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The relationships between cognitive functioning and decision making under value-based conditions in older adults: Findings based on a psychometric network analysis

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ABSTRACT

Decision making (DM) under value-based conditions is pervasive in everyday life and crucial in supporting individuals' wellbeing, especially as age increases and it becomes more difficult to cope with negative consequences of suboptimal choices. Considering that aging induces people to make riskier choices under value-based conditions and that executive functions and memory can support safe choices, the present study investigated the relationships between DM under two of the main value-based conditions (i.e., ambiguity and risk) and the core abilities underlying executive functions and memory in a sample of 138 healthy older adults. Psychometric network analysis was used to assess pairwise associations between such abilities. Results showed positive interconnections between DM under risk and executive functions and memory, whereas DM under ambiguity presented different partial correlations according to the decisional condition (prominent ambiguity vs. ambiguity with a component of risk). The study provided hints for the comprehension of cognitive mechanisms underlying value-based DM in aging.

1. Introduction

Decision-making (DM) abilities are pivotal in several everyday-life domains, such as the financial and medical ones, and are crucial for maintaining the individual's wellbeing and autonomy. This is particularly important in older age, when coping with the negative consequences of suboptimal choices becomes more challenging (Iannello & Colautti, 2023; Salthouse, 2012). A common type of DM encountered in daily life involves the so-called "value-based" decisions, which occur when individuals choose between two or more options based on the subjective value they assign to each. The process involves analyzing the pros and cons for each alternative and predicting possible outcomes (negative and/or positive) (Rangel et al., 2008). Generally, decisions under value-based conditions involve uncertainty as they require evaluating rewards and costs without a complete knowledge of their occurences. In this respect two main different conditions can be identified: ambiguity (the probability of positive or negative outcomes, associated with at least one of the possible choices, is unknown) and risk (the probabilities of the occurrence of possible outcomes are known) (e.g., Brand et al., 2007; Lauriola et al., 2007; Rangel et al., 2008).

To make an advantageous decisional process under such conditions, manifold cognitive and affective abilities are engaged. In particular, executive functions play a central role, including working memory (which is essential for keeping active in memory the mental representations of the choice options and updating the representation of possible options according to information that can gradually be acquired), together with recalling the characteristics previously learned for every option (underlying memory processes). Other executive functions that are pivotal for decisional processes encompass also cognitive flexibility (i.e., being open in considering available information related to choice options), inhibition (i.e., suppressing impulsive and not appropriate responses to a decisional situation), and planning decisional strategies based on feedback (for reviews, see: Antonietti et al., 2023; Colautti et al., 2021, 2022; Schiebener & Brand, 2015). Having in mind that different data are available under conditions of ambiguity and risk, it has been assumed that DM under risk can be primarily supported by

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cognitive flexibility and set-shifting, inhibition, working memory, and other executive functions such as monitoring. On the contrary, DM under ambiguity may rely less on executive functions and more on other factors, such as emotions elicited by feedback (Colautti et al., 2022). Among cognitive abilities, flexibility is thought to play a pivotal role, as it may support the generation of multiple interpretations of the decisional situation involving incomplete information, thereby facilitating the DM process (Brand et al., 2006; Huettel et al., 2006).

Considering the crucial importance of executive functions, it is worth noting that they – together with memory – are among the most vulnerable abilities during the physiological aging process (Bäckman et al., 2006; Damoiseaux, 2017; Ramanoël et al., 2018). Such reduced performances can contribute to older adults' difficulties in engaging in reasoning processes that involve high cognitive load and in adopting functional decisional strategies (Löckenhoff, 2018; Ramchandran et al., 2020). Accordingly, by comparing older adults' and younger ones' performances in decisional tasks under value-based conditions, there is enough agreement – even if the debate is still open and literature presents inconsistent results – that older adults tend to choose risky and suboptimal options especially (i) in new situations (when prior knowledge and crystallized intelligence have a minor role in making a choice), (ii) when there is a high amount of information about the choice options to be taken into account, and (iii) when it is required to learn from previous outcomes to make advantageous choices and avoid risky ones (Bauer et al., 2013; Brand & Schiebener, 2013; Frank & Seaman, 2023; Mata et al., 2011; Schiebener et al., 2014). It is assumed that the result of an advantageous or risky choice is due to the interaction between the individual's age-related cognitive changes and the characteristics of the tasks used to assess value-based DM in terms of cognitive demands (Colautti et al., 2022; Mata et al., 2011). For instance, difficulties in executive functions, such as working memory, can be mirrored in the use of less cognitively demanding DM strategies, in which less information is processed and integrated (Mata et al., 2011). Similarly, low cognitive flexibility can lead to difficulties in changing adequately the DM strategy, especially when tasks involve unexpected results and learning from feedback (Colautti et l., 2022; Frank & Seaman, 2023).

Moreover, age-related neurophysiological changes can play a role in the DM ability, such as the gradual decline in dopaminergic, noradrenergic, and cholinergic functioning that also may bias the activity of the related neural circuits. The mentioned neurotransmitters are assumed to be implied in the affective processing of positive (gain) and negative (loss) feedback occurring after a choice, which is fundamental in the learning process occurring during reward-based conditions (through the neural representation of prediction errors) (for more details, see the review: Frank & Seaman, 2023). Accordingly, it is found that older adults, compared to younger adults, present a decreased neural response in the anticipation of loss but not of gain when choosing under ambiguous and risky conditions. They also experience less negative arousal, supporting the presence of age-related changes in the value assessment that can alter the risk assessment (Samanez-Larkin, 2007; Samanez-Larkin & Knutson, 2015). Thus, under value-based conditions older adults' decisions can be more affected by the prediction of receiving a reward rather than considering the presence of possible losses (Bauer et al., 2013).

Although to date there is a limited number of studies that have analyzed the relationships between executive functions and value-based DM in healthy older adults, the topic is gaining increasing attention in literature. A recent review pointed out that executive functions can be a resource during aging in sustaining an optimal decisional process. Moreover, executive functions can moderate the negative relationship between DM performance and age, especially under conditions of risk, where there is a higher amount of information available to consider during the decisional process compared to conditions of ambiguity. For instance, under risky conditions it is possible to mentally calculate the probabilities of winning under multiple choices, and so the cognitive demand required by the decisional situation is higher compared to ambiguous conditions (Colautti et al., 2022). Nevertheless, two important questions are still not fully clear: 1) how and which abilities encompassing executive functions are involved in older adults' DM under such conditions; 2) the presence of possible differences in these relationships under decisional conditions of risk vs. ambiguity.

