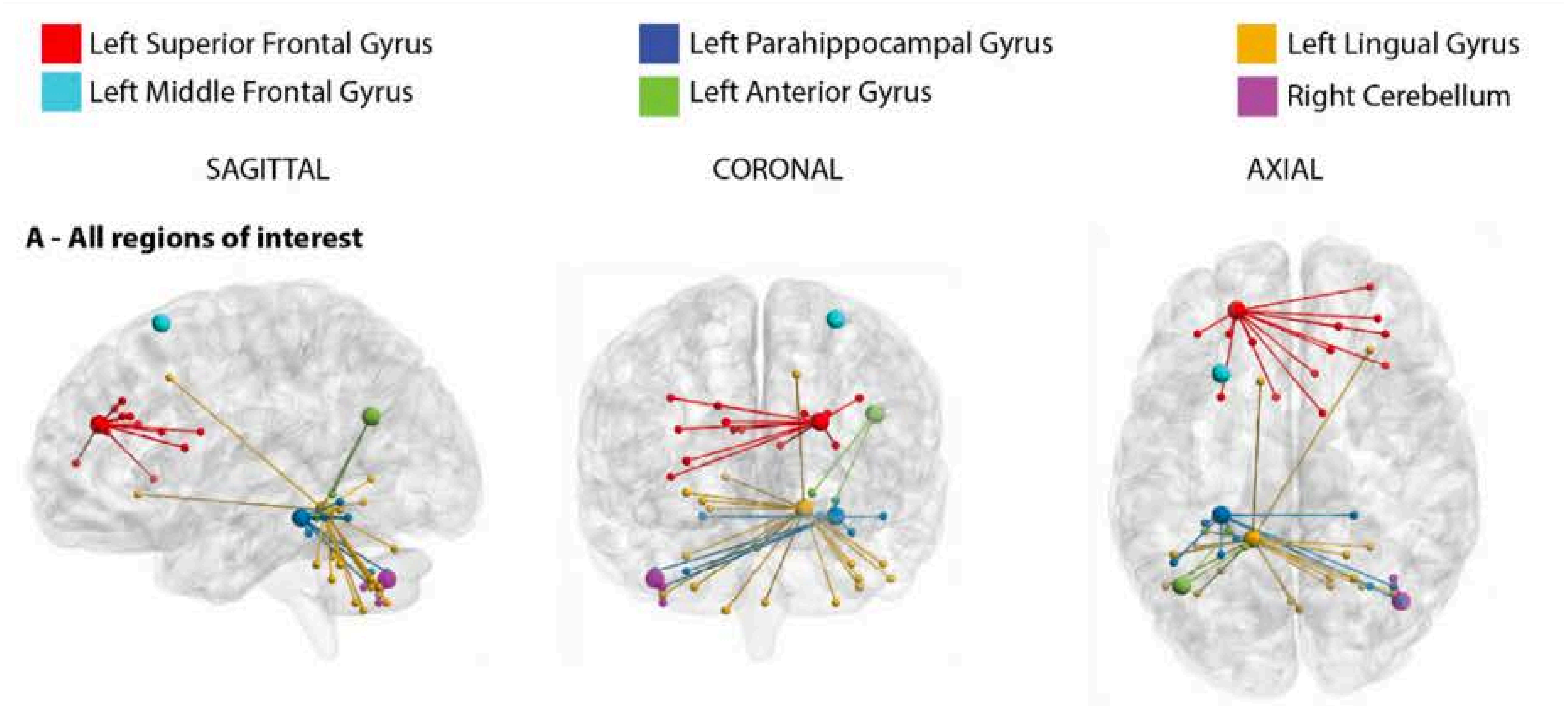
e) Left Lingual Gyrus

f) Right Cerebellum



PPI Analysis Results:

Showing all regions of interest (ROIs) and their co-activation during ideation.



Discussion amd Implications

- **Key Findings**
  - This study provides fundamental knowledge about the brain regions and functional networks involved in design ideation.
  - Design ideation is a complex form of creative cognition that likely depends on multiple interacting cortical networks distributed across the brain.
- **Implications for Design Practice**
  - Offers targets for behavioral and neural interventions to enhance ideation performance.
  - Potential to develop design-specific training exercises targeting cognitive processes linked to the highlighted brain regions in this study.
  - Neurofeedback can help designers become aware of their brain activity and regulate their ideation processes.
  - Neurostimulation methods (e.g., tDCS) could enhance creativity by stimulating brain areas most associated with effective ideation.

Limitations and Future Work

- **Study Limitations**
  - Did not explore how brain activity varies with the creative value of ideas generated.
  - Future work will apply parametric modulation to address this.
  - Control task selection is complex, as ideation involves multiple interacting processes.
  - Future studies may include long-term memory retrieval as a control condition.
- **Future Directions**
  - Clarify the exact role of the motor cortex, e.g., by comparing fMRI ideation tasks with and without sketching to distinguish between imagined sketching and product interaction.
  - Establish the predictive power of brain-behavior correlations, testing whether functional connectivity predicts creative outcomes in design.
  - Further explore the relationship between DMN processes and mental imagery during ideation.

Thank you