Exploratory Network Modelling of Complex Human Systems in Time-Use Research: Results from Wave 1 of the Singapore NCSS-NAK 360 Panel Study

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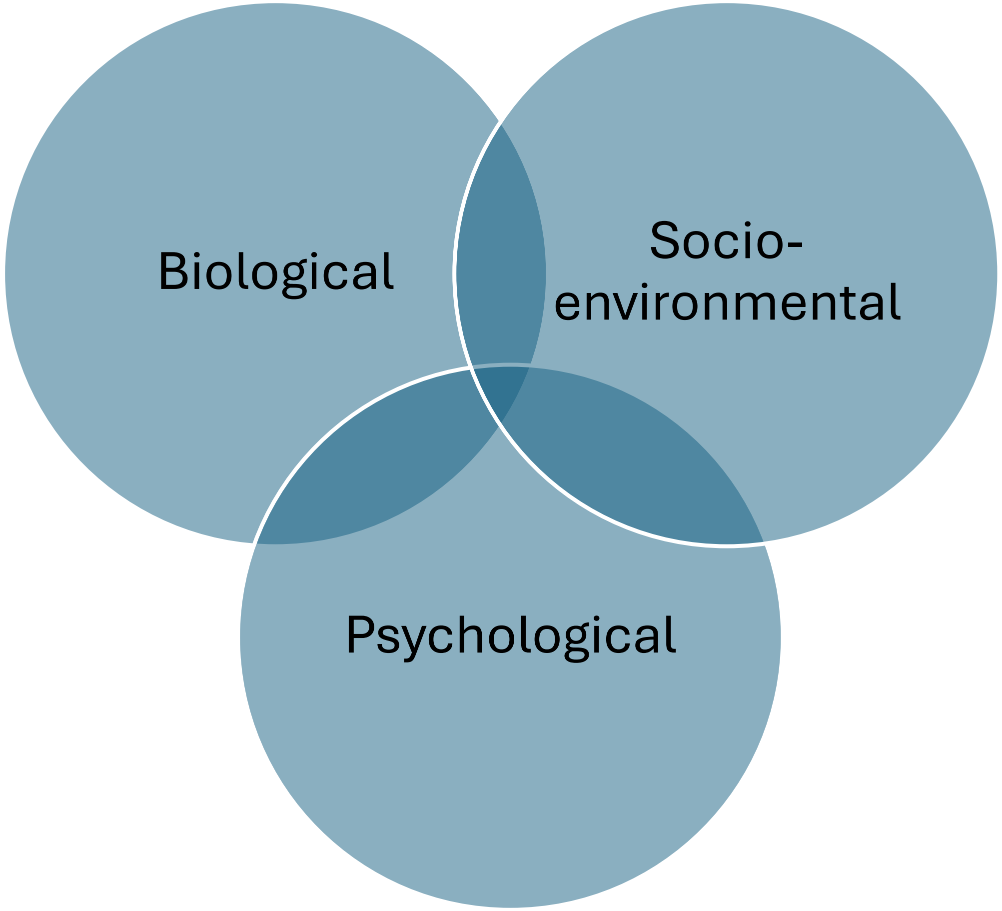
School of Humanities and Behavioural Sciences

Singapore University of Social Sciences

20th Conference on Complex Systems,
Exeter, England

2nd – 6th September 2024

Motivation



Psychological/ human phenomena are known to be complex processes

Background

- To investigate interactions between time-use patterns, Quality of Life (QoL), and socio-demographic factors
- First of 3 waves
- Stratified random sampling by ethnicity and housing type
  - Household listing acquired from Department of Statistics, Singapore
- 1 hour, in-person, verbal interview
  - Conducted across 2021 - 2022
- Final sample - 3013 participants across 1399 households surveyed
  - 47% response rate

Background

Demographics
- 1: Gender
- 21: Number of Household Members
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Heart−Rate Variability Indices
- 30: Average Heart−Rate
- 31: LF/HF Ratio
- 32: HRV_RMSSD
- 33: HRV_SDNN

Time Use Diary
- 2: Travelling
- 3: Sports
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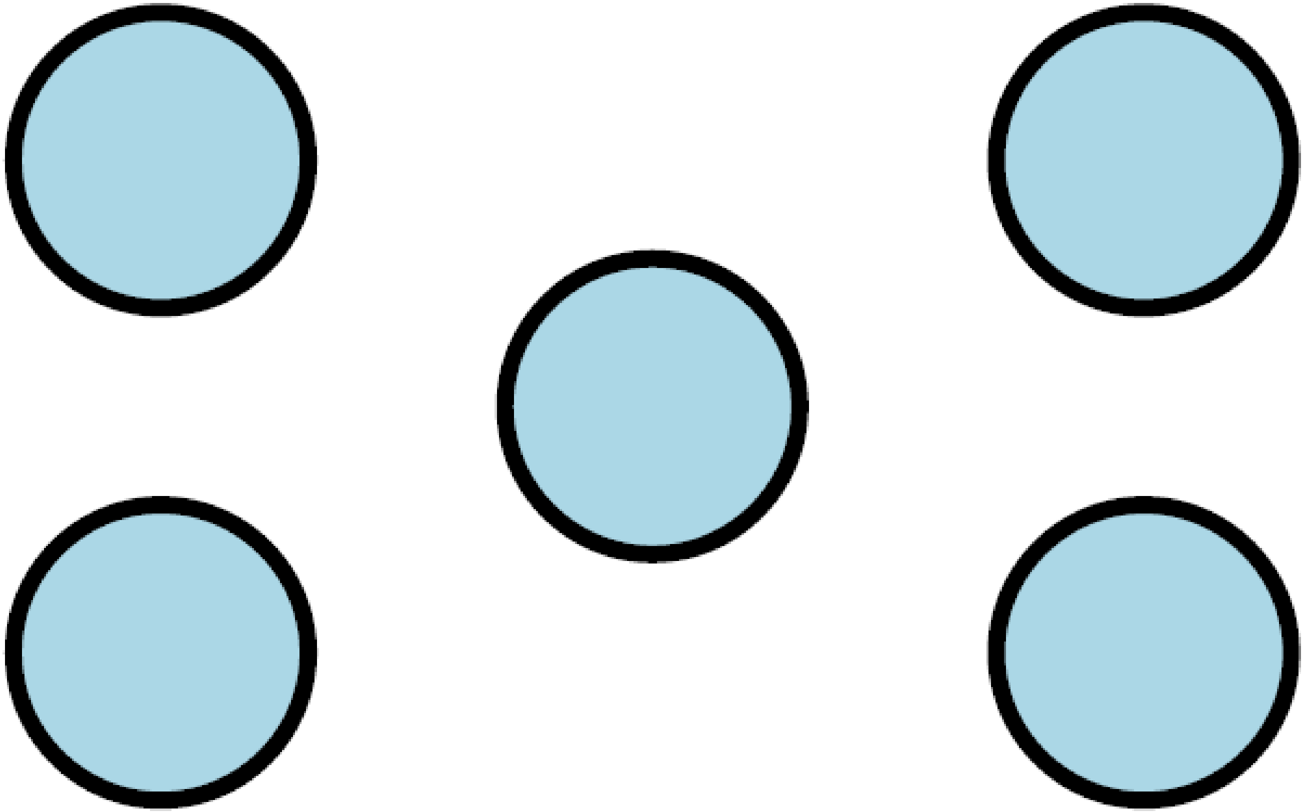
WHOQOL
- 36: WHO_Physical
- 37: WHO_Psychological
- 38: WHO_Social
- 39: WHO_Environmental

Background

$$41 \text{ Variables} \implies \frac{n(n-1)}{2} = \frac{41(40)}{2} = 820 \text{ pairwise comparisons}$$