All that considered, it appears evident that decisional processes and cognitive abilities are functionally interconnected. Hence we can gain a comprehensive overview of older adults' decisional processes from the investigation of the reciprocal interrelations between different abilities and under specific decisional conditions. So far, from empirical evidence, we would expect that decisional performances under conditions of risk, where more data are present (e.g., the probabilities of occurrence of possible consequences), would be positively correlated with several cognitive abilities, including working memory (sustaining the learning process and the representation of data retrieved from memory combining salient information gradually acquired), inhibition (crucial to suppress prepotent responses that can derive from learned associations of choice-feedback that are no longer appropriate), and flexibility (as it is highlighted to be crucial especially for the selection of optimal decisional strategies). DM under ambiguity would be expected to share fewer and less strong unique associations after accounting for the interrelations shared with all the other components, as fewer pieces of information are usually present (e.g., Brand et al., 2006, 2014; Colautti et al., 2021, 2022; Schiebener & Brand, 2015). Nevertheless, we can hypothesize a pivotal role covered by cognitive flexibility, as making an advantageous decision under ambiguity involves the managing of multiple interpretations derived from the absence of explicit data concerning the probabilities of occurrence of possible results (Huettel et al., 2006). Moreover, it would be important to investigate whether different cognitive abilities are involved under conditions of ambiguity and risk also because so far the involvement of executive functions in value-based DM has been assessed mainly through tests that involve more simple cognitive abilities, such as the Wisconsin Card Sorting Test (Heaton, 1981). The risk with those tests is to underspecify the exact abilities involved (Miyake et al., 2000), and so the "weight" of these abilities in the decisional process cannot be isolated and assessed in depth.

1.1. Aims

The present study aimed to investigate, in a sample of healthy older adults, the relationships among those cognitive abilities that in literature are recognized as potentially relevant to the DM processes, such as executive functions (i.e., working memory, inhibition, and flexibility: Diamond, 2013; Miyake and colleagues, 2000) and short-term memory and two different tasks assessing, respectively, DM under ambiguity and risk. Specifically, the Iowa Gambling Task (IGT; Bechara et al., 1994; Bechara, 2007) was chosen to assess DM under ambiguity and the Game of Dice Task (GDT; Brand et al., 2005) to assess DM under risk. They are two widely used tasks to assess DM under value-based conditions of ambiguity and risk, respectively, and both require individual administration (Buelow, 2015).

To delve into the mentioned relationships, we used the psychometric network analysis approach (Borsboom et al., 2021), a data-driven approach that is especially useful to explore the intercorrelations between many variables which are expected to conjunctively generate the functioning of a psychological process. The psychometric network analysis approach has been shown to bring an innovative perspective for analyzing relationships among various cognitive domains which are expected to be reciprocally correlated as it has been recently proved by a number of neuropsychological and cognitive studies (e.g., Ferguson, 2021; Kellermann et al., 2016; Macchitella et al., 2023; Rotstein et al., 2020; Tosi et al., 2020; Zoccolotti et al., 2021). To the aim of this study, this approach should allow us to: (i) better understand the complexity of the cognitive mechanisms involved in decisional processes representing relationships (in terms of partial correlations) among pivotal cognitive abilities; (ii) display the structure of the relationships found and highlight the global structure of the investigated system (Hevey, 2018); (iii) investigate which cognitive abilities are most central (intercorrelated) to DM under ambiguity and risk during aging.

Applying a psychometric network approach exclusively to an older adult sample limits the possibility of direct comparisons with younger populations in the present study. However, the findings may offer a novel perspective on the complex interrelations among cognitive variables specific to the target group. This may contribute to a better understanding of the connections between DM and key cognitive abilities in older adults, providing useful insight into the cognitive mechanisms underlying decision processes. Such insights may inform the development of targeted interventions aimed at supporting or rehabilitating DM under value-based conditions in the context of aging.

2. Materials & methods

2.1. Participants

One hundred and sixty-five older adults were enrolled in the study. None of the participants showed impairments (e.g., dysarthria, bradykinesia, or other symptoms compromising comprehension, speaking, or writing abilities) that could interfere with the administration of a cognitive battery. Twenty-two of them were excluded because they did not match the inclusion criteria (i.e., neurologic impairments, psychiatric disorders, ongoing clinical investigations for cognitive impairments, the presence of a score below the cut-off in the MiniMental State Examination (MMSE; Measso et al., 1993)). Of a total of 143 participants, four were excluded as they had not finished at least one of the tasks proposed and another one because of a system error in recording the score of the GDT. Therefore, a total of 138 participants (30.43 % male; age range: 60-92 years old; mean age: 73 years $\pm$ 6.95; mean years of education: 12.2 $\pm$ 4.26) were included in the study.

2.2. Procedure

The study was conducted between April 2022 and September 2023. Participants were enrolled from sociocultural centers in Lombardy (Milan) and Emilia Romagna (Piacenza and Ferrara), regions of Northern Italy. Each participant was asked to indicate possible further participants from their social circle (e.g., relatives, friends, colleagues).

Inclusion criteria were: (i) age $\geq$ 60 years old; (ii) unimpaired global cognitive functioning (MMSE $\geq$ 24); (iii) signature to the Informed Consent; (vi) absence of psychiatric or mood disorders; (v) absence of severe systemic disorders, neurologic impairments, progressive or severe brain damages, previous neurosurgical interventions; (vi) absence of a history of severe addictions or impulse control disorders.

Firstly, all the participants underwent a brief anamnestic interview and MMSE to verify that they met the inclusion criteria. Each participant took part in two in-person sessions, each lasting approximately 45 minutes, conducted in a quiet room either at the recruitment centers or at the Department of Psychology of Università Cattolica del Sacro Cuore in Milan. During these sessions, participants completed an assessment battery that included cognitive tests and DM tasks. To ensure a randomized order of the scheduled tests and tasks, the "Randomizer" app for Android systems was used. It is a randomized list generator in which all names of the tools used have been inserted, except for the MMSE.

