Executive Cognitive Control of Free Choices

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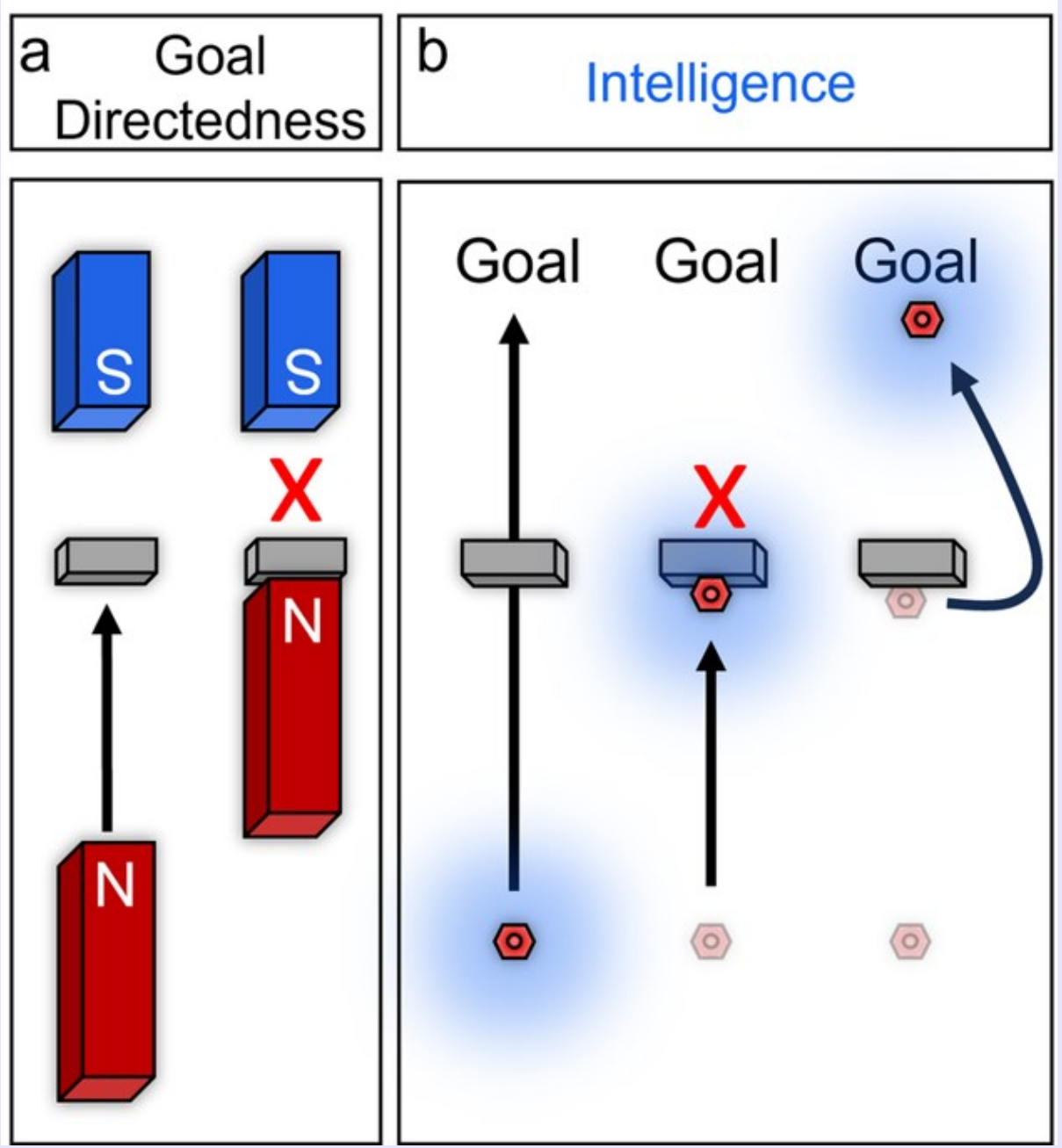
“Cognitive, or executive, control refers to the ability to coordinate thought and action and direct it toward obtaining goals. . . . Executive control contrasts with automatic forms of brain processing.”

Miller & Walis: Executive function and higher-order cognition: definition and neural substrates. In: Squire, L.R. (ed.) Encyclopedia of Neuroscience. vol. 4. Academic Press, Oxford (2009)

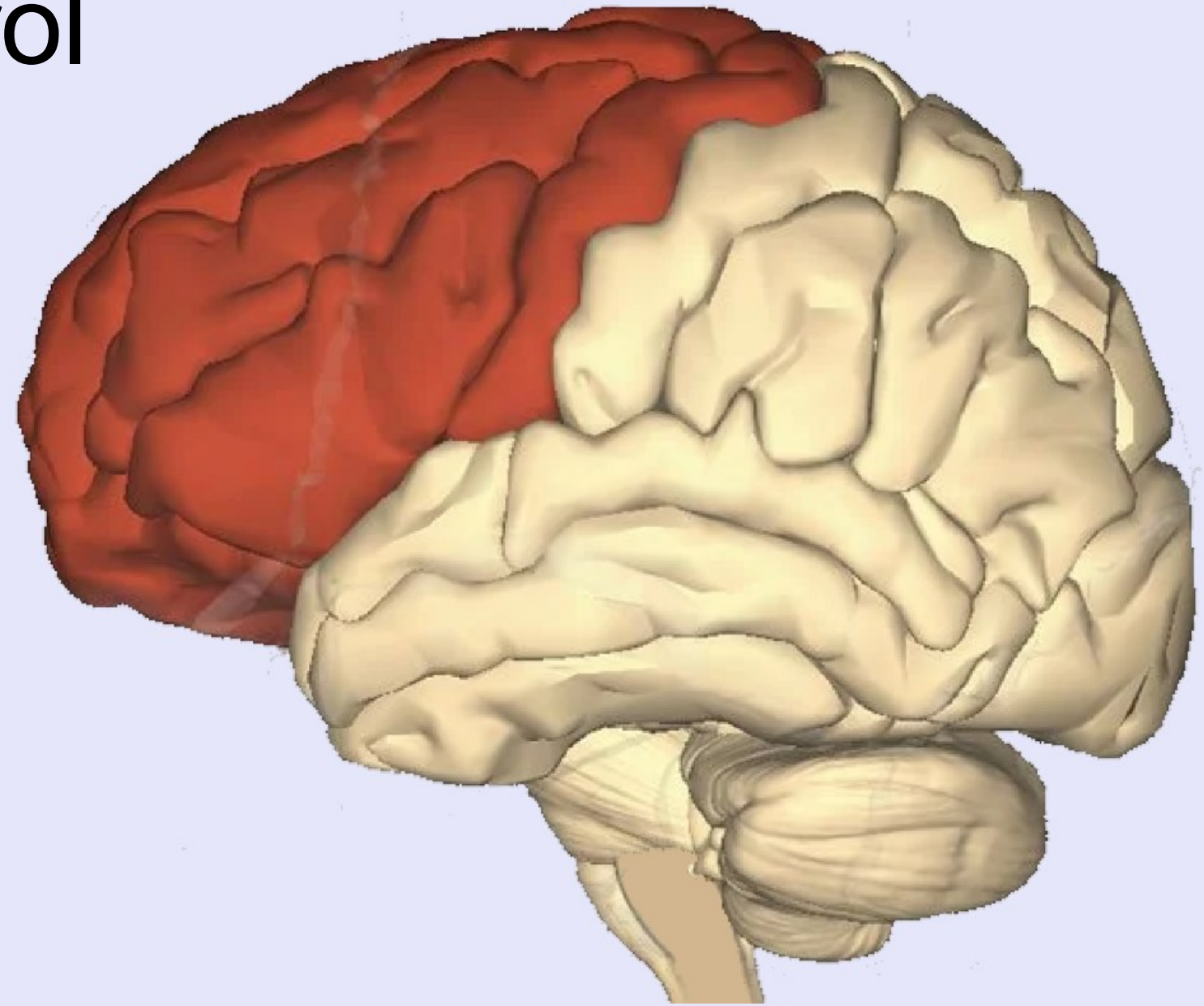
Executive Control & Goal-directedness

- Executive control is about achieving goals.
- But it is also intelligent.