Network Approach



Variables as nodes/ circles

Network Approach

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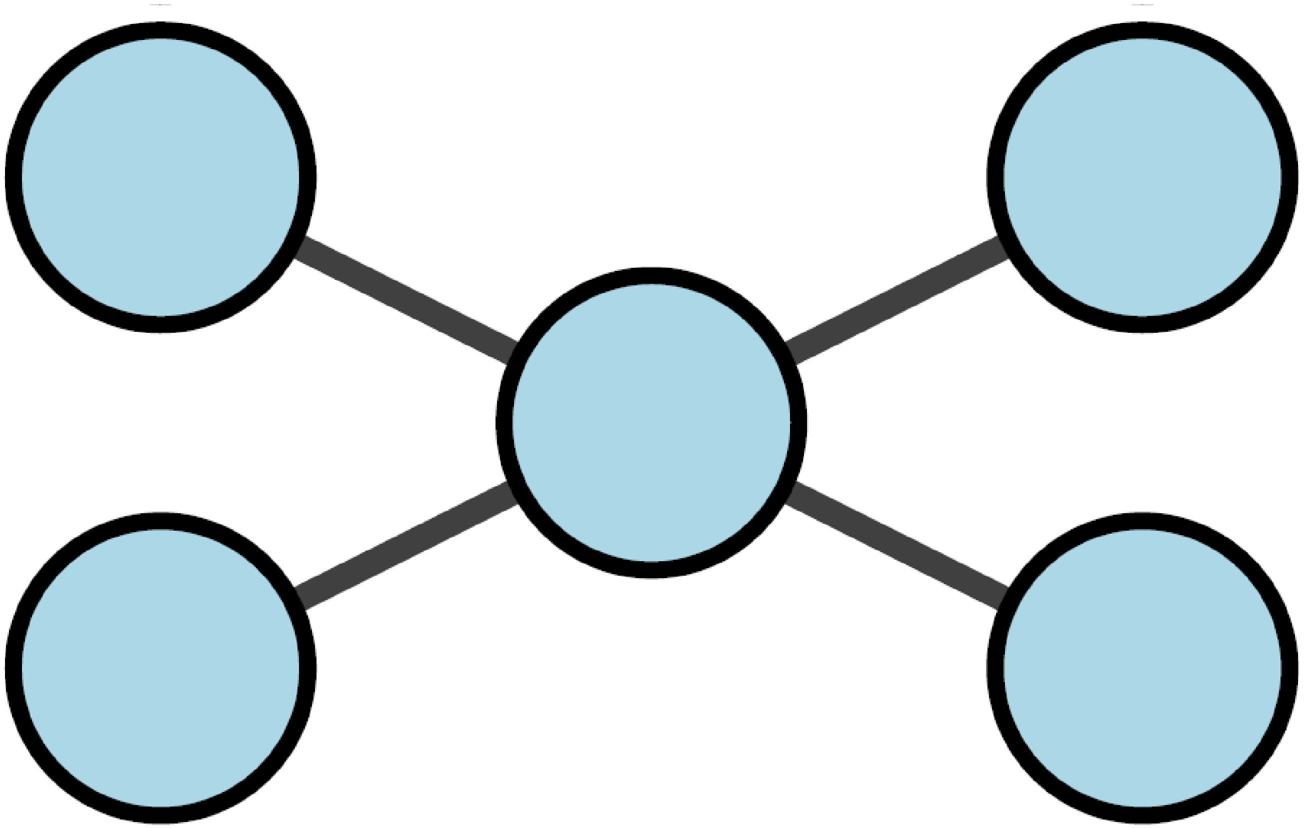
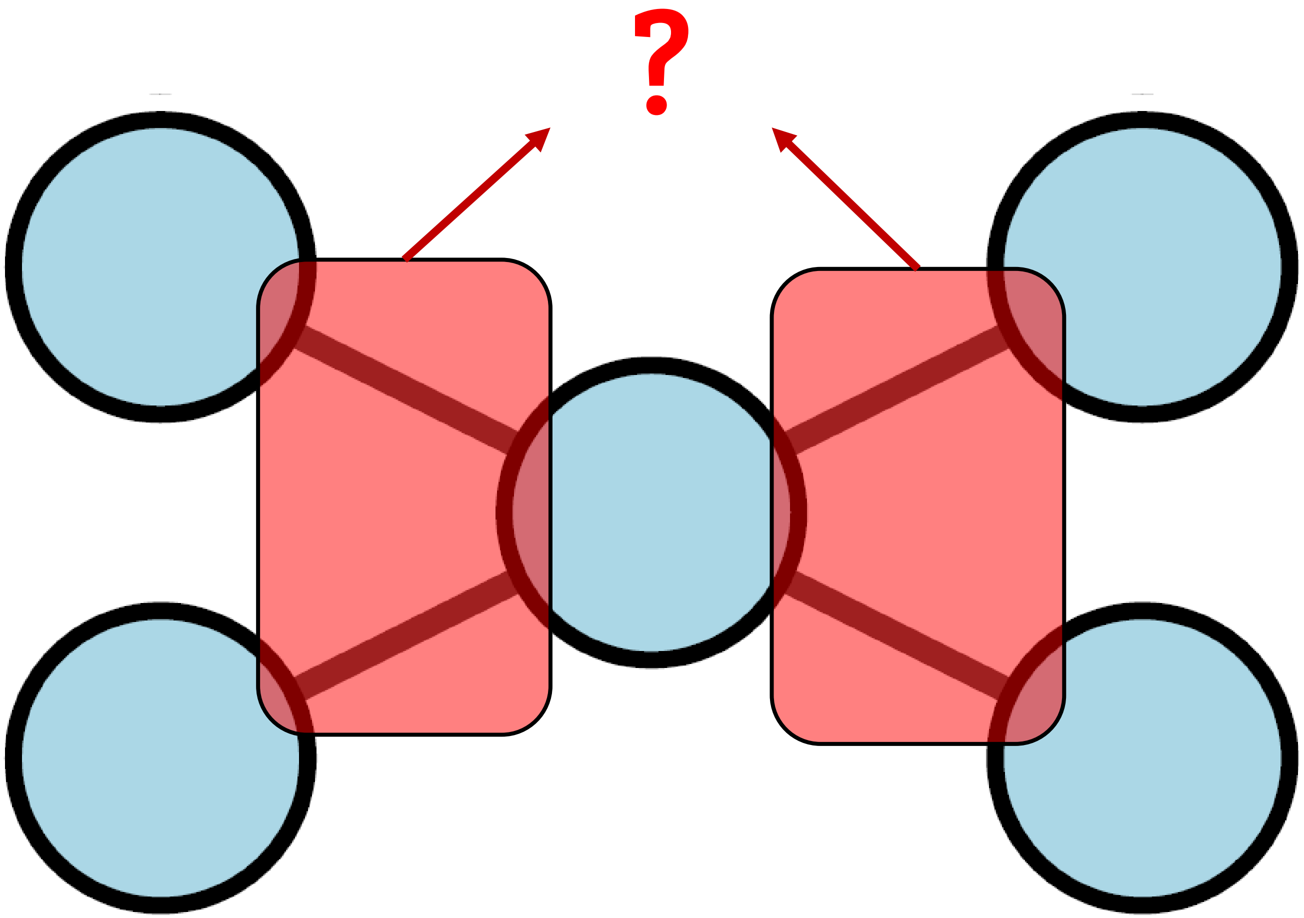


Statistical relations as edges/ lines

Network Approach



Edges/ lines need to be estimated in psychological data

Network Approach

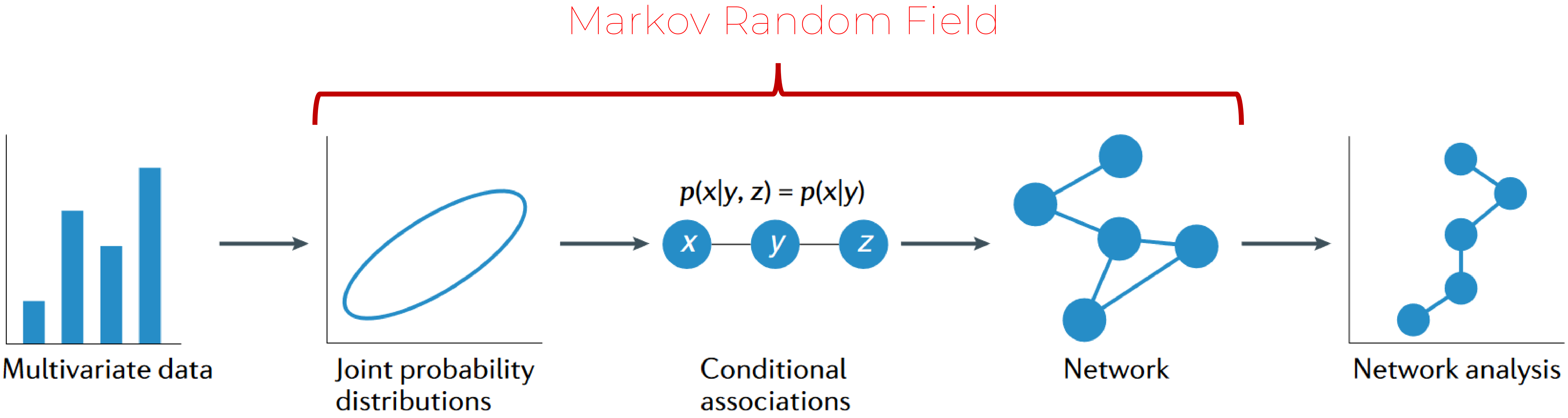


Fig. 1 | **Structure of psychometric network analysis.** Joint probability distribution of multivariate data characterized in terms of conditional associations and independencies. Conditional independencies translate into disconnected nodes; conditional associations translate into links between nodes, typically weighted by the strength of the association. The resulting structure is subsequently described and analysed as a network.

Borsboom, D., Deserno, M. K., Rhemtulla, M., Epskamp, S., Fried, E. I., McNally, R. J., Robinaugh, D. J., Perugini, M., Dalege, J., Costantini, G., Isvoranu, A.-M., Wysocki, A. C., Van Borkulo, C. D., Van Bork, R., & Waldorp, L. J. (2021). Network analysis of multivariate data in psychological science. *Nature Reviews Methods Primers*, *1*(1), 58. https://doi.org/10.1038/s43586-021-00055-w

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Mixed Graphical Model

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Given an undirected graph $G = (V, E)$ — Graph/ Network

where $V = \{X_v | v \in V\}$ — Vertices/ Nodes/ Variables

and E is a set of unordered pairs $\{v_1, v_2\}$ — Edges/ Statistical relations

Yang, E., Baker, Y., Ravikumar, P., Allen, G. & Liu, Z.. (2014). Mixed graphical models via exponential families. *Proceedings of the 17th International Conference on Artificial Intelligence and Statistics*, *33*, 1042-1050. https://proceedings.mlr.press/v33/yang14a.html

Mixed Graphical Model

Global Markov property: Any two disjoint subsets A and B are conditionally independent given a separating subset where every path between nodes in A and B pass through S.

$$X_A \perp\!\!\!\perp X_B | X_S$$

Markov Factorisation property: The distribution of X factorizes according to G if it can be represented as a product of clique functions

$$P(X) \propto \prod_{C \in cl(G)} \psi_C(X_C)$$

Yang, E., Baker, Y., Ravikumar, P., Allen, G. & Liu, Z.. (2014). Mixed graphical models via exponential familie
Proceedings of the 17th International Conference on Artificial Intelligence and Statistics, *33*, 1042-105
https://proceedings.mlr.press/v33/yang14a.htr

Mixed Graphical Model

Global Markov property: Any two disjoint subsets A and B are conditionally independent given a separating subset where every path between nodes in A and B pass through S.

$$X_A \perp\!\!\!\perp X_B | X_S$$

If probability density is positive

Markov Factorisation property: The distribution of X factorizes according to G if it can be represented as a product of clique functions

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Mixed Graphical Model (MGM)

Neighbourhood of node *s*

Base measure

$$P(X) = \exp\left\{ \sum_{s\in V} \theta_s \boxed{\phi_s(X_s)} + \sum_{s\in V} \sum_{\boxed{r\in N(s)}} \theta_{s,r}\phi_s(X_s)\phi_r(X_r) + \right.$$

Sufficient statistic functions specified by exponential family

$$\left. \cdots + \sum_{r_1,\dots,r_k \in \mathcal{C}} \theta_{r_1,\dots,r_k} \prod_{j=1}^{\boxed{k}} \phi_{r_j}(X_{r_j}) + \sum_{s\in V} \boxed{B_s(X_s)} - \Phi(\theta) \right\},$$

Order of interactions

where $\Phi(\theta)$ is the log-normalization constant.