No incentive was given to take part in the study. Written Informed Consents were collected from all participants before starting the individual sessions. The study was approved by the Ethics Committee of the Università Cattolica del Sacro Cuore in Milan (approval code: 96-21), according to the standards of the Helsinki Declaration (World Medical Association, 2013).

2.3. Materials

Decisional tasks

• Iowa Gambling Task (IGT, Bechara et al., 1994; Bechara, 2007; Mueller & Piper, 2014) was employed to assess DM under ambiguity since it is an adequate example of what a task involving learning from previous trials or feedback means. This computerized task is based on the original IGT developed by Bechara and colleagues (1994). Participants are instructed to maximize an initial amount of $2000 by selecting cards from four decks across 100 trials. The decks differ in both the frequency and magnitude of rewards and penalties. Two of the decks (C and D) are considered safe or advantageous, as repeated selections from these decks result in overall gains that outweigh the losses. The other two decks (A and B) are risky or disadvantageous, leading to significant net losses when chosen repeatedly. To perform successfully, participants must infer which decks are advantageous based on feedback from previous choices, as no information about the decks is provided in advance. These characteristics give rise to two distinct conditions within the IGT. In the first part of the task (involving about the first 40 trials), where the participant usually does not infer the probability nor the magnitude of gains and losses related to each deck, a prominent ambiguous condition is present. In the second part of the task (involving approximately the other 60 trials), when usually participants with normal cognitive functioning infer information about the decks by learning from previous feedback, also the condition of risk – at least in part – is present (e.g., Brand et al., 2007, in which significant correlations between a task to assess DM under risk and the IGT netscores emerged only from trial 41 to 100). The parameters considered are the total netscores (advantageous minus disadvantageous selections) of the first (trials 1-40) and the second (trials 41-100) blocks.

• Game of Dice Task (GDT, Brand et al., 2005) was used to assess DM under risky conditions. This computerized task requires participants to place bets on the outcome of each of 18 die rolls, with the goal of increasing an initial sum of money. For each roll, the probabilities and corresponding gains or losses associated with each betting option are clearly displayed and remain stable throughout the task. Participants can choose to bet on a single number – which offers the highest potential reward but the lowest probability of winning (1:6 chance) – or opt for combinations of two, three, or four numbers. These combinations offer lower rewards but progressively higher chances of winning (2:6, 3:6, 4:6 chance, respectively). The main considered parameter is the netscore: safe (three and four faces of the die) minus risky (one or two faces of the die) choices.

In both the decisional tasks, the total final gains and losses were fictitious and did not result in any actualmonetary gain or loss for the participants.

Cognitive tests

Global cognitive functioning:

• MiniMental State Examination (MMSE, Measso et al., 1993) was used to assess global cognitive functioning. The test consists of 30 items underlying seven distinct cognitive domains: temporal and spatial orientation, word registration, attention and calculation, words recall, language, and constructive praxis. The total score ranges from 0 to 30, with one point awarded for each correct response. This test was used to verify one of the inclusion criteria.

Inhibition:

• Stroop test – short version (Caffarra et al., 2002) was administered to evaluate inhibition in the presence of verbal interferences. The test is divided into three parts: (1) the participant reads color words (i.e., "blue", "green", "red"); (2) identifies the color of a series of dots (colored in blue, green, or red); and (3) names the ink color of color words (i.e., "blue", "green", "red"), regardless of the word's meaning. The completion time for each part of the task is recorded. The Stroop test presents a high heterogeneity in scoring methods, ranging from simply considering the reaction time, to the calculation of composite scores that vary according to the reference norms (Guarino et al., 2020; Karr et al., 2018, Scarpina & Tagini, 2017). A commonly adopted approach, recommended by the Italian validation norms according to Caffarra et al. (2002) and widely used in both research and clinic settings (Scarpina & Tagini, 2017), is the computation of the "Time" parameter using the following formula: TI = T3 − (T1 + T2)/2. The more time the participant requires to complete the task, the greater the impact of cognitive interference. However, several criticisms have been raised toward those "traditional scoring approaches" that rely on computing indexes through subtractive scores or fractions, as these methods may suffer from reduced reliability and, therefore, may not accurately reflect the underlying cognitive abilities (e.g., Van der Elst et al., 2006). As an alternative method, a regression-based approach has been suggested (e.g., Van der Elst et al., 2006), which is based on conducting a regression in which the critical condition of the test (the third part) is the dependent variable and the previous conditions (the first and second parts) are included as predictors. The (standardized) residuals can be saved to obtain a measure of the cognitive ability investigated controlling for the general performance on the previous parts. Following this approach, we derived the indicator for inhibition by saving the standardized residual from a regression where the third part of the Stroop test was the dependent variable and the two first parts of the test were the predictors, thus allowing for appropriately weighting the different components of the test (parameter Stroop test_residual).

Shifting:

• Alternate Fluencies (Costa et al., 2014) was used to assess set-shifting and verbal strategic flexibility through lexical access tasks. The test consists of three sections: (1) phonemic fluency, where the participant is required to generate as many words as possible beginning with a given letter within 60 seconds. It is composed of three trials using the letters A, F, and S; (2) semantic fluency, where the participant is required to retrieve as many words as possible from a specific category within 60 seconds. It is composed of three trials and the categories are colors, animals, and fruits; (3) alternate phonemic/semantic fluency, where the participant is required to alternate between producing words that start with a given letter and words from a specified category within 60 seconds. This section includes three trials: A–colors, F–animals, and S–fruits. Each section is scored based on the number of correctly generated words. Considering all the words mentioned across the three sections, a fourth parameter – referred to as the "Shifting Index" – is traditionally calculated with the formula: alternate fluency score/[(phonemic fluency score + semantic fluency score)/2]. This parameter measures an extra-dimensional set-shifting ability, indicating the extent to which the participant can shift between different mental sets (for further information see: Costa et al., 2014). The same criticism regarding index computation in the Stroop test also applies to the Alternate Fluencies measure. Therefore, following the approach adopted for the Stroop parameter, we computed a regression model in which the score obtained from the third section of the test (alternate fluency) was predicted by scores obtained from the first two conditions (phonemic and semantic fluencies). The (standardized) residuals were saved to obtain a measure of alternate fluency performance that is independent of general performance in the phonemic and semantic fluencies sections (parameter: Alternate Fluencies_residual).