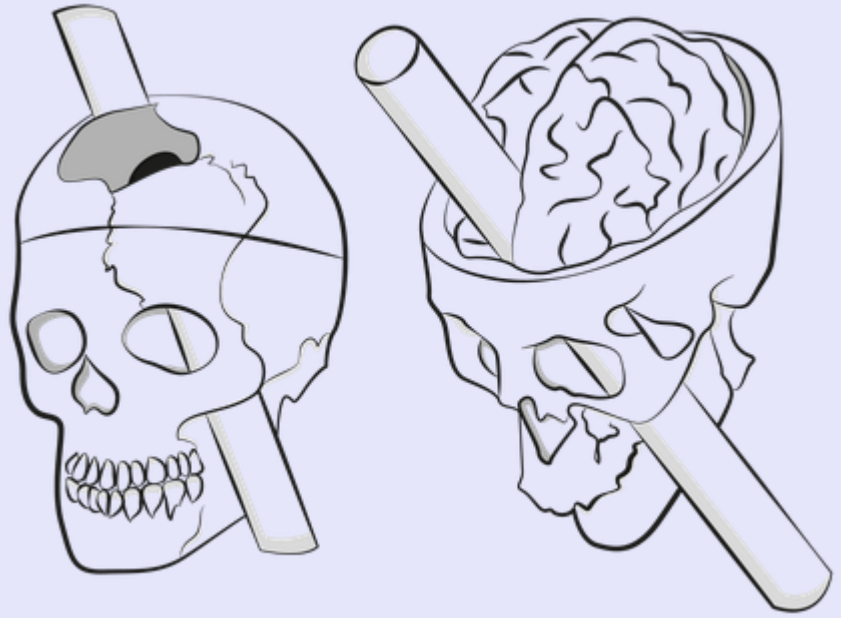
McMillen, P., & Levin, M. (2024). Collective intelligence: A unifying concept for integrating biology across scales and substrates. *Communications Biology*, *7*(1), 378.

Executive Control and the Brain



- Neuropsychological studies, and later imaging studies, have suggested an important role of the frontal lobes.

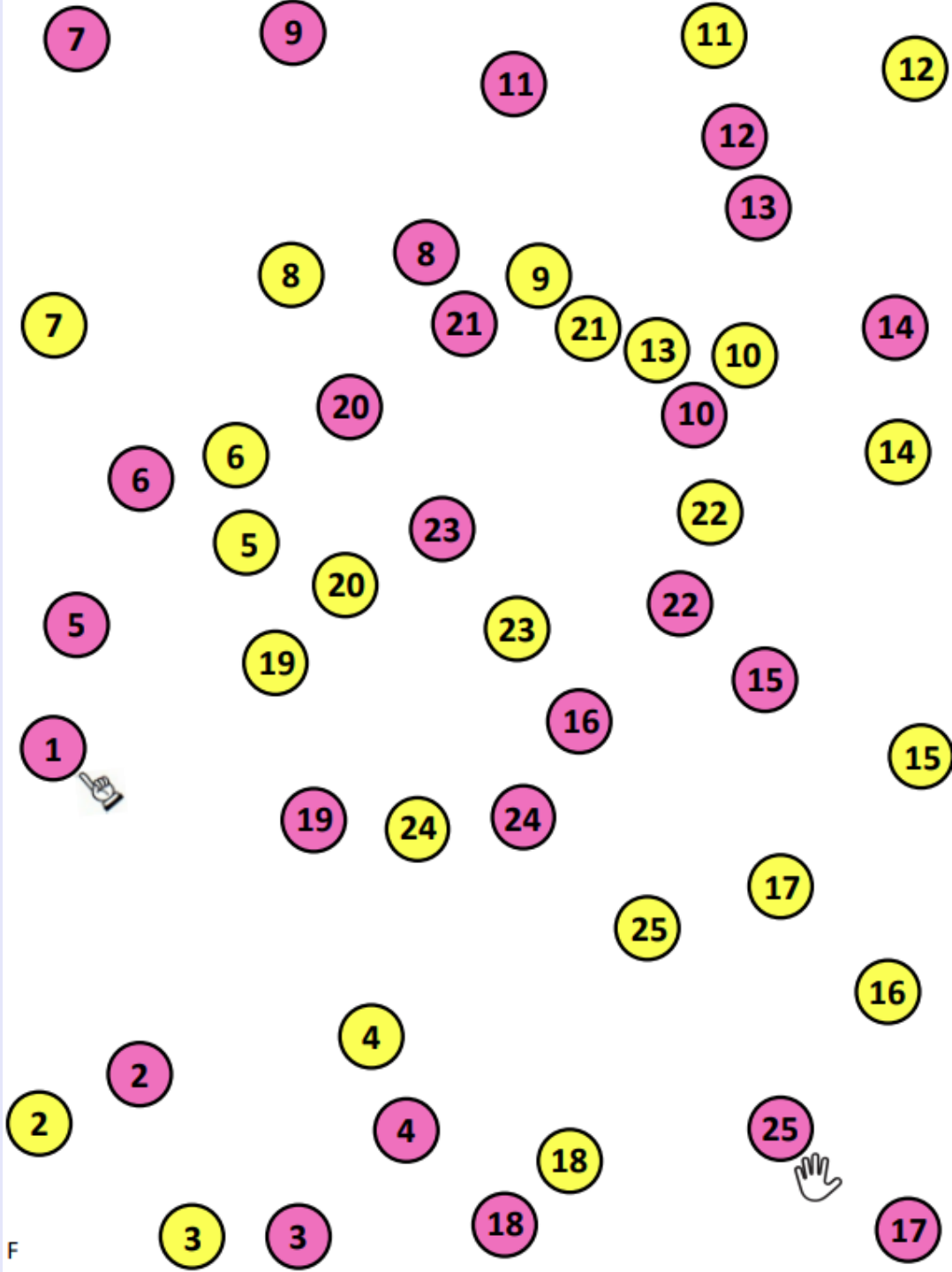
“*one straightforward difficulty common after frontal lesions is defective control of behavior in the face of choice, complexity, or ambiguity*”



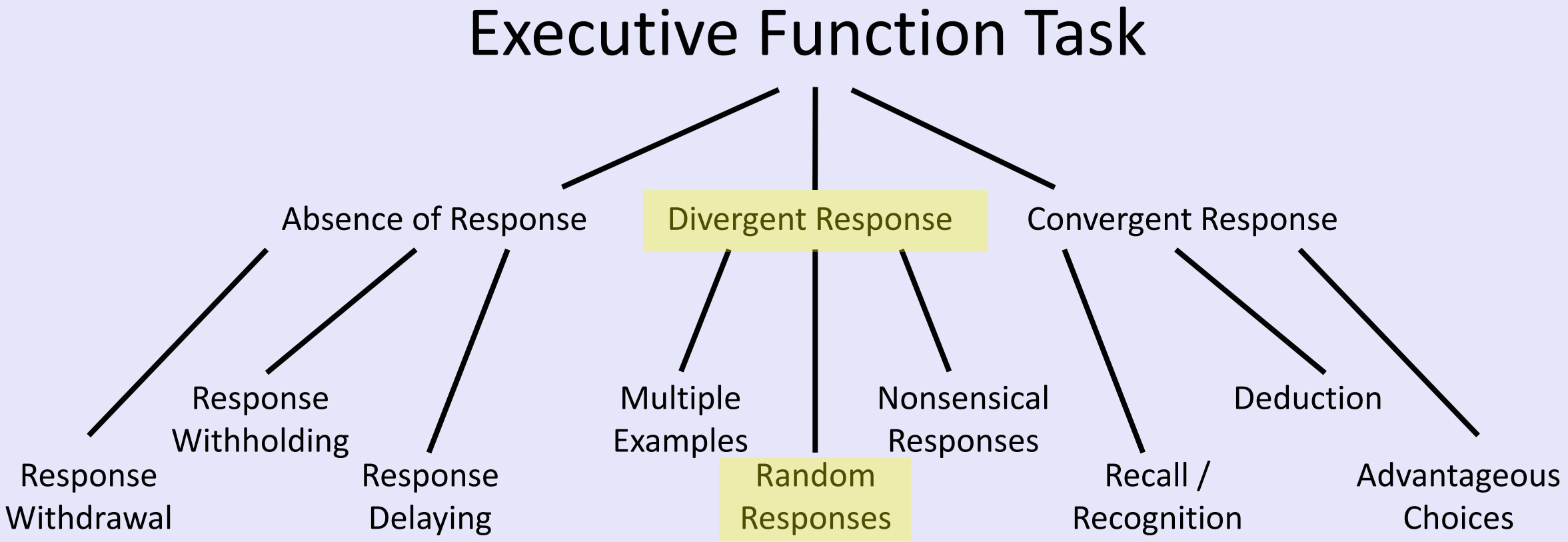
Alexander, M.P., Stuss, D.T., Picton, T., Shallice, T., Gillingham, S.: Regional frontal injuries cause distinct impairments in cognitive control. Neurology 68(18), 1515–23 (2007).