Haslbeck, J. M. B., & Waldorp, L. J. (2020). mgm : Estimating time-varying mixed graphical models in high-dimensional data. *Journal of Statistical Software*, *93*(8). https://doi.org/10.18637/jss.v093.i08

Mixed Graphical Model (MGM)

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$$\hat{\theta} = \arg\min_{\theta} \left\{ \mathcal{L}(\theta, X) + \lambda_n ||\theta||_1 \right\},$$

Algorithm 1 *(Estimating Mixed Graphical Models via Neighborhood Regression)*

1. *For each $s \in V$*
   (a) *Construct design matrix defined by k, the order of the MGM*
   (b) *Solve the lasso problem in* [redacted] *with regularization parameter λ_n*
   (c) *Threshold the estimates at τ_n* (beta-min condition)
   (d) *Aggregate interactions with several parameters into a single edge-weight*
2. *Combine the edge-weights with the AND- or OR-rule*
3. *Define G based on the zero/nonzero pattern in the combined parameter vector*

Haslbeck, J. M. B., & Waldorp, L. J. (2020). mgm : Estimating time-varying mixed graphical models in high-dimensional data. *Journal of Statistical Software*, *93*(8). https://doi.org/10.18637/jss.v093.i08

Network Estimation

```
library(mgm)
fit_mgm <- mgm(data = as.matrix(data),
               type = var_type,
               levels = var_level,
               k = 2,                  → pairwise
               lambdaSel = "CV",       → cross-validation
               lambdaFolds = 10,       → 10-fold
               ruleReg = "AND”)        → AND-rule
```

Haslbeck, J. M. B., & Waldorp, L. J. (2020). mgm : Estimating time-varying mixed graphical models in high-dimensional data. *Journal of Statistical Software*, *93*(8). https://doi.org/10.18637/jss.v093.i08

Node Predictability

For continuous variables:

$$R_A^2 = 1 - \frac{var(\hat{A} - A)}{var(A)},$$

Proportion of variance explained

Haslbeck, J. M. B., & Waldorp, L. J. How well do network models predict observations? On the importance of predictability in network models. *Behavior Research Methods*, *50*, 853–861 (2018). https://doi.org/10.3758/s13428-017-0910-x

Node Predictability

For categorical variables:

Accuracy

$$\mathcal{A} = \frac{1}{n} \sum_{i=1}^{n} \mathbb{I}(y_i = \hat{y}_i)$$

Proportion of correct predictions by marginal distributions

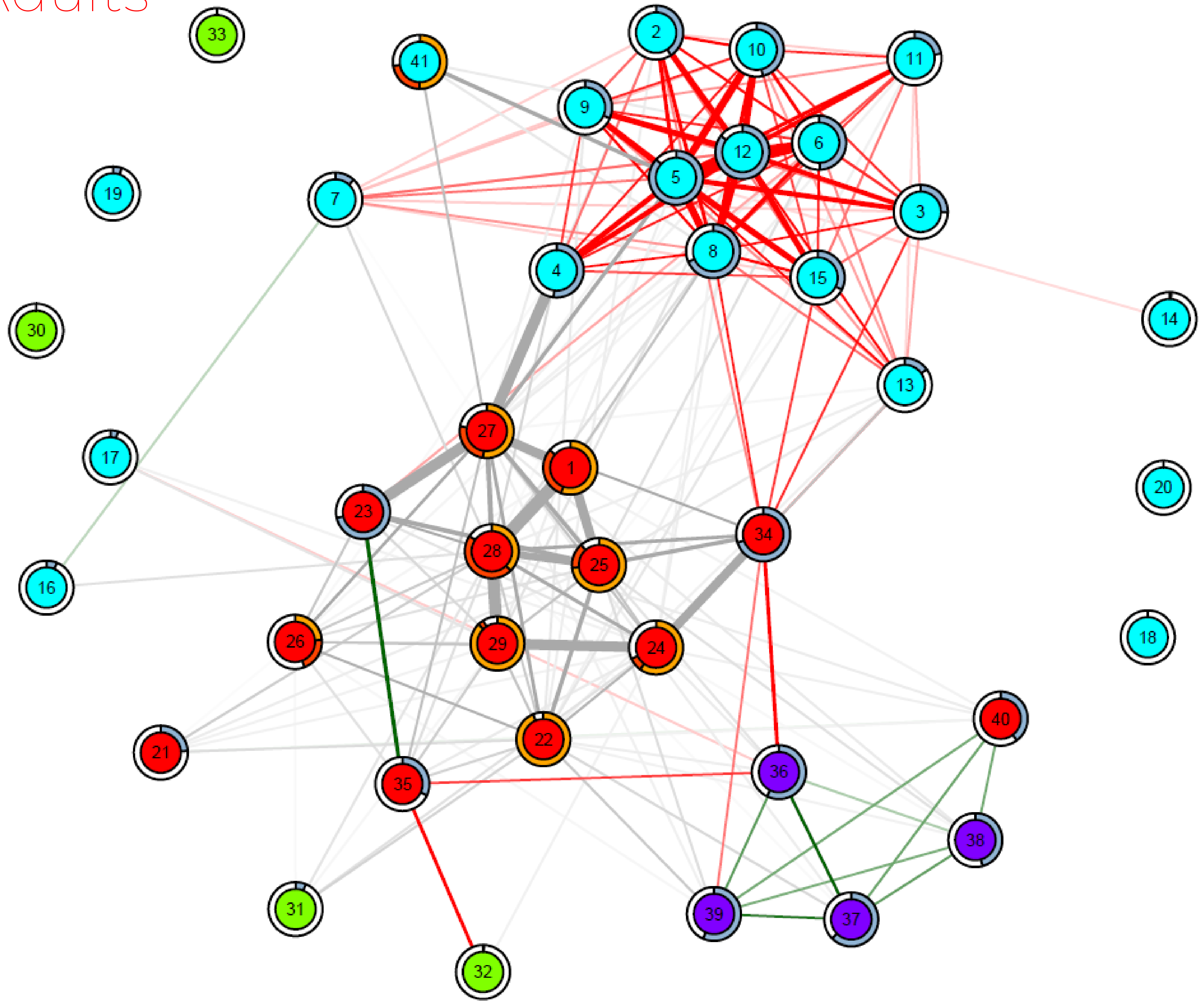
Normalised accuracy

$$\mathcal{A}_{norm} = \frac{\mathcal{A} - \max\{p_0, p_1, \ldots, p_m\}}{1 - \max\{p_0, p_1, \ldots, p_m\}}.$$

Proportion of correct predictions beyond what is predicted by marginal distributions

Haslbeck, J. M. B., & Waldorp, L. J. How well do network models predict observations? On the importance of predictability in network models. *Behavior Research Methods*, *50*, 853–861 (2018). https://doi.org/10.3758/s13428-017-0910-x

Adults



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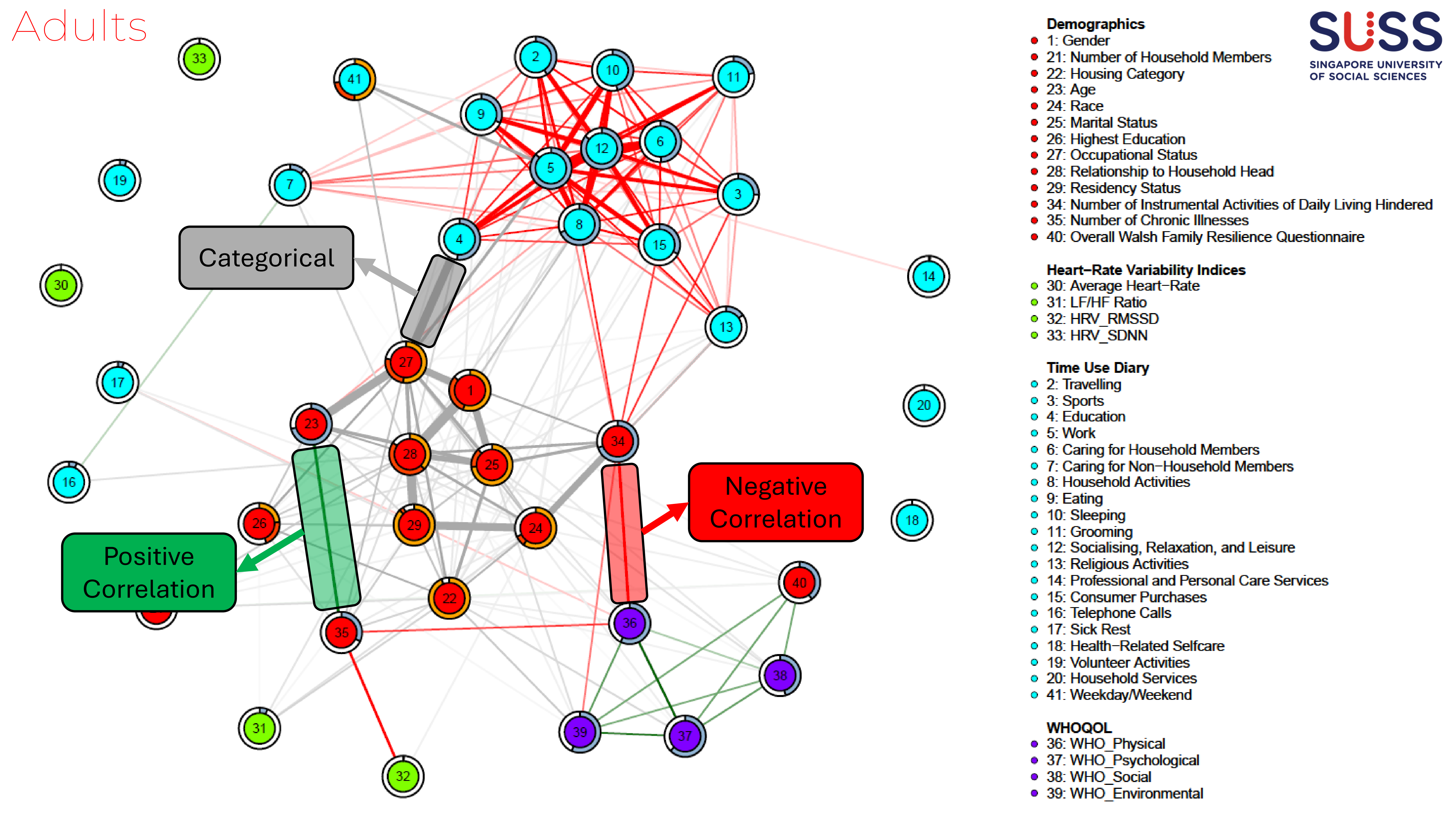
Adults
Categorical
Positive Correlation
Negative Correlation
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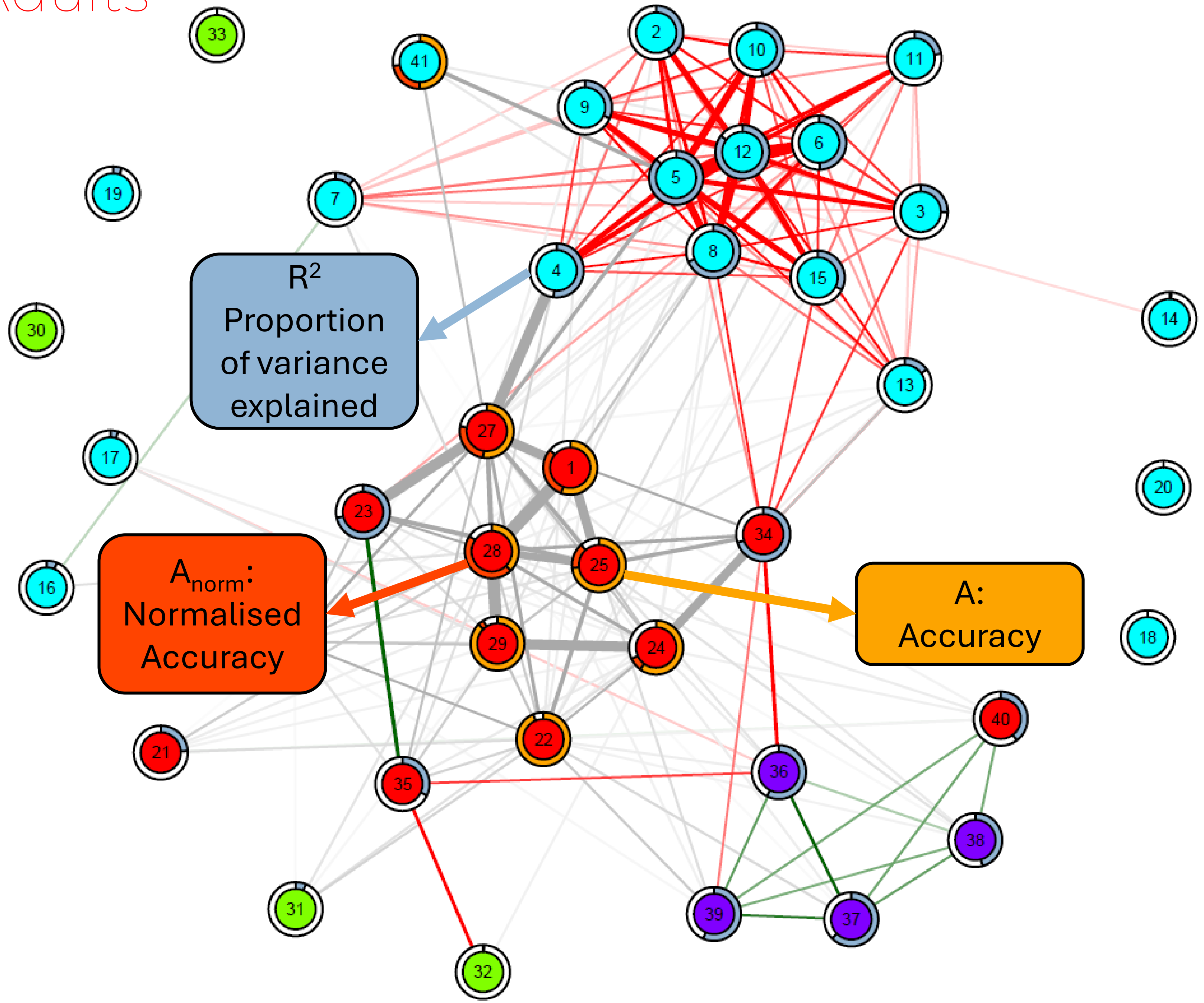