Working memory (updating):

• Digit Span Backward (DB, Monaco et al., 2012) was administered to assess working memory (or updating ability). The participant is asked to repeat a specific sequence of digits in reverse order, with the sequences gradually increasing in length. The score reflects the length of the longest sequence (i.e., number of digits) accurately reported.

Short-term memory:

• Digit Span Forward (DF, Monaco et al., 2012) was used to evaluate short-term memory. The participant is required to repeat a specific sequence of digits in the same order as presented, with the sequences progressively increasing in length. The score reflects the length of the longest sequence (i.e., number of digits) accurately recalled.

3. Analytic plan

3.1. Preliminary analysis

Firstly, to check the normality of the distribution of the variables, the analysis of the asymmetry and skewness and the Shapiro-Wilk test were performed (Hernandez, 2021), revealing that most of the variables were not normally distributed (Shapiro-Wilk: $p < .05$). No missing data were present in the dataset. Descriptive statistics of all indicators are consultable in Table 1. The statistical analyses were performed using R and R-studio (version 4.4.1).

3.2. Psychometric network analysis

A psychometric network model was estimated to investigate the complex pattern of reciprocal associations between decisional tasks and cognitive abilities. Considering the psychometric criticism presented toward the use of traditional composite indexes for measuring inhibition (Stroop test) and flexibility (Alternate Fluencies), we included the standardized residuals obtained from the regression-based approach as indicators of the network presented in the results. In the Supplementary materials, results of the same network psychometric model, including the indicators of inhibition and flexibility computed with the traditional approach, are reported. Specifically, a Gaussian Graphical Model (GGM; Epskamp et al., 2018) was estimated and visualized on the seven variables of interest: DM under risk condition (GDT netscore: GDT), DM

Table 1
Main data about the sample and descriptive statistics of decisional tasks and cognitive measures.

Main characteristics of the sample	N	%
Gender	138	
Male	42	30.4
Female	96	69.6
Marital status		
Single	10	7.5
Married/partnered	82	61.7
Divorced	6	4.5
Widowed	35	26.3
Use of psychoactive drugs		
Benzodiazepine	8	5.8
SSRIs	5	3.62
Others	3	2.17
None	92	66.67
Missed	30	21.74
	M	**SD**
Age	73	6.95
Years of education	12.2	4.26
MMSE	29.2	1.09

Decisional tasks and cognitive tests	M	SD	Asymmetry (standard error)	Kurtosis (standard error)
Decisional tasks				
IGT_block 1	-.55	9.89	3.07 (.21)	21.30 (.41)
IGT_block 2	7.06	21.98	.06 (.21)	.82 (.41)
GDT_netscore	4.65	10.09	-.54 (.21)	-.47 (.41)
Cognitive tests				
Stroop_R	.00	1.01	2.15 (.21)	7.68 (.42)
FA_R	.00	1.01	.62 (.21)	3.28 (.41)
DB_PC	4.45	1.09	-.16 (.21)	1.41 (.41)
DF_PC	6.07	1.09	.19 (.21)	.41 (.41)

Note: SSRIs: Selective Serotonin Reuptake Inhibitors; MMSE: MiniMental State Examination; IGT_1: Iowa Gambling Task block 1; IGT_2: Iowa Gambling Task block 2; GDT: Game of Dice Task netscore; Stroop_R: Stroop test_residual; FA_R: Alternate Fluencies_residual; DB_PC: Digit Span Backward; DF_PC: Digit Span Forward.

under ambiguous condition – first block (Iowa Gambling Task block 1: IGT_1), DM under ambiguous condition with a component of risk – second block (Iowa Gambling Task block 2: IGT_2), cognitive flexibility (Alternate Fluencies_residual: FA_R), inhibition (Stroop test_residual: Stroop_R), working memory (Digit Span Backward score: DB_PC), and short-term memory (Digit Span Forward score: DF_PC).

A cross-sectional GGM is characterized by a structure of variables displayed as nodes which are linked by undirected edges, representing regularized partial correlations between couples of nodes. In a network model, the interest is on the edges, for which it is possible to examine the strength (edge weight) and the valence (positive or negative) of the association between couples of nodes. When an edge between two nodes is present, this means that the variables share a unique association net to the associations that they share with the other variables in the network. In a psychometric network even the absence of an edge is informative, as it represents a conditional independence between the two considered nodes after conditioning to all the other variables. The situation of conditional independence does not exclude the possibility that two nodes are connected indirectly, that is, through shared linkage with at least one other variable in the network, representing a sort of mediating effect.

One of the most important aspects of a GGM is to include only true edges in the network, excluding edges that could be the outcome of spurious relationships between variables due to sampling variation (Epskamp & Fried, 2018). To do this, a regularization is applied to the GGM using the graphical "least absolute shrinkage and selection operator" (LASSO algorithm), which reduces at zero edges with little predictive value (Epskamp et al., 2018; McNeish, 2015), while non-zero edges are those showing sufficient robustness for inclusion in the model. The LASSO algorithm is usually combined with the Extended Bayesian information criterion (EBICglasso) which allows to set a tuning hyperparameter γ to make the regularization more or less stringent (Epskamp et al., 2018). The EBIC hyperparameter is set by default to 0.25 but can be set to 0 to favor sensitivity (i.e., the ability to pick up edges which are present in the true network structure) or to 0.5 to maximize specificity (i.e., exclude all possible false positive edges) (Epskamp et al., 2017). The outcome of a regularized network would be a relatively sparse network (i.e., with only few edges) representing only non-spurious partial correlations between variables, which increase the replicability and interpretability of results compared to the standard correlation coefficients (Epskamp et al., 2018).

In the present study, a regularized partial correlation network was estimated using EBICglasso in *bootnet* R-package (Epskamp et al., 2018). The *huge* method was applied as multivariate normality for the network indicators was not given (Zhao et al., 2015). The tuning parameter for EBIC was set to 0 to increase sensitivity. The network was visualized using *qgraph* (Epskamp et al., 2012).

Additionally, strength centrality has been computed for each of the variables to quantify the influence the focal node has on its neighbors. Strength centrality is calculated by summing all the edge weights that directly connect one node to the others, without mediation from other nodes (Costantini et al., 2015; Robinaugh et al., 2016).

