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Graphical model analysis of subjective well-being and various factors in Japanese adults from the Iwaki cross-sectional study

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The relationship between Subjective well-being (SWB) and other factors is complex. However, few studies have reported a complex relationship between SWB and other factors across domains. We aimed to explore and clarify the one-to-many relationships between SWB and various factors among Japanese adults aged 20–85 years, using graphical modeling and data from the Iwaki Health Promotion Project (IHPP). An undirected graph that included factors such as nutrient intake, eating behavior, mental and physical health, social situations, and SWB was created using data from 519 participants in the IHPP of 2021. The graph indicated that four variables such as "CES-D", "Enjoying the taste of foods", "Health considerations" and "Household financial stability" were directly related to SWB. Additionally, we divided the participants into subgroups based on gender, age, employment status, educational background, and marital status and performed modeling to evaluate the differences in the structure of the SWB based on these attributes. Each graph indicated that the variables directly linked to SWB differed for each subgroup. Therefore, the mechanisms of SWB differed depending on people's backgrounds. We believe that these findings will be useful in proposing policies for improving the SWB of the Japanese people.

Keywords Subjective well-being, Graphical modeling, Japanese, Dietary habits

Relationship between subjective well-being and various factors

Subjective well-being (SWB) refers to the various types of positive and negative evaluations that people make about their lives[1,2]. In other words, SWB is an umbrella term for the valuations people make regarding their lives, the events happening to them, their bodies and minds, and the circumstances in which they live[2]. There has been a growing interest in SWB as an increasing number of SWB-related phrases are appearing in English books annually[3]. SWB has been studied in various fields[3], including medicine, public health, psychology, sociology, economics, and marketing. Research has reported on the relationships between SWB and various factors, including health[4], human relations[5–8], work[9,10], and income[11,12]. Therefore, various factors are associated with SWB, and this relationship is complex.

SWB among the Japanese

According to a previous World Happiness Report for 2020–2023[13–16], Japan ranked 62, 56, 54, and 47, respectively, the lowest among the G7 countries in each year's report. The Japanese government has expressed a desire for the expansion and progress of policies to improve SWB[17]. Additionally, other countries are beginning to introduce

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national policies based on SWB[18,19]; there is a growing trend of incorporating well-being indicators into actual policy processes[18,19].

To actualize this trend in Japan, basic research to understand the complex relationship between SWB and various factors in the Japanese population is necessary because SWB is interpreted differently across various contexts for each country or region[20,21]. However, the research referring to the complex relationship between SWB and various factors has not yet been conducted extensively in Japan.

Therefore, this study aims to elucidate the complex relationships between SWB and various factors across domains among Japanese adults.

Relationships between SWB and various factors

Numerous studies[5,6,10,12,22] have reported a one-to-one relationship between SWB and various other factors. For example, favorable interpersonal relationships correlated with high SWB[5,6], marriage correlated with high SWB[7], perceived income inequality was negatively associated with SWB[12], SWB positively affected job performance in Japan[10], and vegetable and fruit consumption led to an improvement in SWB[22]. Healthy dietary habits not only maintain mental and physical health but are also closely related to SWB[23]. For example, healthy dietary habits are related to the locomotive syndrome in terms of physical health[24] and to depression in terms of mental health[25]. Additionally, a relationship between eating behaviors and SWB has been reported[26,27].

Although these previous studies accurately assessed the relationship between SWB and specific domains, they did not consider the relationship between each domain such as interpersonal relationships and incomes or vegetable and fruit consumption and job performances.

Furthermore, literature[4,8,9,28,29] investigating the relationship between SWB and various factors have been published. These reviews summarized and compared SWB and the factors in a specific domain but did not examine the complex structure of well-being and various factors. Thus, few studies have explored or clarified the one-to-many relationships between SWB and various factors. In other words, the complex structure of SWB and various factors across domains is unclear.

One reason for this is the difficulty in collecting data. It is difficult to obtain indicators of multiple items in one field, such as mental and physical health, including SWB, interpersonal relationships, income, and eating behaviors. Another reason may be the difficulty of hypothesizing and modeling the relationship between SWB and various factors across domains.