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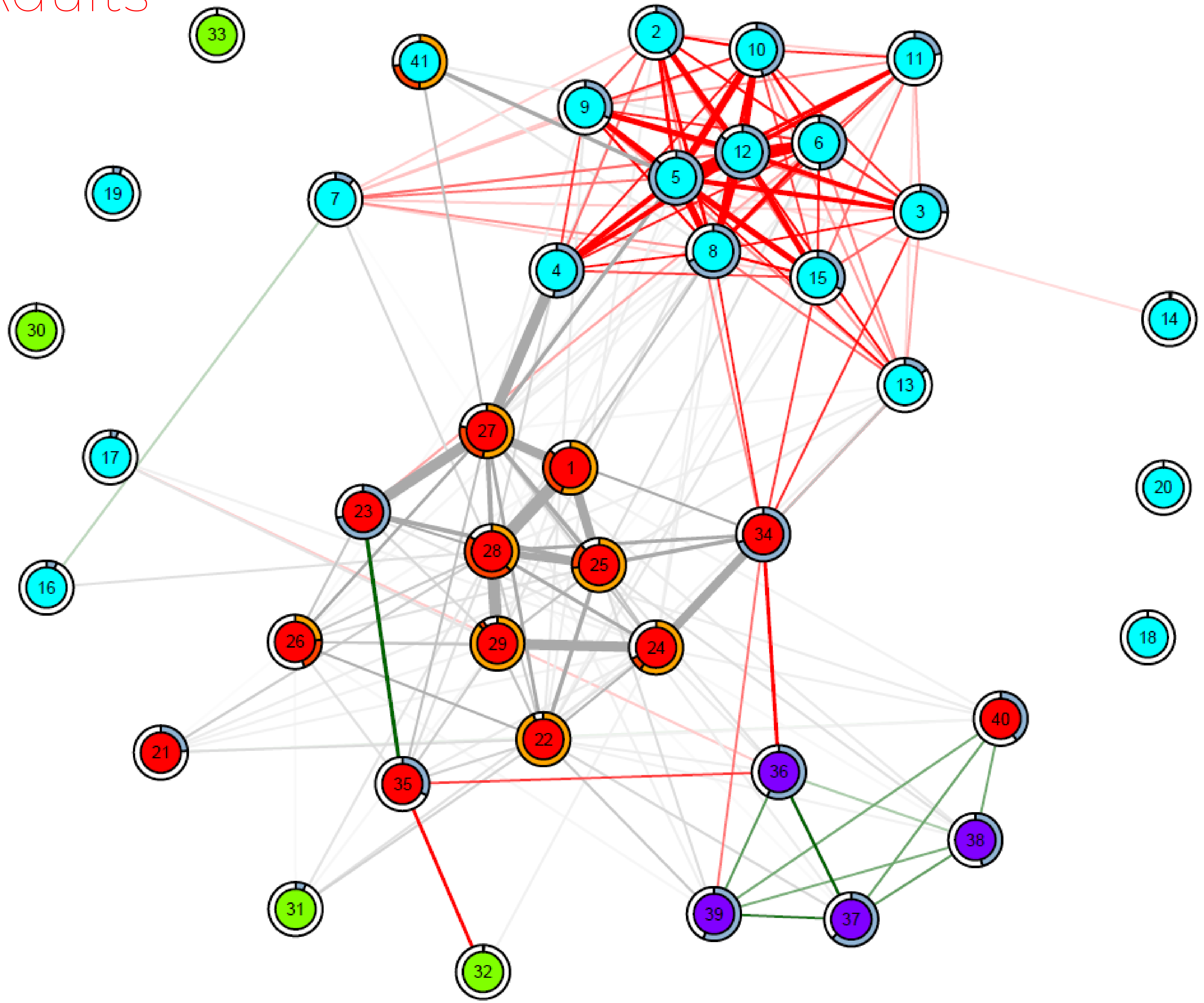

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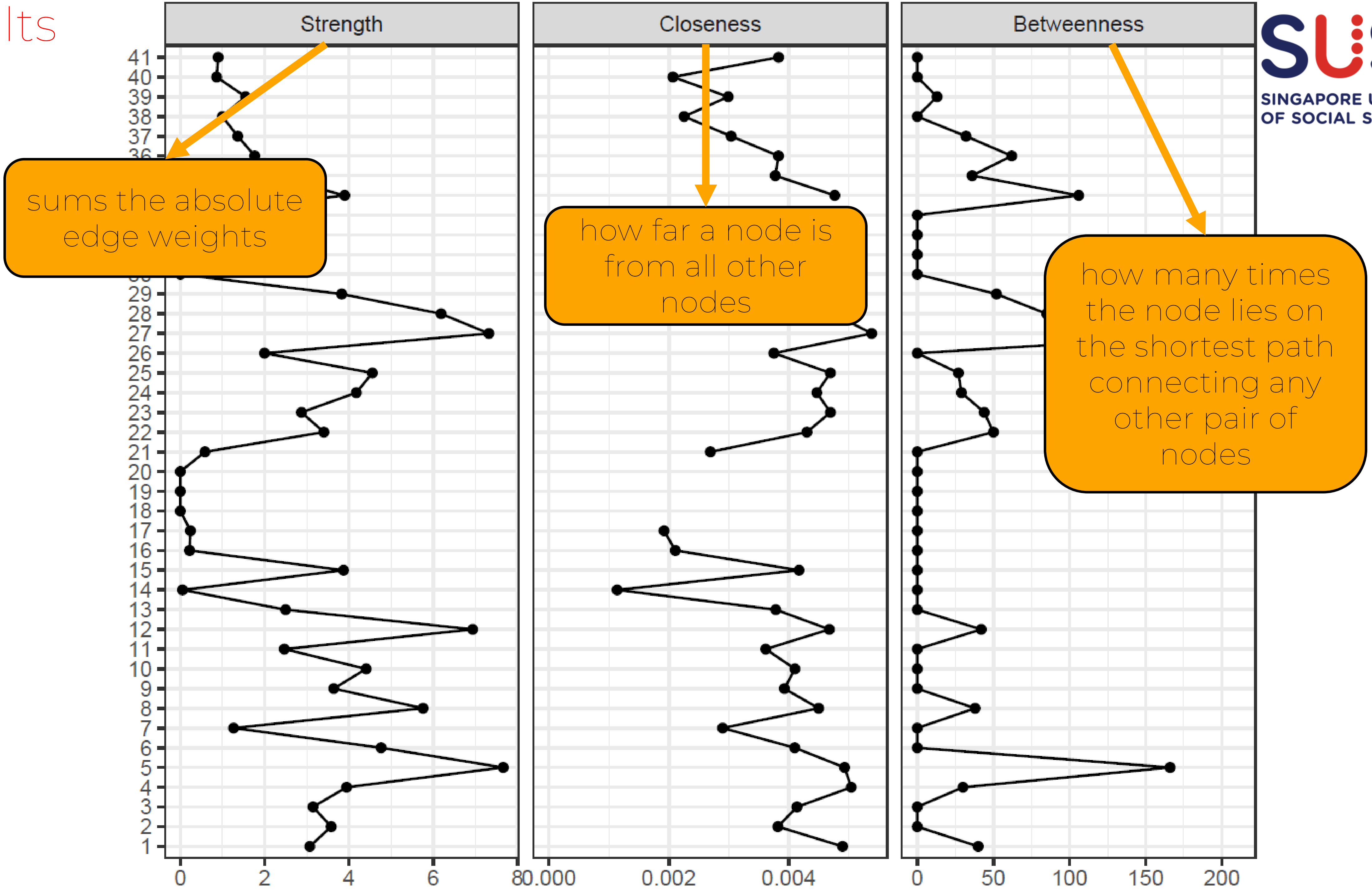