Typical Cognitive Assessment Method

Color Trails Test.



Taxonomy of Executive Task Demands



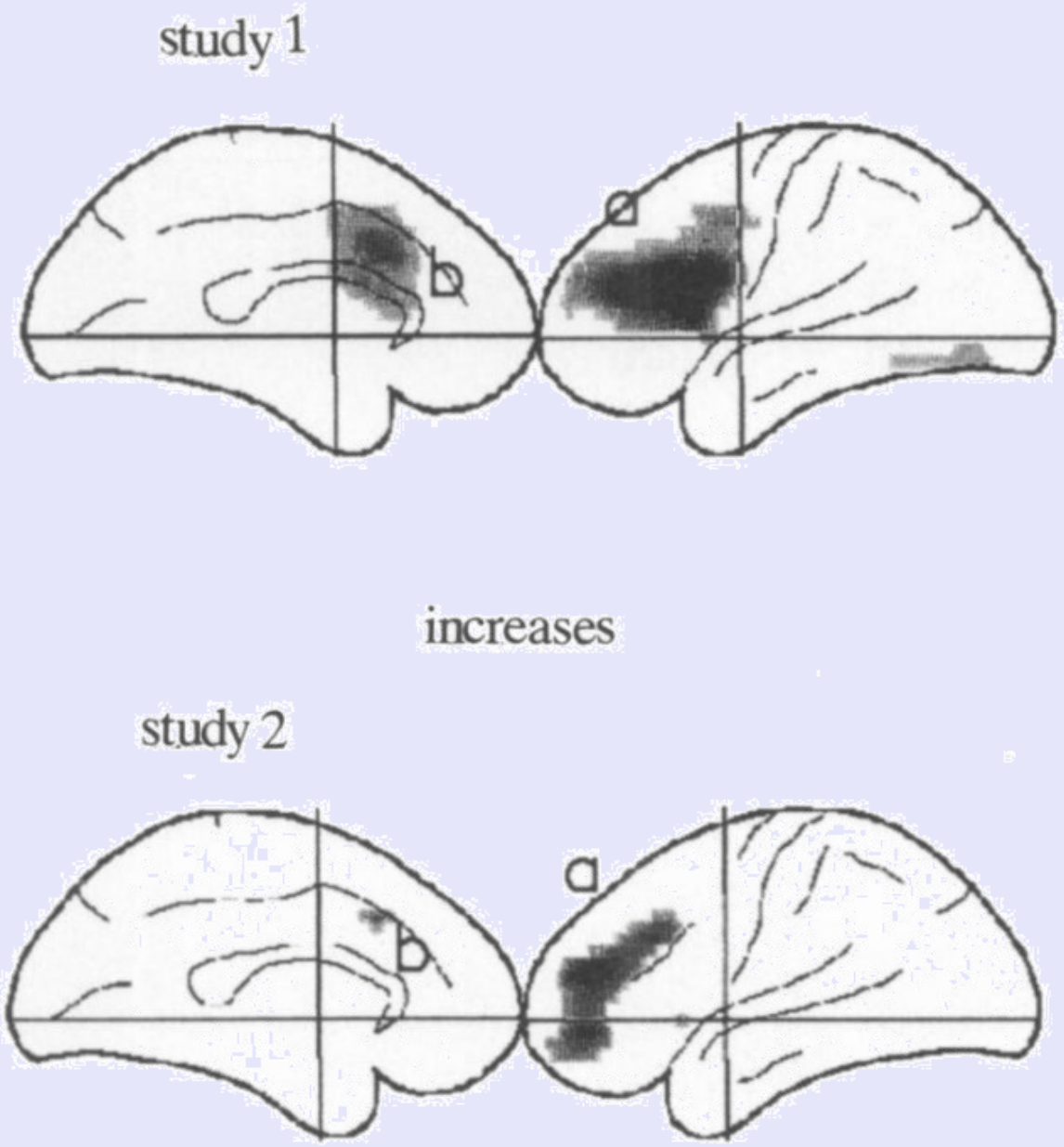
Pluck, et al: Executive function and intelligent goal-directed behavior: perspectives from psychology, neurology, and computer science. In: Masci, P., Bernardeschi, C., Graziani, P., Koddenbrock, M., Palmieri, M. (eds.) Software Engineering and Formal Methods. SEFM 2022 Collocated Workshops. SEFM 2022. Lecture Notes in Computer Science, vol 13765. pp. 324–350. Springer, Cham (2023).

Free Choices in Cognitive Psychology

Experimental methods rely on stimulus-response relationships. Free choice is difficult to study.

Free Choices Studied with Neurophysiology

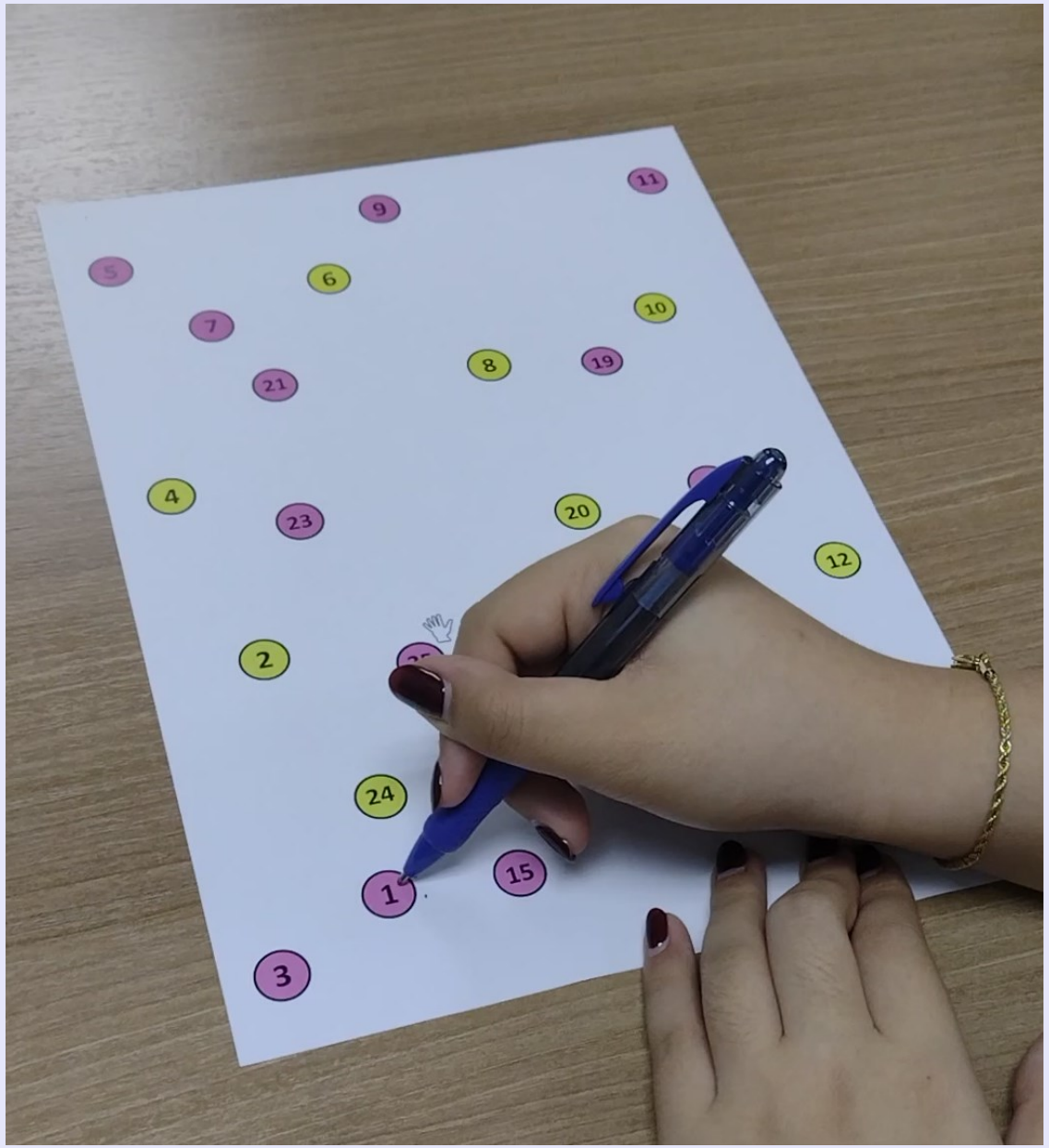
- Early PET study confirmed frontal lobe activity when making ‘willed actions’.
- Contrasts ‘willed’ conditions with ‘pre-defined’ conditions.