Approach to complex structures using multiple items data and graphical model.

This study aimed to elucidate and interpret the relationship between SWB and various other factors in the Japanese population. To achieve this objective, we utilized data from the Iwaki Health Promotion Project (IHPP)[30]. The IHPP has conducted annual health data collection, gathering data on approximately 3000 items per individual. We also attempted to evaluate the associations between SWB and various factors using a graphical model with covariance selection[31–33].

This method makes it possible to express relationships based on partial correlation coefficients between SWB and various factors[32]. Covariance selection is considered effective to search for the complex structure because this method can be applied without prior hypotheses other than variable selection[34]. This study differs from previous studies in structuring the relationship between SWB and various factors across domains.

In addition, the structure of SWB and various other factors are considered to differ depending on attributes, such as gender, age, employment status, educational background, and marital status. These factors have been described to be associated with SWB[3]. Therefore, we divided the participants into subgroups and performed modeling to determine the differences in the structure of SWB according to the participants' attributes.

Our research clarified the complex relationships between SWB and various factors across domains among Japanese adults.

Methods

Study design and participants

This study was a cross-sectional study and used data acquired through the IHPP[30]. Since 2005, the IHPP has conducted annual health data collection, gathering data on approximately 3000 items per individual from approximately 1000 Japanese adults in Aomori prefecture. This project obtained a wide range of health checkup data that comprising the molecular biology, physiology, biochemistry, personal lifestyle, and socio-environmental aspects of the residents of Iwaki district, Hirosaki City, Aomori Prefecture, Japan. The 2021 IHPP data, which included various measurements and added those related to SWB for the first time, was deemed suitable for elucidating the structure of SWB within this population.

We targeted 519 health checkup records of adult participants in 2021 who answered the Japanese version of the subjective happiness scale (SHS) and the brief-type self-administered diet history questionnaire (BDHQ). Only the data from the IHPP in 2021 had SHS, BDHQ and all other variables described below. Therefore, we used this dataset for the analysis.

The study was approved by the Ethics Committee of Hirosaki University School of Medicine (annual approval; the latest approval number: 2020-046-5) and the Ajinomoto Institutional Review Board (annual approval; the latest approval number: 2020-021). The study was conducted in accordance with the principles of the Declaration of Helsinki. Written informed consent was obtained from all the participants before inclusion in this study.

Measurement of variables

The measurements of the variables utilized in this study are detailed in subsections "Subjective happiness scale (SHS)", "Brief-type self-administered diet history questionnaire (BDHQ)", and "Other variables", respectively.

Subjective happiness scale (SHS)
SWB was assessed using the Japanese version of the SHS[35,36], which consists of four items. The participants rated the items on a seven-point scale. In question 1, the participants responded to "In general, I consider myself:" with a choice of "1: not a very happy person" to "7: a very happy person" to represent their levels of happiness. In question 2, the participants responded to "Compared to most of my peers, consider:" with a choice of "1: Less happy" to "7: more happy". In question 3, the participants responded to "Some people are generally very happy. They enjoy life regardless of what is going on, getting the most out of everything. To what extent does this characterization describe you?:" with a choice of "1: not at all" to "7: a great deal". In question 4, the participants responded to "Some people are generally not very happy. Although they are not depressed, they never seem as happy as they might be. To what extent does this characterization describe you?:" with a choice of "1: not at all" to "7: a great deal". Only the scale for question 4 was reversed. After reversing question 4, the average score for the four questions was calculated as a single composite score for the SHS. This score was indicated as the "Averaged SHS". Therefore, the possible range of the Averaged SHS was 1.0–7.0, with higher scores reflecting higher levels of happiness. The reliability and validity of the scale were satisfactory[35].