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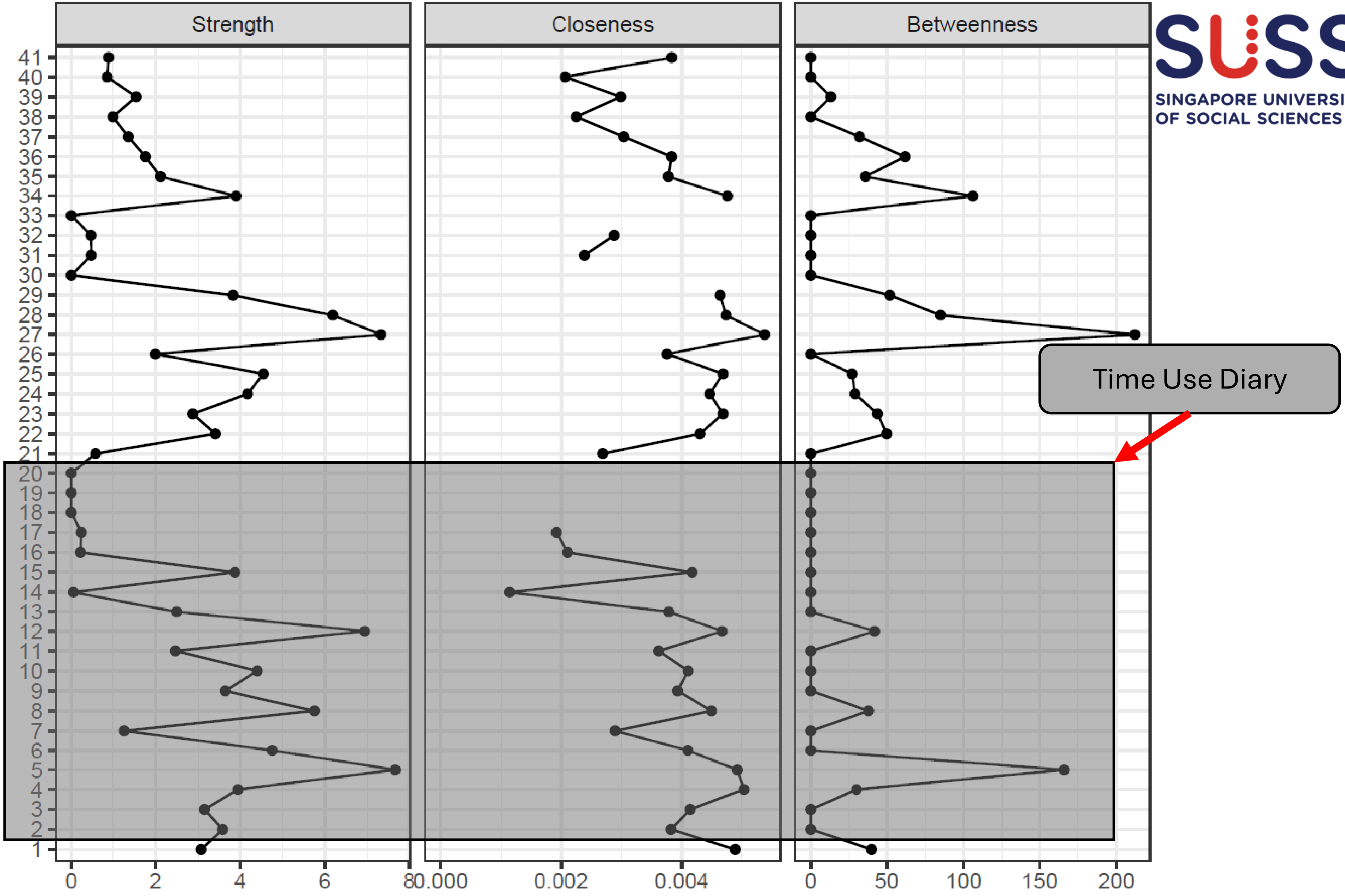
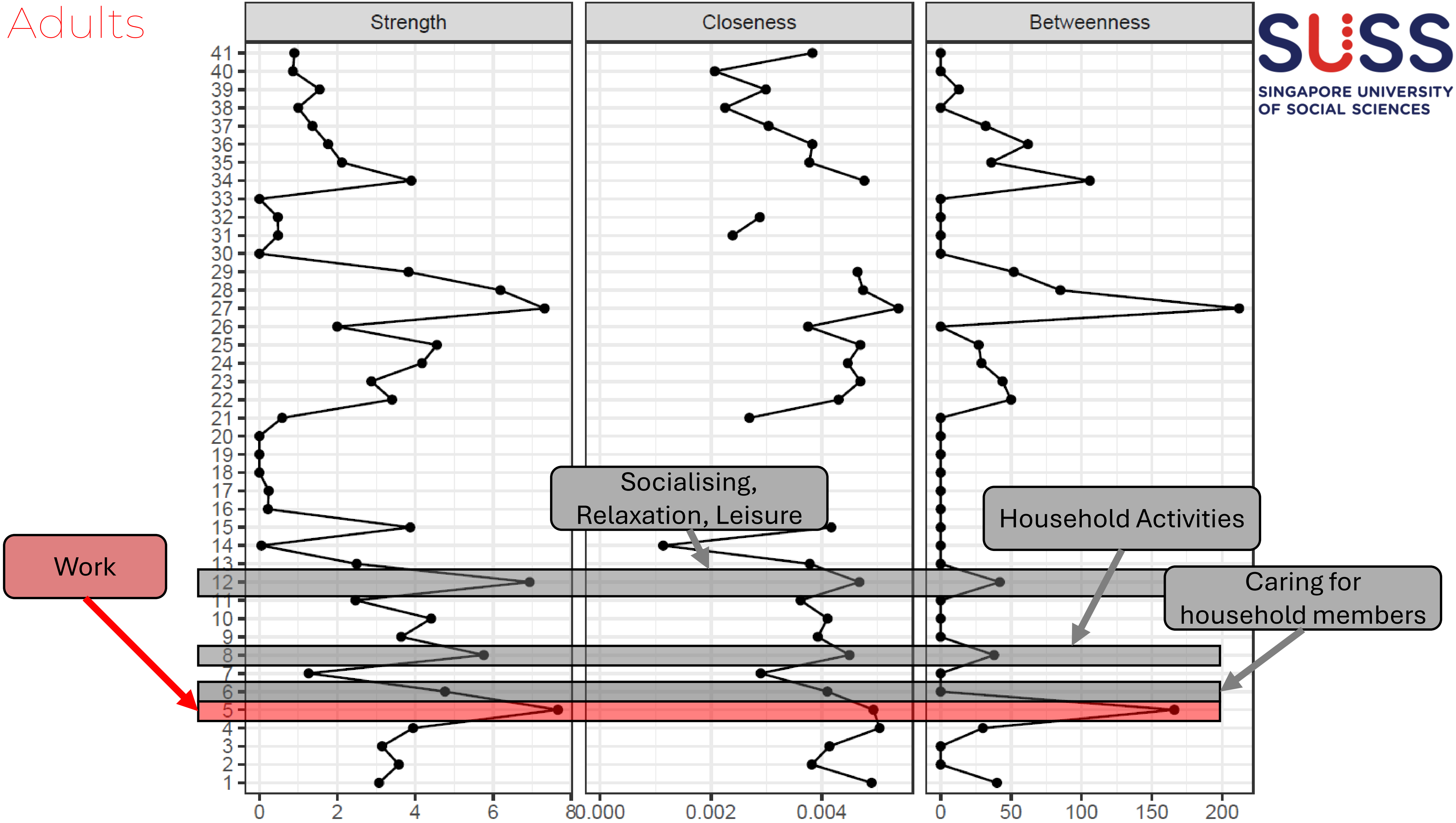

Strength
Closeness
Betweenness
Time Use Diary
0
2
4
6
8
0.000
0.002
0.004
0
50
100
150
200