Frith, et al.: Willed action and the prefrontal cortex in man: a study with pet. Proc. R. Soc. Lond. B Biol. Sci. 244(1311), 241–6 (1991)

Color Trails Test

- Join the circles in number sequence (the colors are irrelevant).
- Time to completion is recorded.

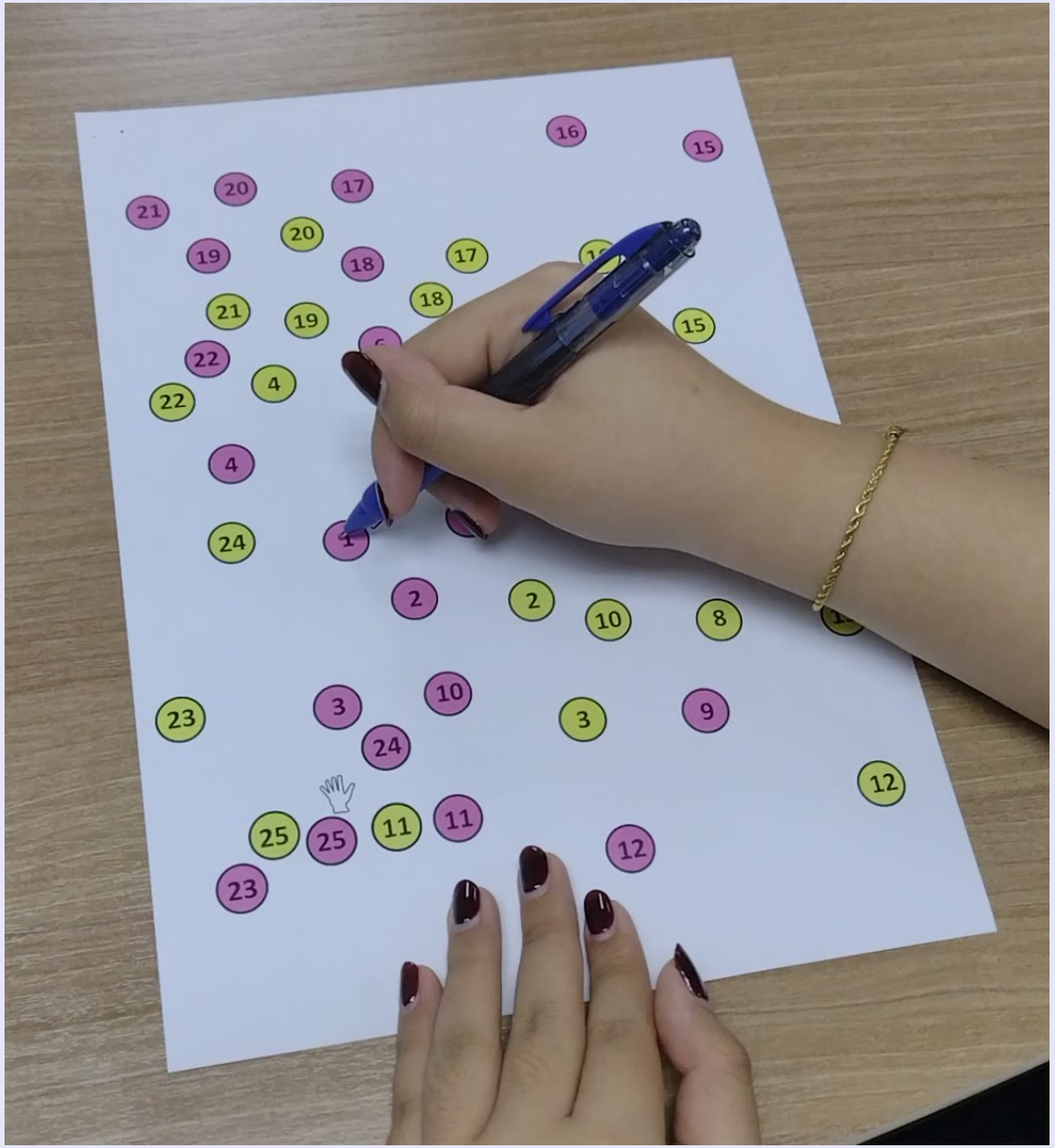


Routine Condition

Maj, et al: Evaluation of two new neuropsychological tests designed to minimize cultural bias in the assessment of hiv-1 seropositive persons: a who study. Arch. Clin. Neuropsychol. 8(2), 123–35 (1993).

Color Trails Test

- Join the circles in number sequence, but alternating between pink and yellow.
- Time to completion is recorded.



Switching Condition

Maj, et al: Evaluation of two new neuropsychological tests designed to minimize cultural bias in the assessment of hiv-1 seropositive persons: a who study. Arch. Clin. Neuropsychol. 8(2), 123–35 (1993).

Choice Trails Test

- Our aim was to produce a similar test that would be more divergent.
- Participants would have to choose a different color at each step.