Brief-type self-administered diet history questionnaire (BDHQ)
Foods and nutrients intake were assessed using the BDHQ. The details of the BDHQ have been published elsewhere[37,38]. Briefly, the BDHQ is a four-page self-administered questionnaire on dietary habits during the previous month. It includes structured questions about the eating frequency of commonly consumed foods and general dietary behaviors. Estimates of the daily intake of food groups, energy, and nutrients were calculated using a custom computer algorithm for the BDHQ. The energy-adjusted food or nutrient intake (weight/1000 kcal) was calculated, and the values were used in logistic regression and graphical modeling.

Other variables
Variables related to SWB were selected from the measurements. Variables corresponding to mental and physical health, social situations, and eating behaviors were selected based on WHR[16] assessment items and six dimensions of Positive Health[39]. These variables were assessed using self-administered questionnaires. Details of the individual questions are listed in Table 1. Age, gender, job, final educational background, and partner were used to categorize the subgroups, which were described as SWB components in the publication[3]. Descriptions of the variables and the values of the range of variables used for the categorization are presented in Table 1.

Statistical analysis

Means ± SDs were calculated for the continuous variables, and numbers and percentages (%) were calculated for the categorical variables. Mann–Whitney U tests that suitable for non-normally distributed or ordinal scale data were performed to compare the characteristics of the participants in each subgroup.

Multivariate logistic regression analyses were performed to estimate the odds ratios (ORs) with 95% confidence intervals (CIs) of the high quartiles of food or nutrient intake for participants scoring five or more points on all SHS questions, using the lowest quartiles of food or nutrient intake as a reference. The covariates in the logistic regression were age, gender, BMI, smoking, drinking, and exercise habits. The trend associations were assessed by assigning the food or nutrient intake quartiles to ordinal scale variables 1, 2, 3, and 4. All statistical analyses were conducted using Python version 3.10.5.

Procedure of graphical modeling

In this study, the undirected graph obtained through the procedure described below was used for "graphical modeling".

Covariance selection was performed as previously described[31–33]. The undirected graphs were created by sequentially removing the edges from the partial correlation coefficient matrix. The edges were removed by setting the partial correlation coefficient between the variables with the smallest partial correlation coefficient to 0. The number of partial correlation coefficients set to 0 at one time was limited to one pair. We obtained an undirected graph by repeating this process. The criteria for ending the repetition are described below.

The model before replacing the partial correlation coefficients set to 0 was defined as the full model (FM). The correlation coefficient matrix in the FM was defined as R_{FM}. The model in which the partial correlation coefficient between the variables with a small absolute value of the partial correlation coefficient was set to 0 was defined as the reduced model (RM). The correlation coefficient matrix in the RM was defined as R_{RM}. The model with one partial correlation coefficient set to 0 was named RM_1, the model with two partial correlation coefficients set to 0 was named RM_2, and the model with m partial correlation coefficients set to 0 was called RM_m. The deviation between RM_m and RM_{m-1} was calculated according to Eqs. (1)–(4), as follows:

$$\ln L\left(FM\right) = -np\ln 2\pi/2 - n\ln\left|R_{FM}\right|/2 - np/2 \tag{1}$$

$$\ln L\left(RM\right) = -np\ln 2\pi/2 - n\ln\left|R_{RM}\right|/2 - np/2 \tag{2}$$

$$\begin{aligned} dev\left(RM\right) =& 2\left[\ln L\left(FM\right) - \ln L\left(RM\right)\right] \\ =& n\ln\frac{\left|R_{RM}\right|}{\left|R_{FM}\right|} \end{aligned} \tag{3}$$

$$dev\left(RM_m - RM_{m-1}\right) = dev\left(RM_m\right) - dev\left(RM_{m-1}\right) \tag{4}$$