Adults



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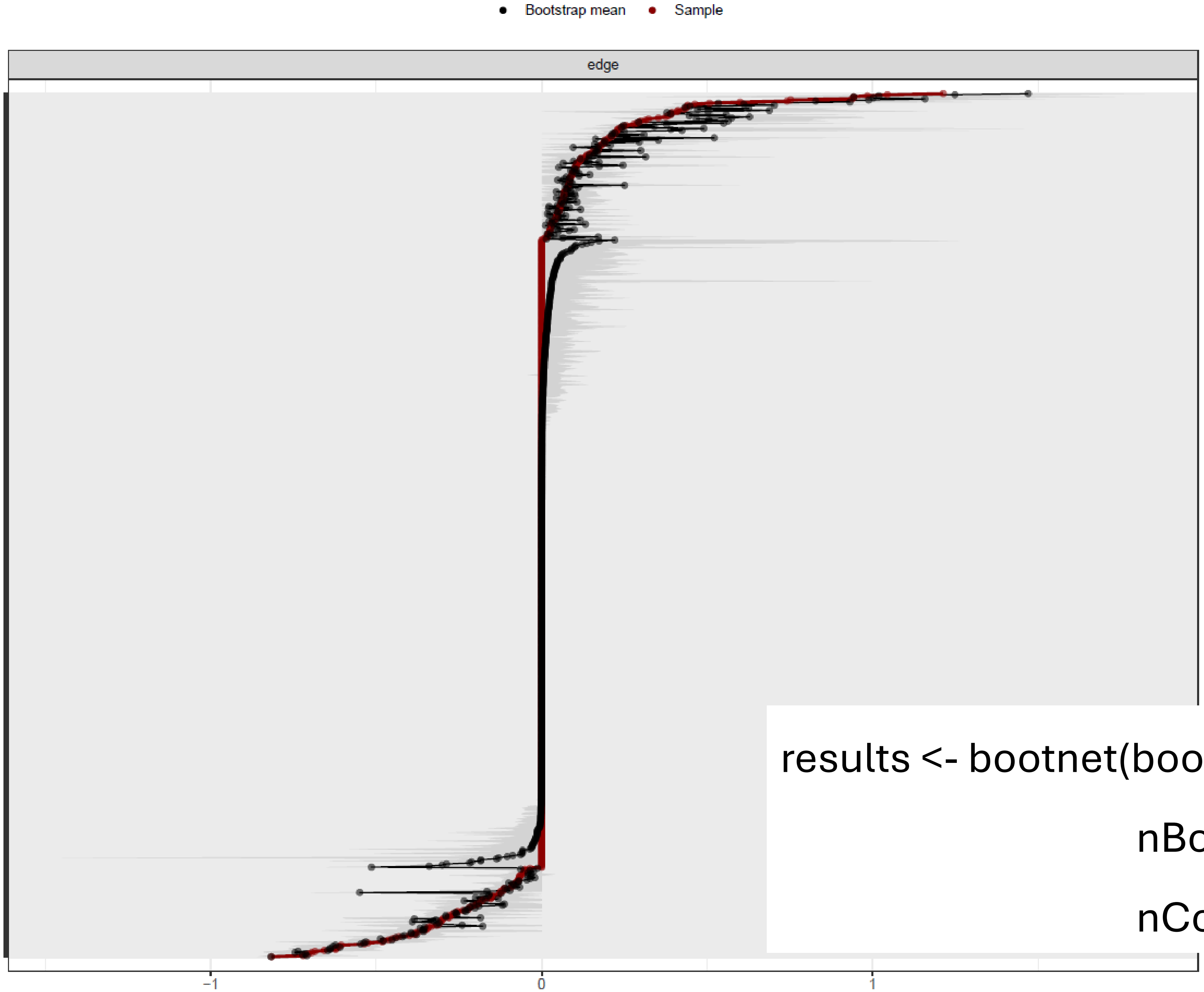


```
results <- bootnet(boot_data,
                   nBoots = 500,
                   nCores = 12)
```

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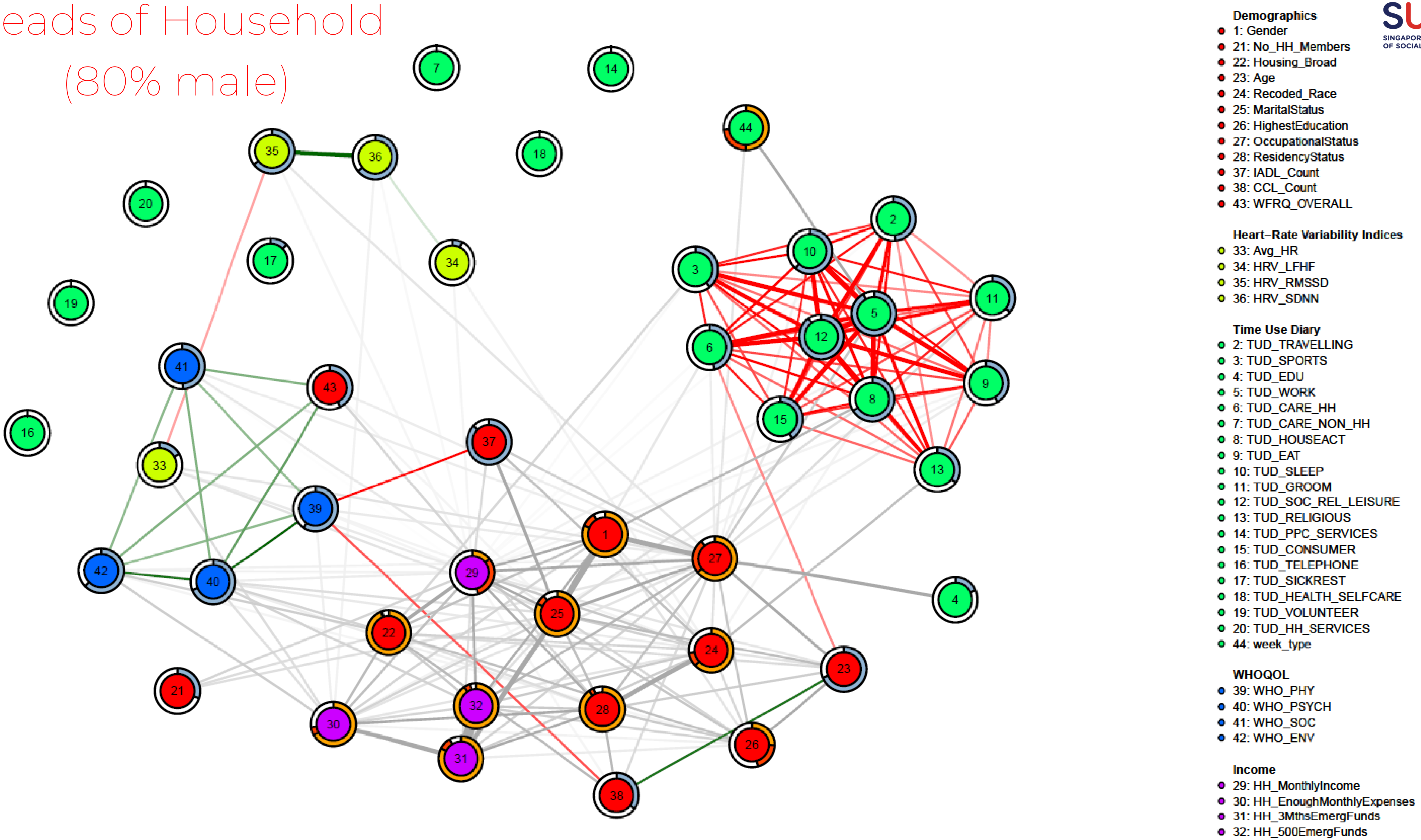
Heads of Household (80% male)



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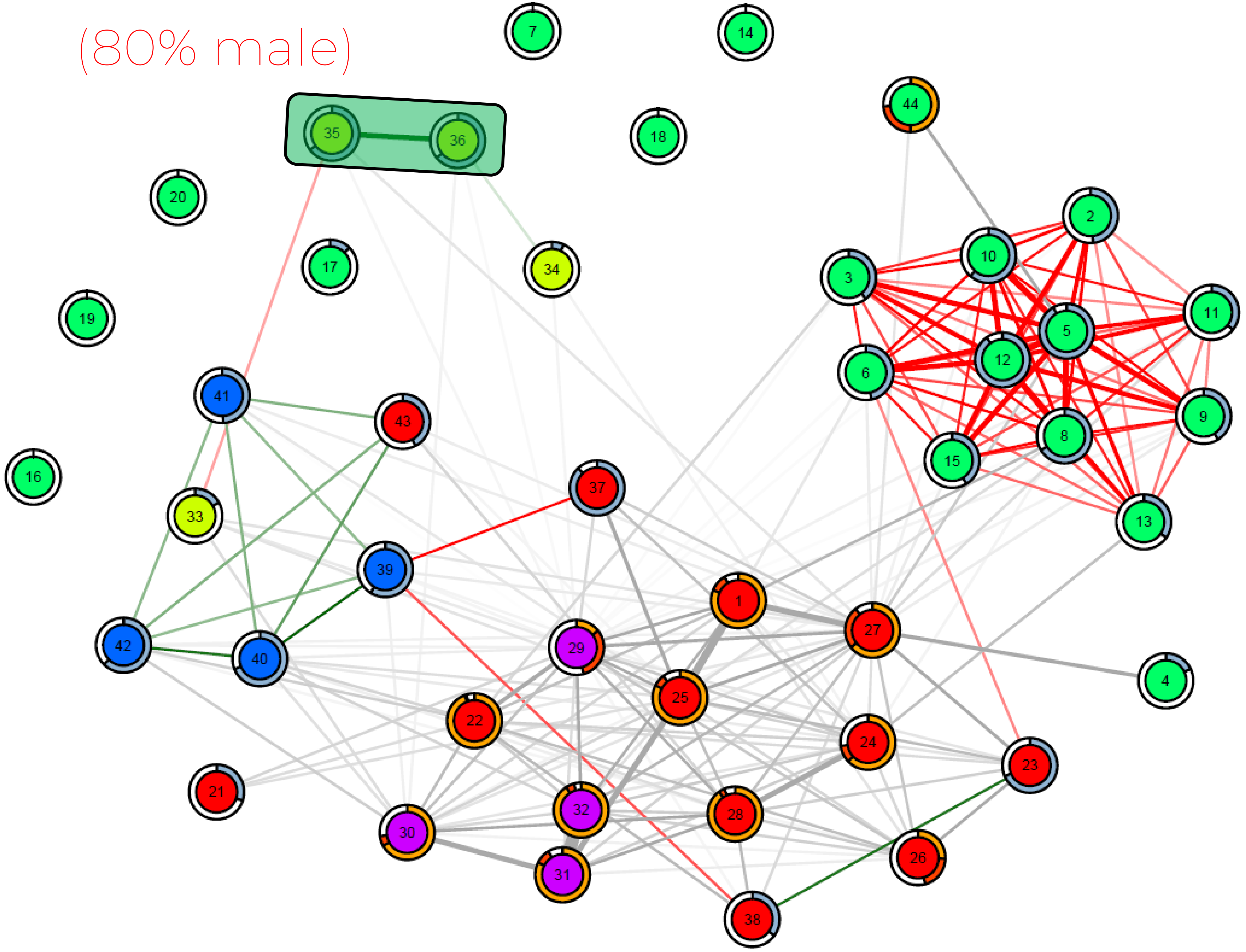