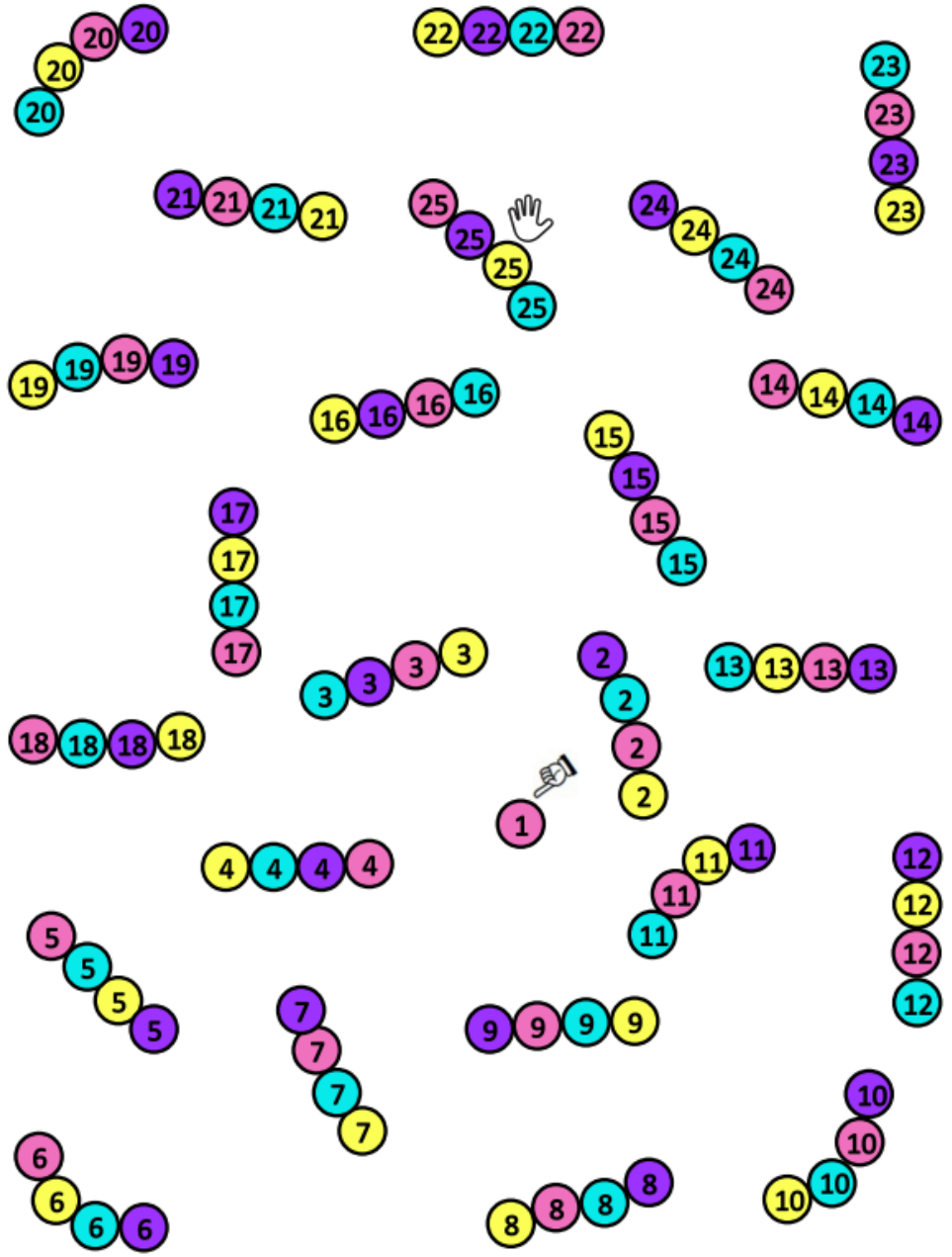
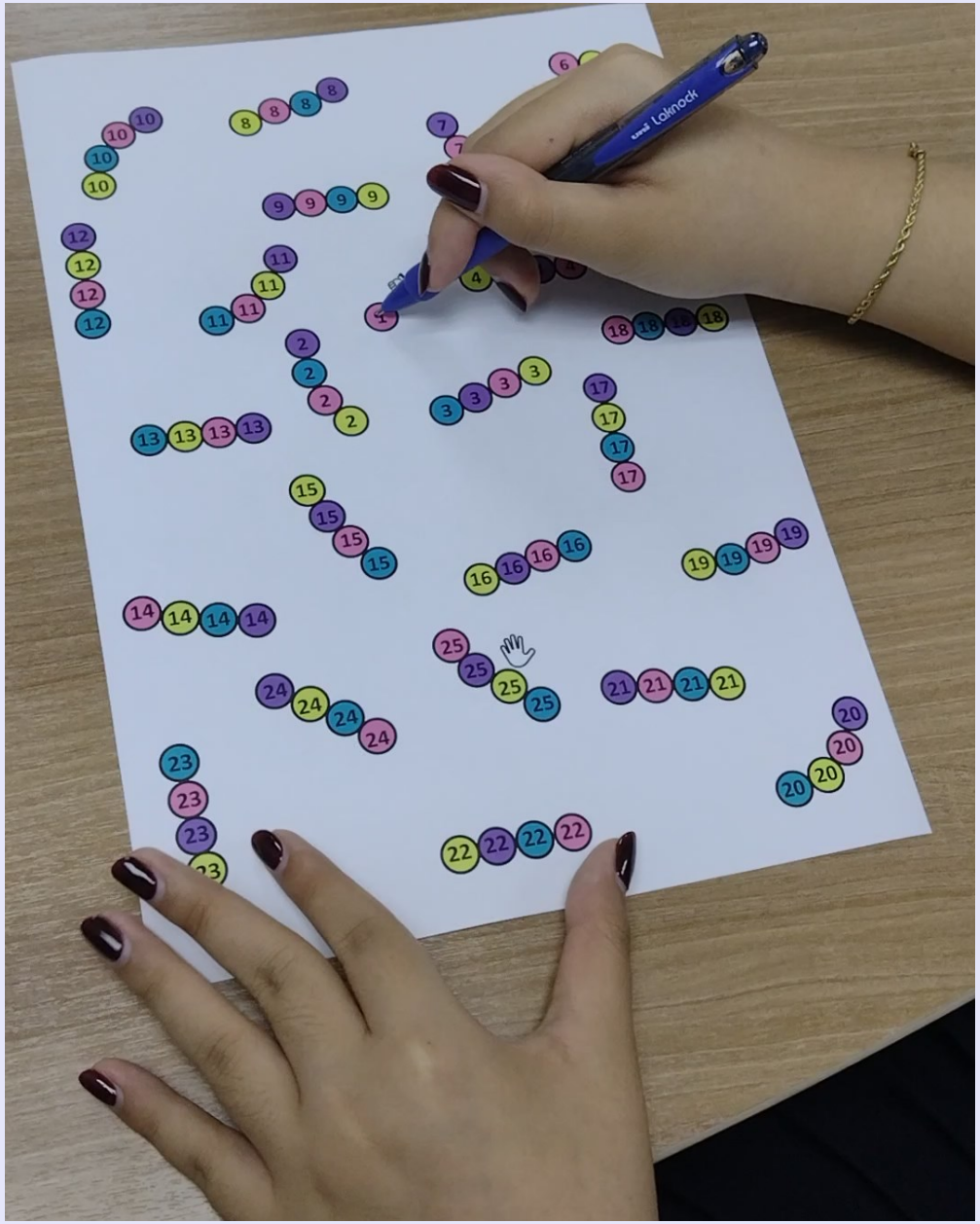


Fig. 1. The Choice Trails Test.