The stability of edge weights estimates was examined with non-parametric bootstrapping procedure implemented in *bootnet* (Epskamp et al., 2018) which is based on recurrently estimating the model under resampled data. We resampled data 1000 times to obtain 95 % confidence interval (CI) of each edge and the average edge estimates from resampled data. We also conducted the bootstrapped difference test for edge weights to examine whether edges significantly (α = .05) differ from each other in strength.

4. Results

4.1. Estimation and visualization of the psychometric network of cognitive abilities and decisional tasks

Fig. 1 shows the network of associations between decisional tasks and cognitive abilities. The exact values of all edges and the standard correlation parameters (to favor reproducibility) are reported in Table 2, together with the strength centrality for each of the nodes. Results showed a network of theoretically sounding interconnections between cognitive abilities. Focusing on associations between cognitive abilities and decisional tasks, DM under risk presented positive pairwise correlations with multiple cognitive abilities: short-term memory (.08), working memory (.16), and flexibility (.16). Only the second block of DM under ambiguity presented a positive association with flexibility (.13), while the first block only presented a marginal positive association with short-term memory (.01), other than a consistent direct association with the second block of the IGT (.39). As expected, working memory and short-term memory showed a positive partial correlation (.31) and short-term memory also shared a marginal linkage with flexibility (.06). After accounting for the associations with all other nodes, inhibition showed marginal negative correlations with few of the other variables: flexibility (-.08), DM under ambiguity block 2 (-.06), and DM under risk (-.03).

Strength centrality confirmed that all variables, except inhibition, shared comparable connections within the network, with DM under ambiguity (block 2), working memory and short-term memory presenting the stronger overall connections, supporting the crucial role of memory and executive functions as cognitive abilities related to DM in aging.

4.2. Stability analysis and simulation study

The results of the stability analysis pointed out that most of edge-weights did not significantly differ in strength, as their CIs overlapped (Fig. 2), meaning that the differences in the edge strength that are

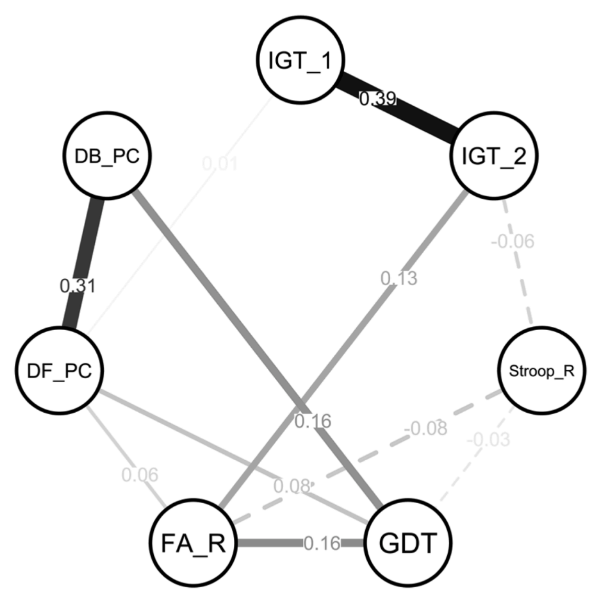

Fig. 1. Estimated network for decisional tasks and cognitive parameters. Note: Solid edges represent positive regularized partial correlations, dashed edges represent negative regularized partial correlations. The nodes indicate the following variables: DB_PC: Digit Span Backward; DF_PC: Digit Span Forward; GDT: Game of Dice Task netscore; IGT_1: Iowa Gambling Task block 1; IGT_2: Iowa Gambling Task block 2; FA_R: Alternate Fluencies_residual; Stroop_R: Stroop test_residual.

Table 2
The lower diagonal reports regularized partial correlations obtained from the GGM. The upper diagonal reports standard Pearson's correlations with significant coefficient for alpha .05 reported in bold. On the diagonal, the strength centrality of each node is reported.

Variable	Parameter used	1.	2.	3.	4.	5.	6.	7.
1. DM under risk	GDT_netscore	.443	.046	.068	**.266**	**.274**	**.243**	-.059
2. DM under ambiguity (block 1)	IGT_block 1	.000	.406	**.520**	-.017	.143	.042	-.012
3. DM under ambiguity (block 2)	IGT_block 2	.000	.393	.580	.053	.032	**.199**	-.128
4. Working memory	DB_PC	.162	.000	.000	.473	**.402**	.059	.009
5. Short-term memory	DF_PC	.084	.000	.013	.311	.466	**.172**	-.043
6. Flexibility	FA_R	.165	.000	.127	.000	.058	.429	**-.183**
7. Inhibition	Stroop_R	-.031	.000	-.059	.000	.000	-.080	.170

Note: GDT_netscore: Game of Dice Task netscore; IGT_block 1: Iowa Gambling Task block 1; IGT_block 2: Iowa Gambling Task block 2; DB_PC: Digit Span Backward; DF_PC: Digit Span Forward; FA_R: Alternate Fluencies_residual; Stroop_R: Stroop test_residual.