Category	Measurements	Real questionnaire items and description
Basic information	Age	This measurement indicates the age of the participants
		Participants were divided into three groups 20 to 44, 45 to 64 and Over 65
	Gender	This measurement indicates the gender of the participants
		Participants were divided into two groups, male and female
Mental and physical health	CES-D[40]	CES-D indicates degree of depression
		High score indicates a risk for depression
	Exercise habits	"How many days per week do you engage in light exercise (including physical activities such as farming)?" with the following options: 1. Every day 2. 5–6 days 3. 2–4 days 4. 1 day or less 5. Not at all
		The results were reversed so that higher frequencies correspond to higher scores
	Locomo 25[41]	High score indicates progressing of locomotive syndrome
	Vitality from SF36	High score indicates high vitality
Social Situations	Final educational background	"Please answer the option that corresponds to your highest level of education" with the following options: 1. Elementary school 2. Junior high school 3. High school 4. Junior college/Vocational school 5. University or higher 6. Other
		Participants were divided into three groups: high school diploma or less, graduated from a vocational school or a junior college and bachelor's degree or higher. Other was excluded
	Household financial stability	"How do you feel about your current living situation economically?" with the following options: 1. Very difficult 2. Somewhat difficult 3. Average 4. Somewhat comfortable 5. Very comfortable
	Job category	"What has been your primary occupation (including full-time homemaker) over the past year?" with the following options:
		1. Professional/Technical Worker 2. Managerial Worker 3. Clerical Worker 4. Sales Worker 5. Service Worker 6. Security Worker 7. Agricultural Worker 8. Forestry Worker 9. Fishery Worker 10. Transportation/Communication Worker 11. Production/Manual Labor Worker 12. Homemaker (Full-time) 13. Unemployed 14. Student 15. Unclassifiable
		Participants were divided into 3 groups primary industry, non-primary industry and unemployed
		Primary industry includes 7, 8 and 9. Non-primary industry includes 1, 2, 3, 4, 5, 6, 10, 11 and 15. Unemployed includes 12, 13 and 14
	Number of family members communication with	"How many family members or relatives do you meet or talk with at least once a month?"
	Number of friends communication with	"How many friends do you meet or talk with at least once a month?"
	Having any partner	"Please answer marital status" from the following options: 1. Married 2. Not married (bereavement) 3. Not married (divorced) 4. Not married (single)
		Participants were divided into 2groups with partner and without partner
		Those who experienced bereavement were excluded
Eating behaviors	Cooking frequency	"How often do you usually cook and prepare your own meals?" with the following options: 1. Every day 2. 5–6 days a week 3. 3–4 days a week 4. 1–2 days a week 5. Rarely
		The results were reversed so that higher frequencies correspond to higher scores
	Culinary confidence	"I am confident in my cooking skills." with the following options: 1. Strongly agree 2. Somewhat agree 3. Somewhat disagree 4. Strongly disagree
		The results were reversed so that higher confidence correspond to higher scores
	Dietary improvement	"Regarding improvements towards a healthier diet, please select the one option that best applies to you" with the following options: 1. I do not intend to improve my diet 2. I plan to improve my diet in the future (within approximately 6 months) 3. I intend to improve my diet soon (within approximately 1 month) and have started making small changes 4. I am already working on improving my diet (for less than 6 months) 5. I am already working on improving my diet (for more than 6 months)
	Enjoy eating	"I like eating." with the following options: 1. Strongly agree 2. Somewhat agree 3. Somewhat disagree 4. Strongly disagree
		The results were reversed so that higher frequencies correspond to higher scores
	Enjoying the taste of foods	"I enjoy my meals." with the following options: 1. Strongly agree 2. Somewhat agree 3. Somewhat disagree 4. Strongly disagree
		The results were reversed so that higher frequencies correspond to higher scores
	Frequency of eating out	"How often do you eat out (meals at restaurants)?" with the following options: 1. Twice or more per day 2. Once per day 3. 4–6 times per week 4. 2–3 times per week 5. Once per week 6. Less than once per week 7. Never
		The results were reversed so that higher frequencies correspond to higher scores
	Frequency of eating	"How often do you use commercially prepared foods?" with the following options: 1. Twice or more per day 2. Once per day 3. 4–6 times per week 4. 2–3 times per week 5. Once per week 6. Less than once per week 7. Never
	Prepared foods	The results were reversed so that higher frequencies correspond to higher scores
	Health considerations	"I am conscious of my health and pay attention to my diet." with the following options: 1. Strongly agree 2. Somewhat agree 3. Somewhat disagree 4. Strongly disagree
		The results were reversed so that higher frequencies correspond to higher scores
	BDHQ	Energy-adjusted food or nutrient intakes (weight/1000 kcal) were used

Table 1. Measurements used in the analysis.