Choice Trails Test

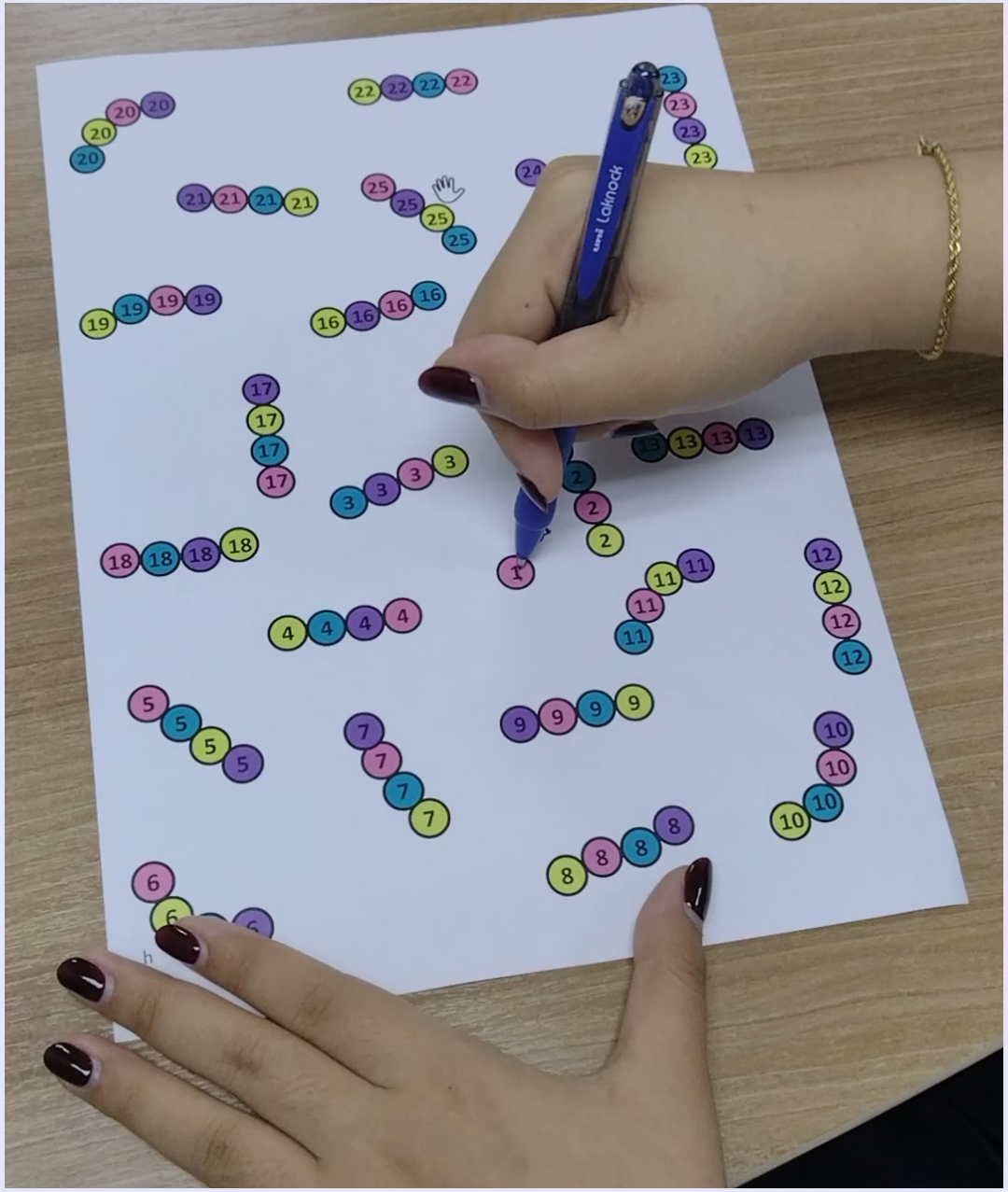
Join the pink circles
in number sequence



Routine Condition

Choice Trails Test

I. Join the numbers in sequence with the pen.
II. Perform as quickly as possible without making mistakes.
III. Do not choose the same color twice in succession.
IV. Try to choose all the colors equally often.
V. Avoid using any plans or strategies



Switching Condition

Data Analysis

- 30 participants
- 3 trials each
- Each trial requiring 24 choices
- Totaling 72 separate responses
- Are the responses random or contain patterns?

Y = Yellow	
P = Pink	
B = Blue	
V = Violet	

Trial	Participant	Sequence	Response
	1	X101	2 Y
	1	X101	3 V
	1	X101	4 Y
	1	X101	5 P
	1	X101	6 B
	1	X101	7 V
	1	X101	8 P
	1	X101	9 V
	1	X101	10 B
	1	X101	11 Y
	1	X101	12 V
	1	X101	13 Y
	1	X101	14 P
	1	X101	15 V
	1	X101	16 Y
	1	X101	17 P
	1	X101	18 B
	1	X101	19 Y
	1	X101	20 P
	1	X101	21 B
	1	X101	22 V
	1	X101	23 P
	1	X101	24 Y
	1	X101	25 B

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	1	X101	11 Y
	1	X101	12 V
	1	X101	13 Y
	1	X101	14 P
	1	X101	15 V
	1	X101	16 Y
	1	X101	17 P
	1	X101	18 B
	1	X101	19 Y
	1	X101	20 P
	1	X101	21 B
	1	X101	22 V
	1	X101	23 P
	1	X101	24 Y
	1	X101	25 B

Measuring Randomness

“You can't tell if something is random – you can only catch it out as non-random”

- Darren Hurley-Smith, Senior Lecturer in Information Security at Royal Holloway, University of London

BBC News website: The search for the random numbers that run our lives, 6 July 2024, https://www.bbc.com/future/article/20240704-the-search-for-the-random-numbers-that-run-our-lives

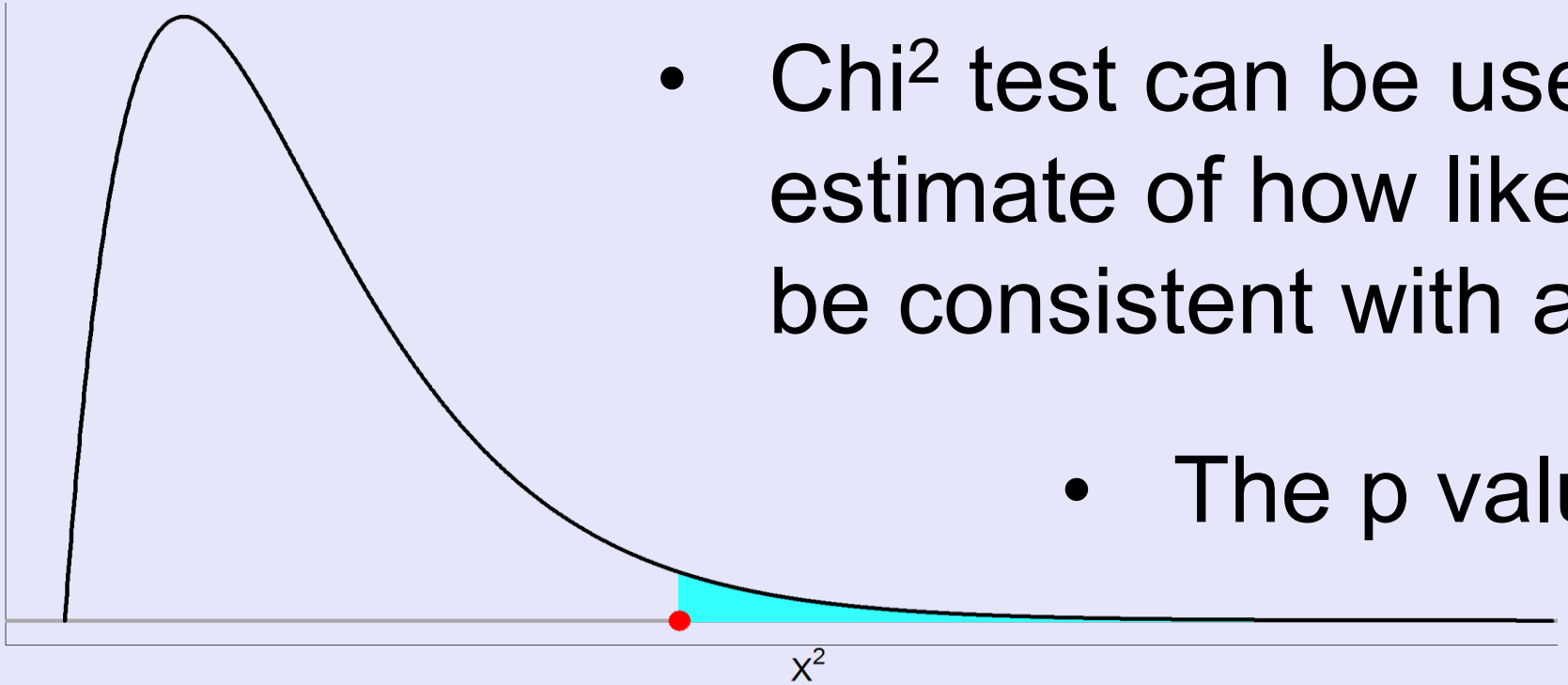
Methods for Assessing Randomness

- Several industries require random numbers.
- Computers are poor at random number generation.
- Many ingenious systems available.
- Much research on assessing the randomness of the strings produced.

Hurley-Smith, D., Patsakis, C., Hernandez-Castro, J.: On the unbearable lightness of fips 140–2 randomness tests. IEEE Trans. Inf. Forensics Secur. 17, 3946–3958 (2020).

Assessing Randomness with p values

- "*a p value,…is the most useful and standard way to determine whether the randomness hypothesis holds*"



- Chi^2 test can be used to output an estimate of how likely the string is to be consistent with a random sample.
- The p value is that estimate.