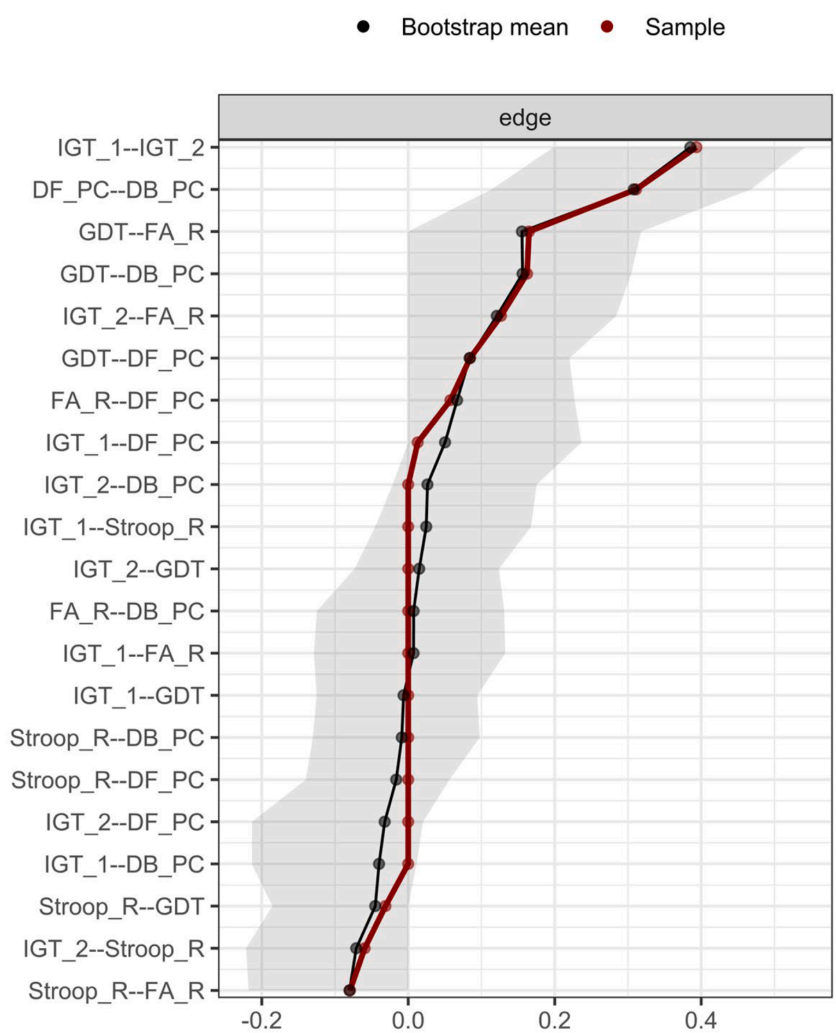

Fig. 2. Accuracy of the edge-weights obtained from 1000 bootstraps. Note: estimated edge weights (red dots) and bootstrap mean of edge weights (black dots) and their 95 % confidence intervals (grey areas). DB_PC: Digit Span Backward; DF_PC: Digit Span Forward; GDT: Game of Dice Task netscore; IGT_1: Iowa Gambling Task block 1; IGT_2: Iowa Gambling Task block 2; FA_R: Alternate Fluencies_residual; Stroop_R: Stroop test_residual.

observed cannot be generalized to the entire population and should instead be interpreted as descriptive of the functioning of the process within the present sample. Notably, most of the smallest edges (e.g., GDT_netscore - Stroop_R) had confidence intervals approaching zero, indicating that it has some likelihood of not being found in different data collections. However, none of the edges had CIs crossing zero, suggesting that we can be confident about the valence of the associations found for all the edges.

To determine to what degree the stability of the results is due to sample size and to inform future replication studies, we ran a simulation study to determine the sample size needed to replicate the parameters obtained in the network assuming that they are equal in the underlying population. We used the *netSimulator* function in *bootnet* (Epskamp & Fried, 2018) to simulate data from samples of 200 to 500 units, using the estimated network as input and 1000 repetitions. The simulation gives back information about the replicability of the network structure in terms of correlation (i.e., between the original and the simulated edges), sensitivity (i.e., the probability of detecting all the edges that were present in the original model), and specificity (i.e., the probability of discarding edges that were absent in the original model). As shown in

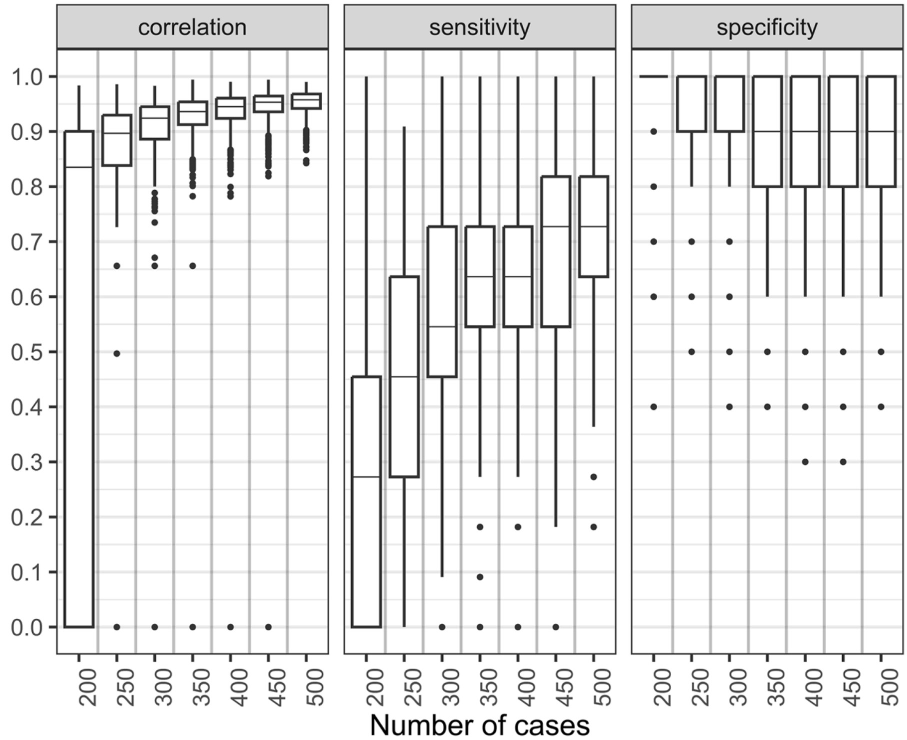

Fig. 3. Results of the simulation study conducted in *bootnet*. Note: The x-axis represents the number of cases tested (200, 250, 300, 350, 400, 450, 500). The y-axis represents the correlation between the original estimates and the simulated ones. Increasing the sample size to at least 250 cases would benefit correlation and sensitivity.

Fig. 3, the simulation suggested the collection of N = 250 to obtain a correlation ≥ 0.80 between the original edge estimates and the ones recovered from the simulation. Sensitivity also increased with the sample size, while specificity did not benefit from further increasing the sample size as expected by using a regularization technique that sacrifices specificity to maximize sensitivity.

The results of the network of partial correlation obtained by including the composite scores for cognitive flexibility (Shifting Index from Alternate Fluencies test) and inhibition (Time parameter from the Stroop test) computed with the traditional approach are detailed in the Supplementary materials. Overall, no major changes were observed in the relationships between cognitive flexibility with DM tasks, except for a few partial correlations of cognitive flexibility with inhibition and short-term memory which was not retrieved when flexibility was calculated with the traditional approach. In contrast, substantial differences can be noted for inhibition. Indeed, when the Time parameter was calculated with the traditional approach, as suggested by the Italian validation norms considered (Caffarra et al., 2002), the parameter appeared isolated, as it did not correlate with anything else.