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- 38: CCL_Count
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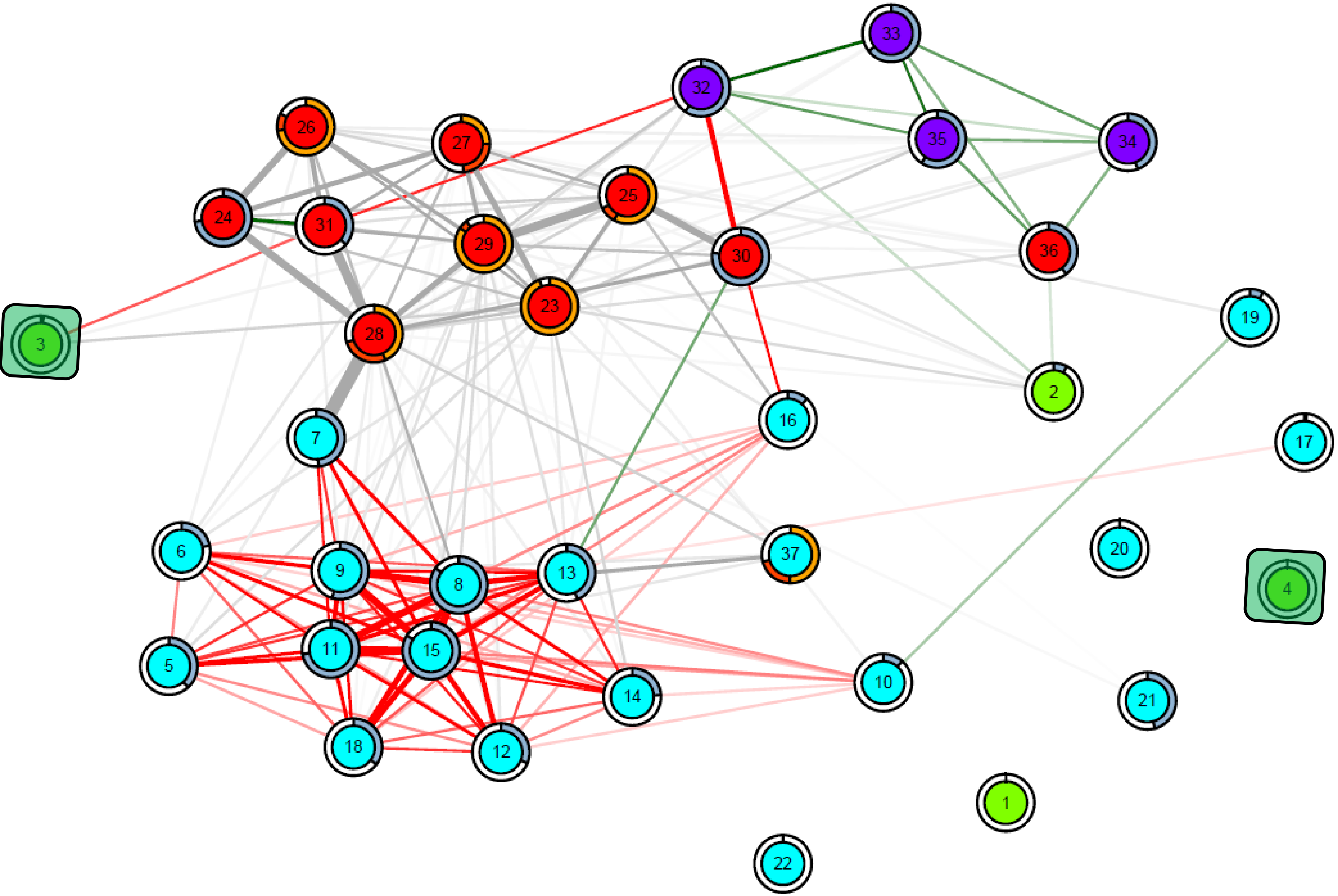
- 18: TUD_HEALTH_SELFCARE
- 19: TUD_VOLUNTEER
- 20: TUD_HH_SERVICES
- 44: week_type

WHOQOL
- 39: WHO_PHY
- 40: WHO_PSYCH
- 41: WHO_SOC
- 42: WHO_ENV

Income
- 29: HH_MonthlyIncome
- 30: HH_EnoughMonthlyExpenses
- 31: HH_3MthsEmergFunds
- 32: HH_500EmergFunds

Male



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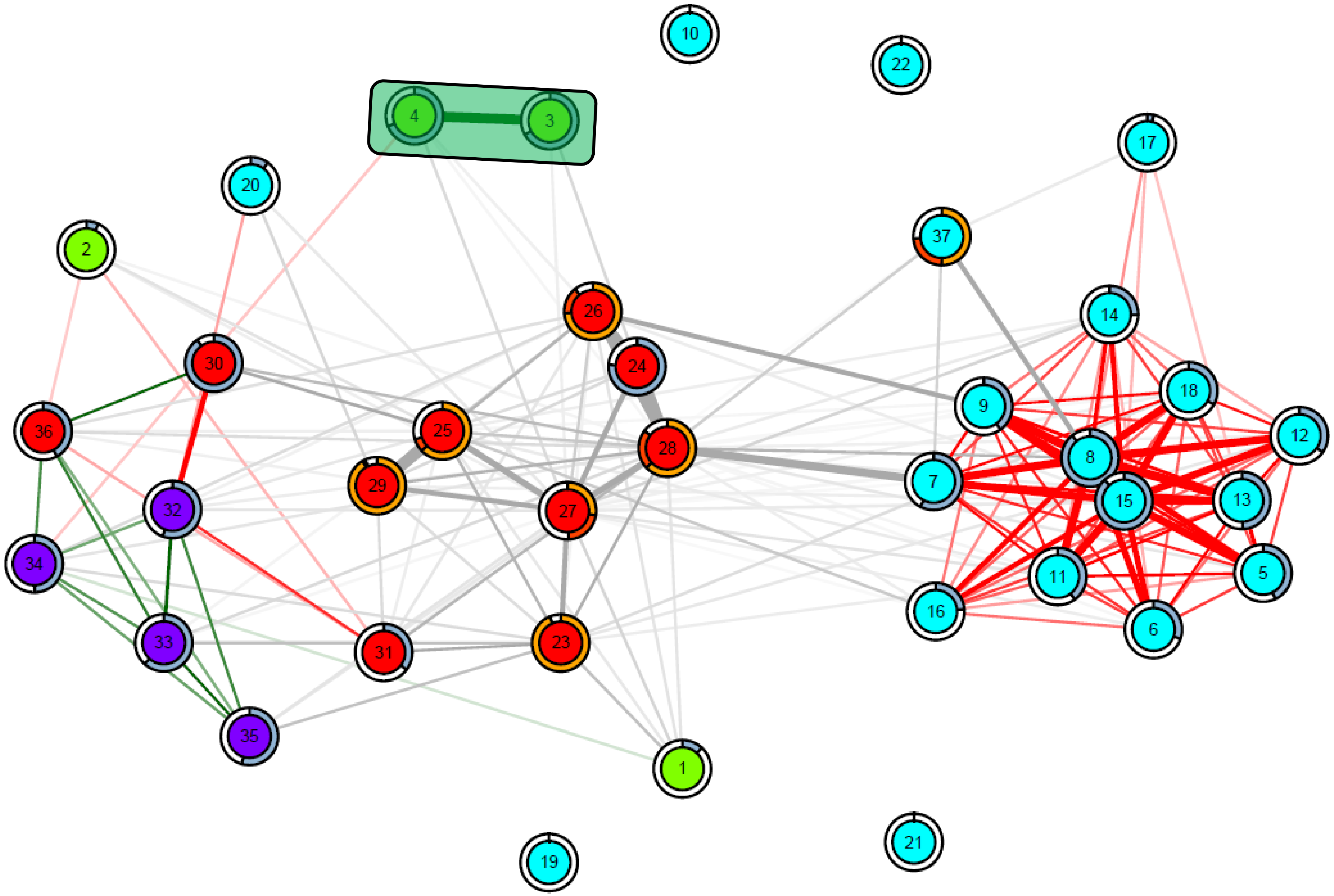
Female



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Gender moderates relationship b/w RMSSD & SDNN

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Review article

Sex differences in healthy human heart rate variability: A meta-analysis

Julian Koenig[a,b,*], Julian F. Thayer[a,**]

[a] Department of Psychology, The Ohio State University, Columbus, OH, USA
[b] Section for Translational Psychobiology in Child and Adolescent Psychiatry, Department of Child and Adolescent Psychiatry, Centre of Psychosocial Medicine, University of Heidelberg, Germany

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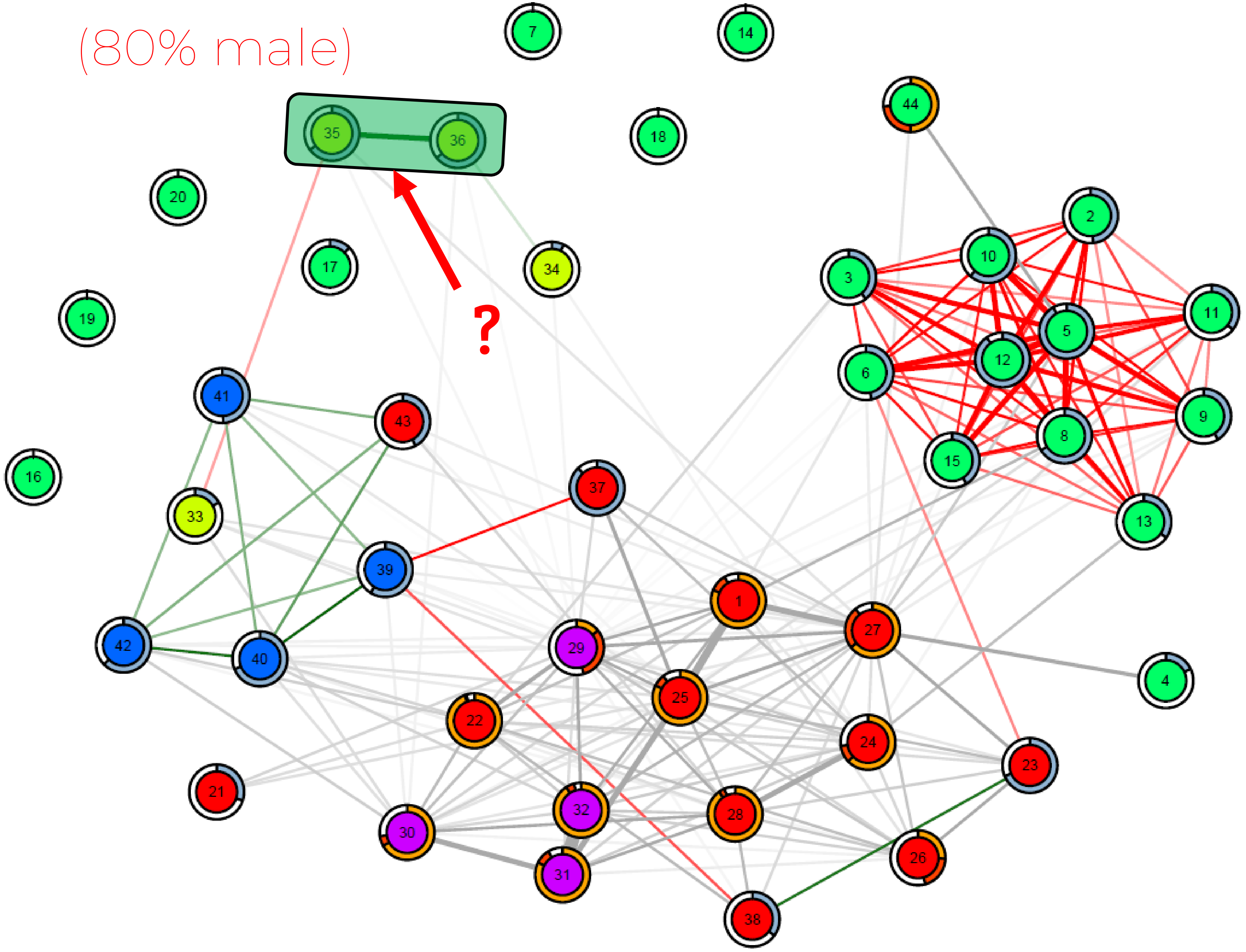
Heart rate
Sex differences
Autonomic nervous system
Parasympathetic nervous system
Vagus nerve
Meta-analysis