Equation (1) shows the log likelihood of FM, whereas Eq. (2) shows the log likelihood of RM. The number of models was n; for example, n represents 1 in the FM, and p represents the number of dimensions used in the model. The deviation between the RM and FM was calculated using Eq. (3). Subsequently, the deviation between RM_m and RM_{m-1} ($dev\,(RM_m - RM_{m-1})$) was calculated using Eq. (4). $dev\,(RM_m - RM_{m-1})$ follows a chi-square distribution with one degree of freedom. This property was used to obtain the p-values. The p-value < 0.30 was used as the threshold for stopping repetition. This threshold was set with reference to values used in experiments in the literature[32]. The RM before $p < 0.30$ was adopted. An undirected graph was plotted by connecting pairs with the partial correlation coefficients that were not set to 0. Covariance selection was performed using Python version 3.10.5.

Results

Demographic characteristics of study participants

The measurements used in this study and their interpretation are presented in Table 1. To clarify the characteristics of the participants using these measurements, an overview of the 2021's IHPP data related to mental and physical health, social situations, eating behaviors, and the SHS as indicators of SWB are presented in Table 2 and Fig. 1. The average of the four questions was indicated as the "Averaged SHS". The Averaged SHS of all the participants was 4.8 ± 1.0. Since Averaged SHS has been validated among Japanese people, it can be utilized as an indicator of SWB within this population[35,36]. On the Averaged SHS, four points indicated neither happiness nor unhappiness, whereas five points or above indicated happiness. Additionally, a study investigating the Averaged SHS in Japanese people reported it to be 4.4 ± 1.2[36]. This result indicated that the participants felt a certain level of happiness.

Regarding other measurements, "CES-D" as an index of mental health, had an average score of 9.7 points, which is lower than the 16 points required to be classified as depression[40]. The Locomo25, as an index of physical health, had a mean score of 4.9 points, which was less than the 7 points required for the locomotive syndrome[41].

Food groups, foods, and nutrients associated with SHS score

To determine the variables applied in the graphical model from the BDHQ, multivariate logistic regression and trend tests were conducted with food and nutrient intake from the BDHQ as explanatory variables and the SHS scores as the dependent variables. Energy-adjusted food or nutrient intake (weight/1000 kcal) was used. The results are presented in Table 3. Regarding nutrient intake, non-energy-producing nutrients were shown in the Supplemental Table 9.

First, we demonstrated the relationship between SHS and the intake of proteins, fats, and carbohydrates, known as macronutrients. A higher SHS score was associated with higher protein and fat intake according to the trend test in logistic regression. However, a higher SHS score was associated with a lower carbohydrate intake according to the trend test in logistic regression. For other nutrients, a higher SHS score was associated with a higher intake of minerals, such as potassium, calcium, magnesium, iron, βcarotene, vitamins B, vitamin C, saturated fatty acids, and dietary fiber. Regarding food groups, a higher SHS score was associated with a higher

Category	Measurements	Unit	Mean	SD
Subjective well-being	Averaged SHS	–	4.8	1
Basic Information	Age	Years	52.7	14.9
Mental and physical health	CES-D	–	9.7	7.4
	Exercise habits	–	3.2	1.4
	Locomo 25	–	4.9	6.5
	Vitality from SF36 (Vitality)	–	52.2	9
	Inbody score	–	72.7	4.9
Social situations	Household financial stability	–	2.8	0.7
	Number of family members in communication with	People	4.6	2.8
	Number of friends in communication with	People	2.9	2.4
Eating behaviors	Cooking frequency	–	3.1	1.7
	Culinary confidence	–	1.9	0.9
	Dietary improvement	–	2.4	1.5
	Enjoy eating	–	3.4	0.7
	Enjoying the taste of foods	–	3.5	0.6
	Frequency of eating out	–	2.2	1.1
	Frequency of eating prepared foods	–	2.8	1.3
	Health considerations	–	2.9	0.8
Food or nutrition intakes	Protein intake per energy (PRT/EN)	g/1000 kcal	37.5	6.8
	Fat intake per energy (FAT/EN)	g/1000 kcal	29.7	6.3
	Carbohydrate intake per energy (CHO/EN)	g/1000 kcal	130.6	20.2
	Vegetable intake per energy (VEG/EN)	g/1000 kcal	121.1	61.1

Table 2. Characteristics of participants.