5. Discussion

The present study sheds light on the relationships between DM, under the value-based conditions of ambiguity and risk, and key cognitive abilities (such as core executive functions and memory) in older adults. The adoption of an innovative approach allowed us to explore direct relationships (in terms of partial correlations) among many variables. This method reduces the probability of overestimating such parameters (and so, allows investigating the unique association between any two variables after accounting for all others; Macchitella et al., 2023) and providing a comprehensive depiction of the DM processes within the recruited sample.

5.1. *Decision making under value-based conditions and cognition in older adults: Evidence from the network analysis approach*

The first important finding is the confirmation, in older adults, that the different involvement of cognitive abilities, and in particular executive functions, would be dynamic, depending on (i) the characteristics of the decisional situation, (ii) contingent information available as the task progresses, and (iii) the cognitive load required by the task (Brand et al., 2007; Colautti et al., 2022; Huettel et al., 2006) .

In the GDT, where a higher amount of information is available, older adults' DM performance was uniquely associated with a broader range of cognitive abilities (including short-term memory, working memory, cognitive flexibility, and inhibition) if compared to the second block of the IGT (which only correlated with cognitive flexibility and inhibition) and the first block of the IGT (where only a weak relationship with short-term memory was found). These findings suggest that under conditions of prominent ambiguity – such as in the first block of the IGT when limited information is available – learning processes and other individual factors (e.g., affective responses, intuitive hunches, and implicit cues), which were not investigated in the present study, may have a predominant role (in line with Brand et al., 2006, 2007; Colautti et al., 2022; Schiebener & Brand, 2015). As the task progresses, and more feedback becomes available (reducing ambiguity and introducing elements of risk), executive functions appear to gain a more crucial role in guiding decisions. Focusing on the positive partial correlations that both working memory and short-term memory shared with GDT, the present findings support the assumptions that these cognitive abilities can be relevant to correctly support mental operations involving a higher cognitive load (e.g., temporary storage and simultaneous processing of information; Brand et al., 2014; Süß et al., 2002), as it especially happens under risky conditions. Furthermore, the weak correlation observed between short-term memory and the first block of the IGT aligns with previous findings (e.g., Brand et al., 2007), suggesting that short-term memory may also support the DM process when limited initial information is available. In such conditions, individuals must build preliminary mental representations to make early predictions (as it occurs in the first block of the IGT). In other words, short-term memory may aid in the initial categorization of decks and facilitate their recall (Brand et al., 2007). However, further studies are needed to better estimate the magnitude of the partial correlation between these two abilities, which may have been underestimated in the present study due to low statistical power. Whereas, in both ambiguous conditions with a component of risk (IGT block 2) and risky conditions (GDT), cognitive flexibility seems to be crucial for making advantageous choices, with also an involvement of inhibition. This finding appears consistent with studies in the DM field which highlighted the pivotal role of cognitive flexibility in considering salient information, building a correct representation of the decisional options, and adopting advantageous decisional strategies based on feedback from previous choices. In this way, cognitive flexibility can enable the decision-maker to shift between sets of options instead of persisting on previous responses if they are no longer functional (Brand et al., 2007; 2014; Colautti et al., 2021, 2025a). Accordingly, inhibition can also support this process by enabling individuals to make advantageous choices in situations that demand high levels of cognitive control. For example, it can help suppress impulsive decisions biased by high immediate rewards that are ultimately associated with greater long-term losses. Similarly, when small losses follow choices from advantageous options, inhibition allows the decision-maker to resist the impulse to switch prematurely to riskier, disadvantageous options (Colautti et al., 2025b; Schiebener & Brand, 2015).

5.2. *Insights from different scoring approaches*

A final note should be dedicated to the results of the network of partial correlation obtained by including the composite scores for cognitive flexibility (Shifting Index from Alternate Fluencies test) and inhibition (Time parameter from the Stroop test) computed with the traditional approach (see the Supplementary materials). The fact that the network of partial correlations obtained using traditional composite scores for inhibition and flexibility appears less dense, and exhibits lower overall strength of edges, may be attributed to the reduced reliability of indicators derived through subtractive methods such as those used with the Alternate Fluencies and Stroop tasks (e.g., Van der Elst et al., 2006). These methods can compromise measurement precision, thereby diminishing the sensitivity needed to identify the unique associations between these cognitive components and other components within the DM process. This claim is confirmed by the results of the stability analysis of the edges and the simulation study, which showed better results for the network conducted with the indicators constructed by regression-based method.

Although this paper does not aim to systematically compare different methods of constructing indicators for cognitive variables, we believe that it is important to encourage reflection on the psychometric methods used to assess these constructs. As demonstrated in the present study, measurement choices have an important effect on the results of empirical investigations and their interpretation, and consequently on the implications of these results on clinical practices.

5.3. *Limitations and future directions*

<u>The cognitive assessment</u>

Firstly, we decided to focus on DM tasks under value-based conditions involving economic decisions and an individual assessment. Thus, results cannot be generalized to other types of DM involving other aspects. Moreover, DM tasks may exhibit reduced ecological validity when applied to the decisional contexts of daily life. However, some studies, such as Brady et al. (2021), have shown that DM tasks can be linked to older adults' risky behaviors, including on-road driving safety. In this phase, our main focus was on conducting an in-depth analysis of the cognitive processes involved in DM, addressing unresolved issues in the literature. Incorporating daily life scenarios, while potentially more realistic, may introduce additional experience-based biases that are difficult to control. Future research should aim to replicate these findings using DM scenarios more closely aligned with real-world situations.

Secondly, following a principle of parsimony, only one test per ability (including both DM and other cognitive functions) was administered to minimize the risk of potential dropouts. This approach was crucial given that data collection occurred shortly after the end of the COVID-19 state of emergency in Italy, with a limited in-presence assessment time scheduled for each participant. Future research could include at least two different tools for each ability to gain a more comprehensive understanding of the mechanisms involved in DM in later adulthood. As well, further studies should widen the assessment of memory by including a broader range of tests that consider learning and long-term memory processes. In this study, simple span tasks were selected due to evidence indicating their comparable predictive validity to more complex measures in assessing higher-order cognitive functioning. Moreover, these tasks are widely adopted in aging research, including both cognitively intact individuals and those with memory concerns (e.g., Kurt et al., 2011; Unsworth and Engle, 2007).