Almaraz Luengo, et al: Stringent test suite: Ent battery revisited for efficient p value computation. J. Cryptogr. Eng. 13(2), 235–249 (2023).

Assessing Randomness with Chi^2

- Consecutive bigrams analyzed (e.g., Blue-Yellow, -Blue-Yellow)
- 12 possible different-color bigrams.
- 24 choices in a single trial produce 23 permutations of 2 different colors. The expected counts of 2 different color bigrams chosen consecutively is (=23/12) in a single trial, and (23/4) in three trials combined.
- For each participant the expected frequency of consecutive different-color bigrams is 5.75

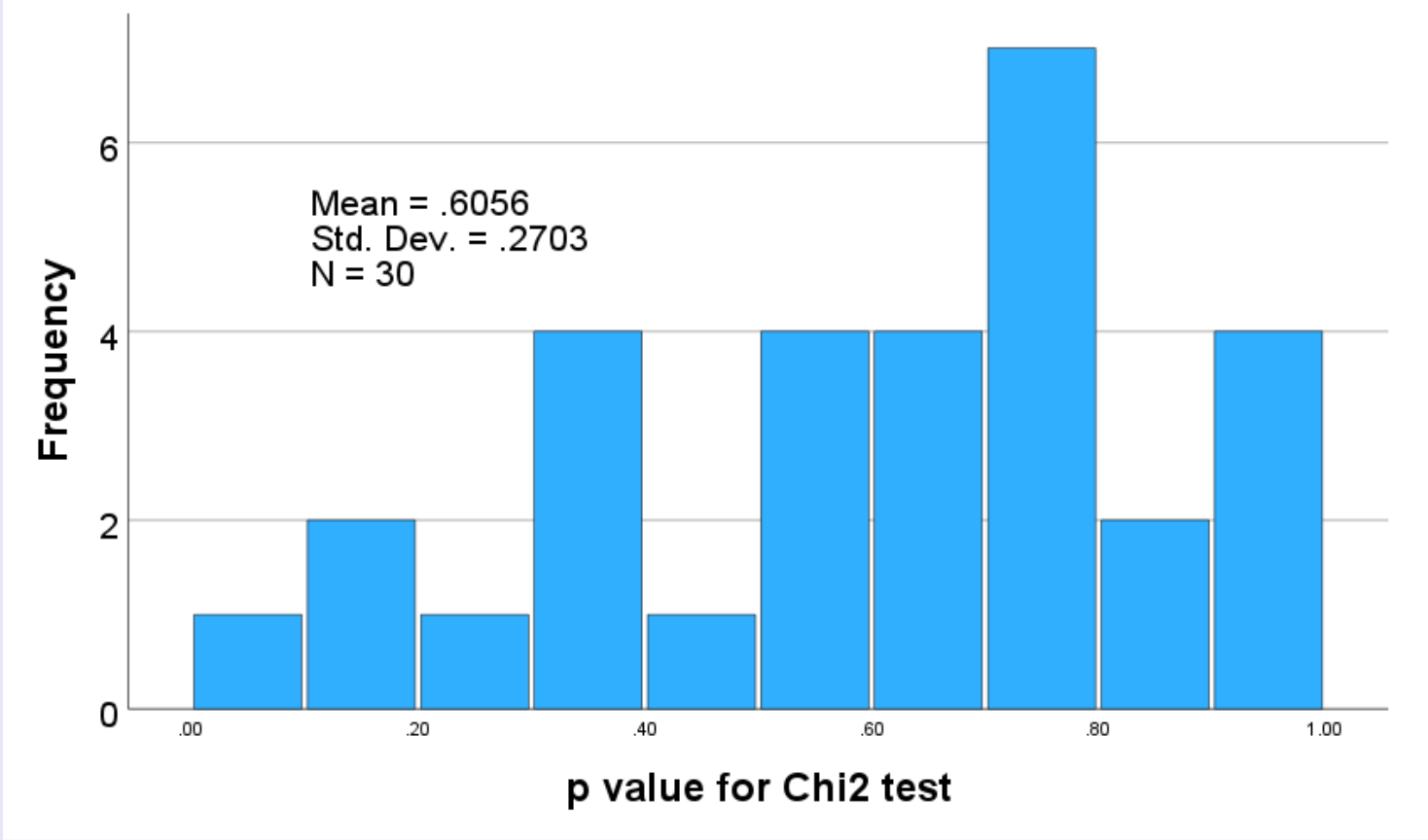
Chi^2 as Data on Executive Control

Single Participant Chi^2

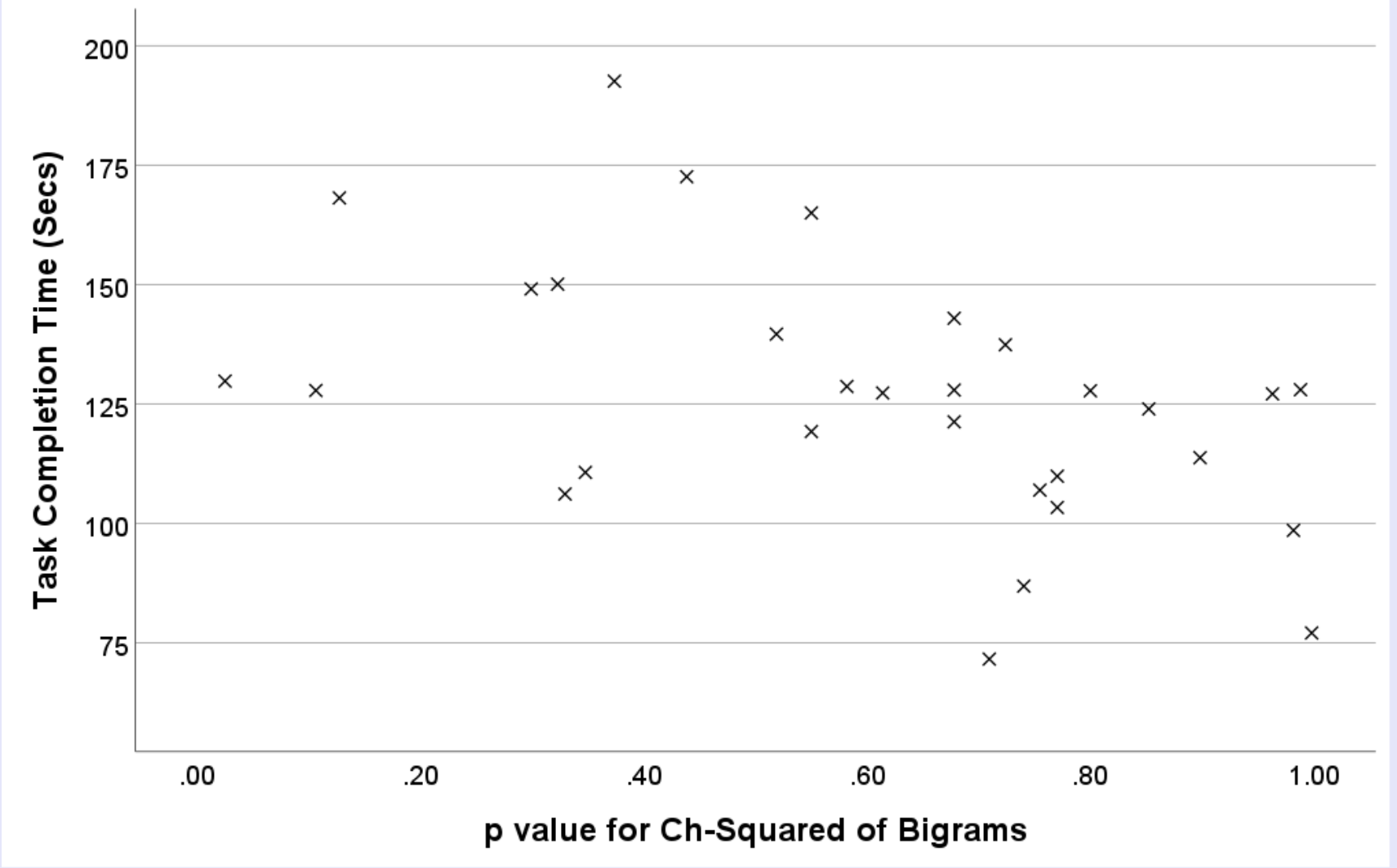
Chi-Square Test for Equal Proportions	
Chi-Square	7.3478
DF	11
Pr > ChiSq	0.7703