ABSTRACT

The present meta-analysis aimed to quantify current evidence on sex differences in the autonomic control of the heart, indexed by measures of heart rate variability (HRV) in healthy human subjects. An extensive search of the literature yielded 2020 titles and abstracts, of which 172 provided sufficient reporting of sex difference in HRV. Data from 63,612 participants (31,970 females) were available for analysis. Meta-analysis yielded a total of 1154 effect size estimates (k) across 50 different measures of HRV in a cumulated total of 296,247 participants. Females showed a significantly lower mean RR interval and standard deviation of RR intervals (SDNN). The power spectral density of HRV in females is characterized by significantly less total power that contains significantly greater high- (HF) and less low-frequency (LF) power. This is further reflected by a lower LF/HF ratio. Meta-regression revealed significant effects of age, respiration control and the length of recording available for analysis. Although women showed greater mean heart rate, they showed greater vagal activity indexed by HF power of HRV. Underlying mechanisms of these findings are discussed.

Heads of Household (80% male)



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Demographics
- 1: Gender
- 21: No_HH_Members
- 22: Housing_Broad
- 23: Age
- 24: Recoded_Race
- 25: MaritalStatus
- 26: HighestEducation
- 27: OccupationalStatus
- 28: ResidencyStatus
- 37: IADL_Count
- 38: CCL_Count
- 43: WFRQ_OVERALL

Heart−Rate Variability Indices
- 33: Avg_HR
- 34: HRV_LFHF
- 35: HRV_RMSSD
- 36: HRV_SDNN

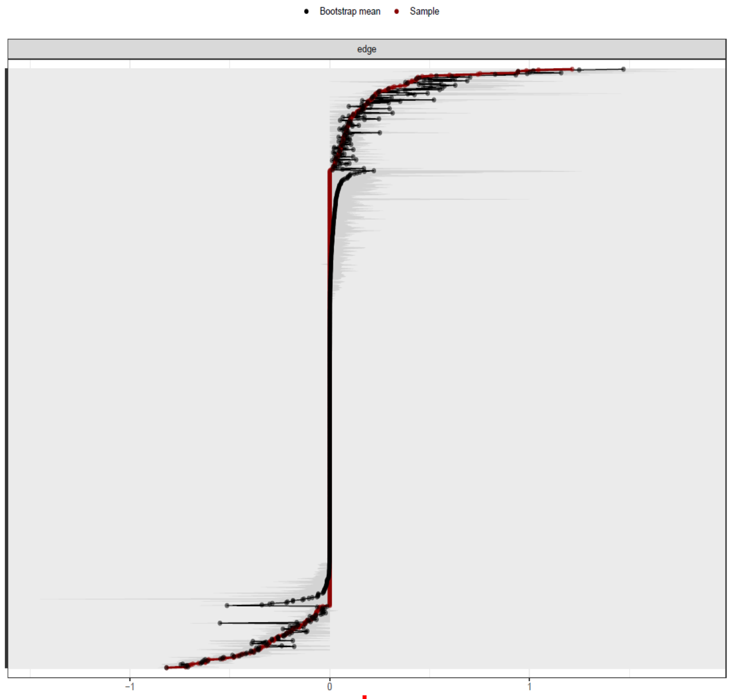
Time Use Diary
- 2: TUD_TRAVELLING
- 3: TUD_SPORTS
- 4: TUD_EDU
- 5: TUD_WORK
- 6: TUD_CARE_HH
- 7: TUD_CARE_NON_HH
- 8: TUD_HOUSEACT
- 9: TUD_EAT
- 10: TUD_SLEEP
- 11: TUD_GROOM
- 12: TUD_SOC_REL_LEISURE
- 13: TUD_RELIGIOUS
- 14: TUD_PPC_SERVICES
- 15: TUD_CONSUMER
- 16: TUD_TELEPHONE
- 17: TUD_SICKREST
- 18: TUD_HEALTH_SELFCARE
- 19: TUD_VOLUNTEER
- 20: TUD_HH_SERVICES
- 44: week_type

WHOQOL
- 39: WHO_PHY
- 40: WHO_PSYCH
- 41: WHO_SOC
- 42: WHO_ENV

Income
- 29: HH_MonthlyIncome
- 30: HH_EnoughMonthlyExpenses
- 31: HH_3MthsEmergFunds
- 32: HH_500EmergFunds

Limitations

- Stability analysis is subjective



- Computationally demanding

~ 21 hours

Limitations

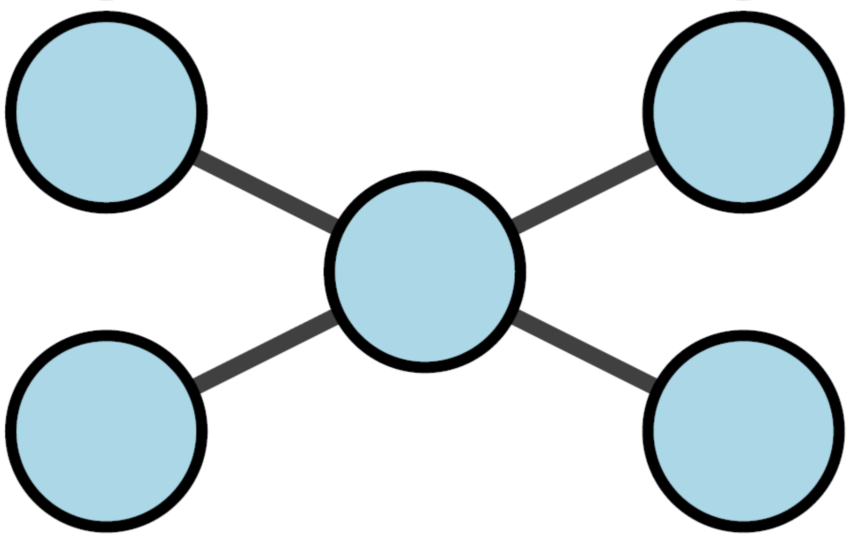
$$P(X) = \exp\left\{\sum_{s\in V}\theta_s\phi_s(X_s) + \sum_{s\in V}\sum_{r\in N(s)}\theta_{s,r}\phi_s(X_s)\phi_r(X_r) + \right.$$
$$\left.\cdots + \sum_{r_1,\ldots,r_k\in\mathcal{C}}\theta_{r_1,\ldots,r_k}\prod_{j=1}^{k}\phi_{r_j}(X_{r_j}) + \sum_{s\in V}B_s(X_s) - \Phi(\theta)\right\},$$

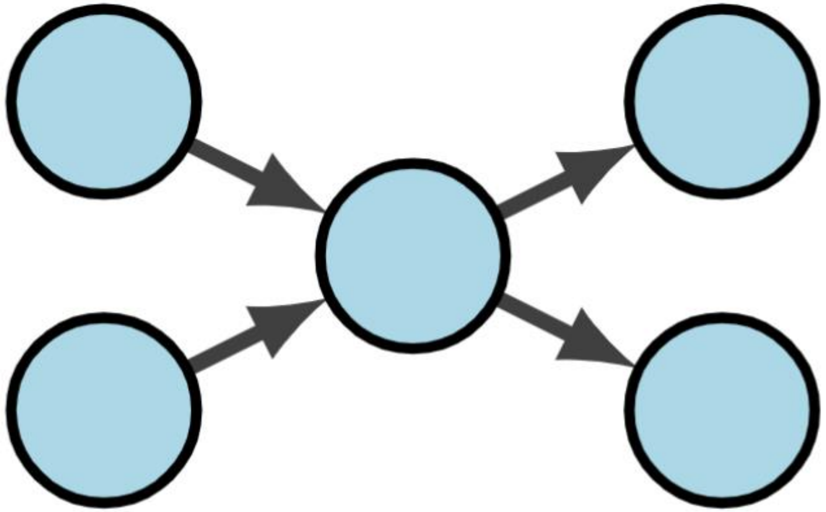
Does not always factorise into a well-defined (normalisable) joint distribution

Chen, S., Witten, D. M., & Shojaie, A. (2015). Selection and estimation for mixed graphical models. *Biometrika*, *102*(1), 47–64. https://doi.org/10.1093/biomet/asu051

Limitations

- Edges are undirected





Limitations

- Loss of temporal information
- Non-i.i.d. observations → consider multilayer networks for hierarchical data
- Only considered pairwise interactions → higher-order interactions? 3-way, moderating variables?

Conclusion

- Networks are convenient for visualizing multivariate data and their statistical relations
- Enables high-dimensional exploratory data analysis with little assumptions
- Integrates multi-modal data into a coherent entity

Thank you

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