<u>The sample</u>

The number of participants could not be fully representative of the population, calling caution in the generalization of results. Indeed, sampling variation affected the stability of the results, indicating that the study lacked sufficient power to confidently determine whether the edges differed in the strength of their connections. However, the fact that the confidence intervals of all the edges did not cross zero suggests robust evidence for the existence of these associations. What is potentially less reliable, given the sample size, is the exact magnitude of the connections (edge weights), which may have been underestimated due to suboptimal statistical power. As suggested by the simulation study, with a sample size of approximately 250 participants, the network structure – both in terms of edge correlations and specificity – would be highly replicable. Crucially, the simulation study pointed out that specificity estimates in our simulation were excellent, even for samples smaller than the one used in our study. This suggests a low risk of false positive associations, adding confidence to the reliability of the existence of most identified edges. Replication studies are needed to further test their generalizability and make more robust inferences about the functioning of this process at the population level.

Given the difficulty in collecting data from this population, one possibility could be to combine datasets from different studies to achieve adequate power to accurately detect even the smallest associations among network components. Collecting neuropsychological data from older populations is notoriously challenging, especially when cognitive tests are employed as in the present study. Indeed, sample sizes similar to that of the present study are quite common in neuropsychological and cognitive studies adopting network analysis (e.g., Kellermann et al., 2016; Macchitella et al., 2023; Zoccolotti et al., 2021), showing similar results when examining the stability of psychometric networks. Despite these challenges, the psychometric network approach offers a systemic interpretation of cognitive and decisional processes and potentially allows to delve into the mechanisms of cognitive functioning by reducing the risk of overestimating correlations between variables. This methodology aligns well with numerous research questions in the field, providing valuable insights that extend beyond traditional analyses.

Although the results of this study may have limited generalizability, they represent a significant contribution to the literature since they offer insights that lay the groundwork for future replication studies using larger and more diverse samples to bolster the robustness and applicability of the results. Another promising direction for future research is to collect data from various studies that have applied the same tools to assess cognitive abilities and DM and to conduct a meta-analysis using the MAGNA (Meta-Analytic Gaussian Network Aggregation) approach (Epskamp et al., 2022). MAGNA is based on estimating a Gaussian

Graphical Model by aggregating data from multiple datasets, which allows for the examination of similarities and differences in the network structure across multiple studies (e.g., Zambelli et al., 2025). This approach holds significant potential in addressing the need within social science research to aggregate multiple studies to achieve a sufficiently large sample size, thereby increasing the reproducibility and reliability of statistical inferences. Employing MAGNA could enhance the robustness of our findings and provide a more comprehensive understanding of cognitive and executive functions in the older population.

Moreover, a limitation that deserves attention is the absence of a younger adult comparison group, which prevented us from conclusively attributing the emerging results specifically to aging-related processes. It would be interesting if further studies should widen the sample and make comparisons between older and younger adults, to deepen possible differences supporting optimal decisional processes under conditions of ambiguity and risk. In this regard, several methods are available within the network psychometric framework to conduct multi-group comparisons and test whether the network of reciprocal associations between cognitive functioning and DM is invariant across groups (e.g., van Borkulo et al., 2023). It is also worth mentioning that, in line with our aims, this is a cross-sectional study and causal relationships cannot be drawn from the results.

5.4. Conclusions and implications

Despite its limitations, this study represents, to our knowledge, the first attempt to investigate DM specifically in healthy older adults. The adoption of psychometric network analysis offers an innovative approach to capture the complex interplay among the cognitive mechanisms involved in value-based decisional processes. By focusing on DM under both ambiguous and risky conditions, our findings revealed how executive functions – particularly cognitive flexibility and inhibition – and memory can jointly sustain adaptive DM in aging, depending on the cognitive demands of the task.

From a theoretical perspective, this work advances the current literature by moving beyond traditional correlational approaches and supporting a dynamic and integrative model of DM, where the characteristics of the decision-maker (i.e., cognitive profile) interact with contextual decisional features (i.e., ambiguity vs. risk). In doing so, it bridges a critical gap in the study of DM in later life, a field where research remains scarce and fragmented.

In this way, our results contribute to refining cognitive models of DM by highlighting the cognitive architecture that links executive functions and memory to value-based processing in aging. Also, these findings highlight potential cognitive resources that may sustain older adults' autonomy and adaptive functioning in making everyday decisions where value-based conditions are present.

Several practical implications can follow. First of all, the present findings – providing an intuitive representation of the global structure of the decisional processes which can be easily understood by practitioners – can contribute to developing the theoretical bases for designing cognitive training programs to effectively foster and rehabilitate DM, also through the enhancement of the considered cognitive abilities. So far, although DM abilities are recognized as fundamental for everyday life, they are little considered in the field of cognitive enhancement and rehabilitation, even if consequences derived from poor choices become more blatant and serious for the quality of life. This is true particularly in aging, considering that the process of recovering from a significant loss or a suboptimal choice in older adulthood may be particularly complex, as the reduced lifespan can limit the available time for recovering from the negative consequences and bolstering the emotional resilience (e.g., Frank & Seaman, 2023; Iannello & Colautti, 2023). Secondly, further studies could verify if the presence of impairments in cognitive abilities related to DM under value-based conditions – which are commonly assessed in clinical practice – could be an early indicator to detect those people who may present or are prone to develop initial fragility in making decisions under ambiguous and/or risky conditions. Considering that aging is a life stage characterized by new challenges and decisions, aged people are called to face ambiguity and risk in manifold fields, such as in medical or financial situations. So, it appears important to keep focus on the present issues, to sustain older adults' autonomy and higher levels of quality of life.

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CRediT authorship contribution statement

Laura Colautti: Conceptualization, Data curation, Investigation, Methodology, Writing – original draft. **Michela Zambelli:** Data curation, Formal analysis, Methodology, Writing – original draft. **Alessandro Antonietti:** Conceptualization, Methodology, Supervision, Writing – review & editing. **Semira Tagliabue:** Methodology, Supervision, Writing – review & editing. **Paola Iannello:** Conceptualization, Methodology, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.crbeha.2025.100194.

Data availability

Data and code are available at https://doi.org/10.17605/OSF.IO/QB8TW.

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