Sample Size = 69

p values of all 30 participants

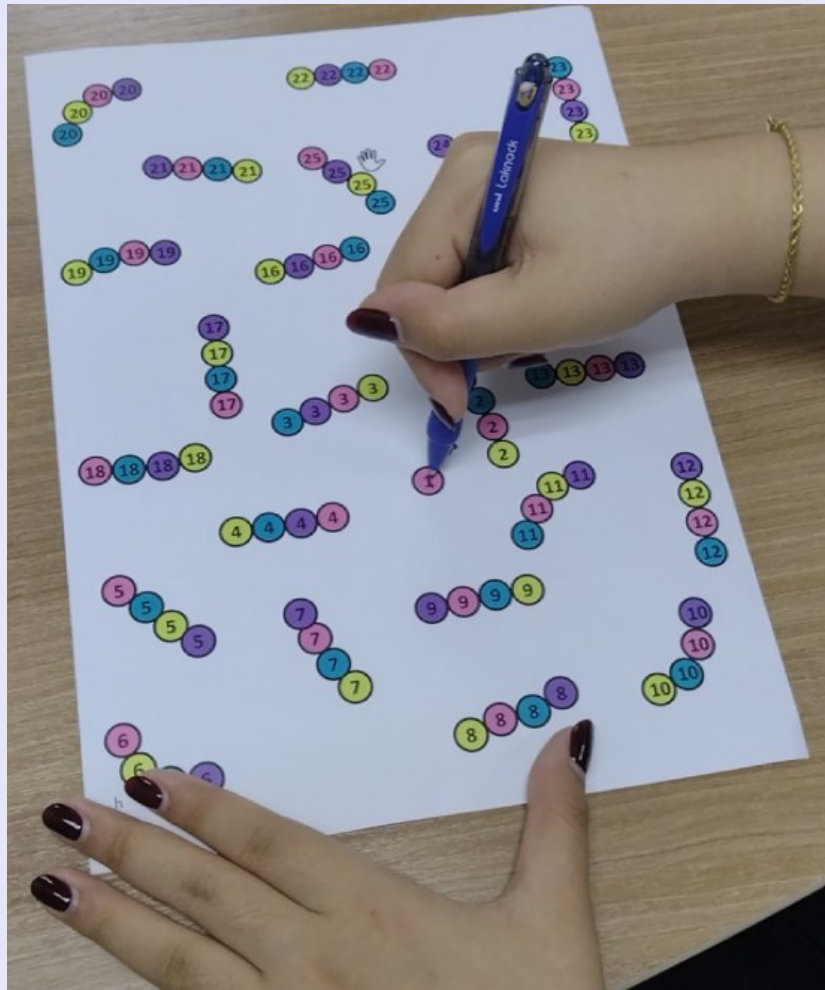


p values negatively correlate with task completion time, r = -.49



Conclusions

- We altered a common cognitive test to introduce free choices. This produces more detailed data than old version of the test.
- We show that Chi-square tests and their p values can be used to estimate the randomness of responses.
- This allows cognitive data with greater ‘density’ (Simon, 1975)
- It is a more ‘executive’ and ‘divergent’ test.



Simon, H.A.: Information processing models of cognition. Annu. Rev. Psychol. 30(1), 363–396 (1979).

Criticisms

- Sample size of 30 is too small
- Are all the rules needed?

I. Join the numbers in sequence with the pen.
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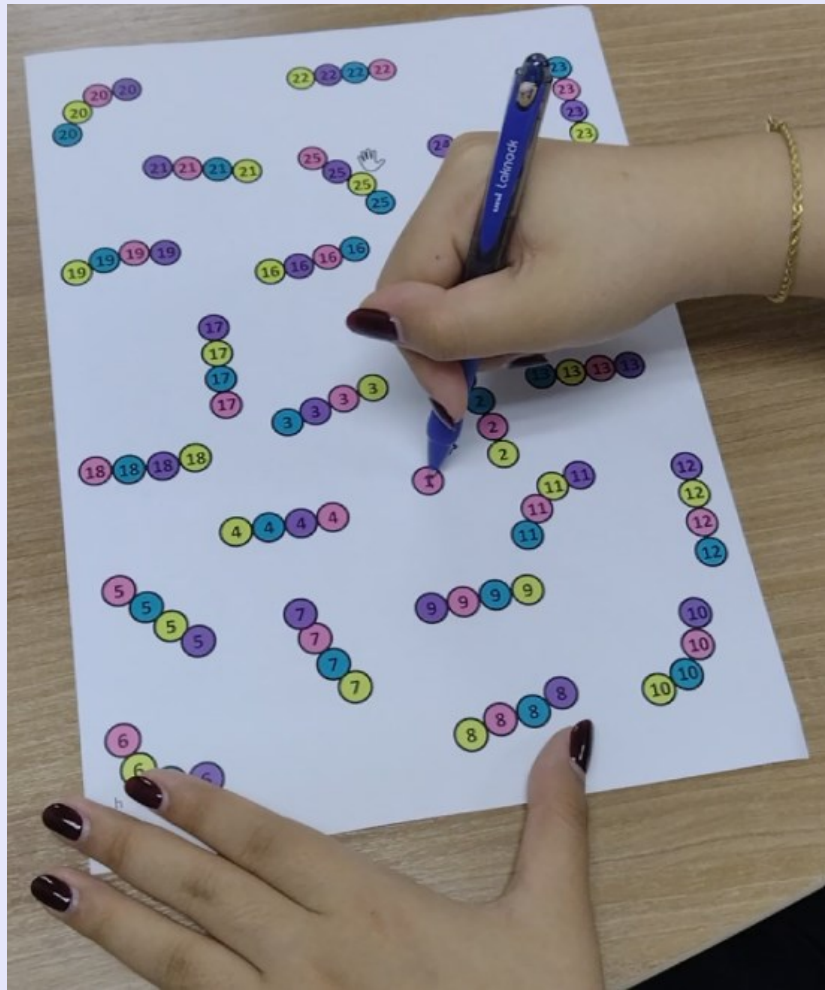

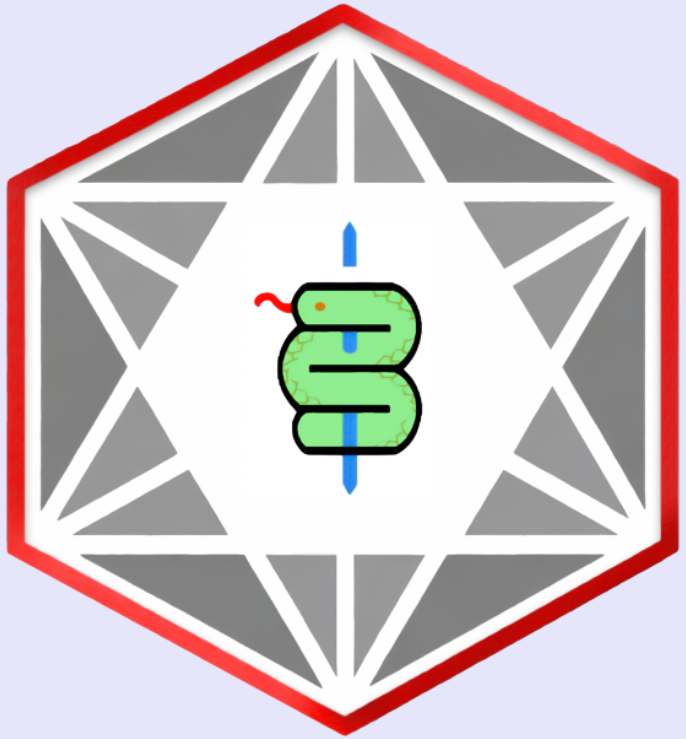

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