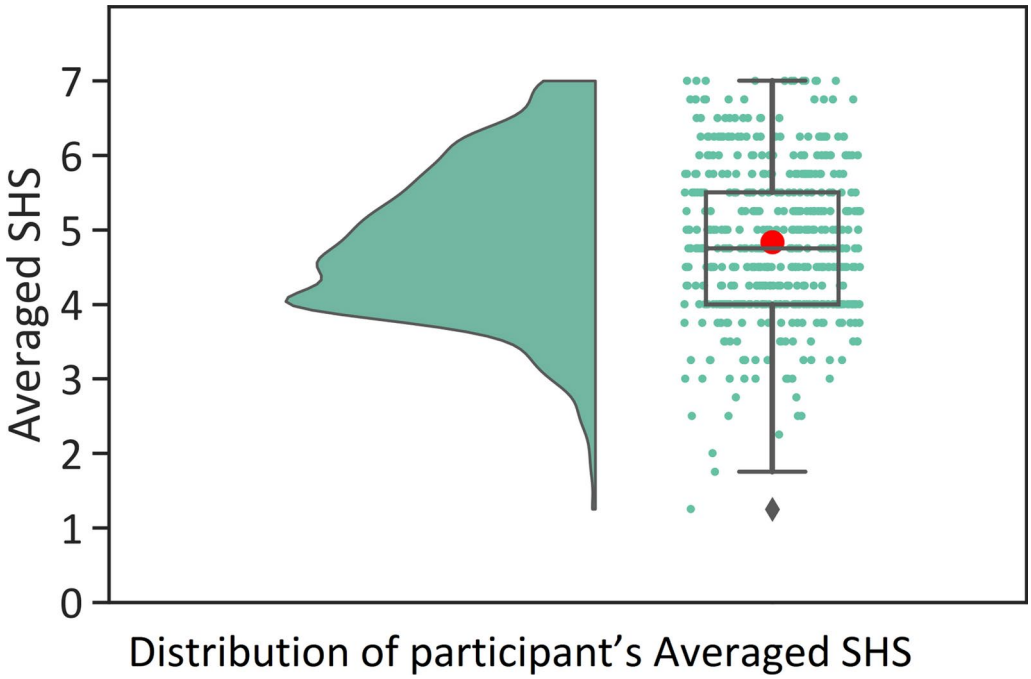


Fig. 1. Histogram of Averaged SHS is on the left side of the figure. The box-and-whisker diagram is on the right, the red dots are the average values, the black solid line is the median, the top of the box indicates the top 75%, and the bottom indicates the bottom 25% of the data. The whiskers indicate the upper end + 1.5 × interquartile range, and the lower end − 1.5 × interquartile range.

Category	Name	ORs (CI) Q1 vs Q2	ORs (CI) Q1 vs Q3	ORs (CI) Q1 vs Q4	*p value* for trend test
Food groups	Grains	0.99 (0.59–1.66)	0.84 (0.49–1.42)	0.44 (0.25–0.8)**	0.008
	Potatoes	1.28 (0.74–2.24)	1.16 (0.67–2.03)	2 (1.17–3.44)*	0.020
	Pulses	1.21 (0.68–2.15)	1.82 (1.05–3.17)*	2.26 (1.28–3.97)**	0.002
	Green and yellow vegetables	1.35 (0.76–2.41)	2 (1.14–3.53)*	2.02 (1.13–3.61)*	0.007
	Other vegetables	1.19 (0.66–2.16)	2.01 (1.15–3.52)*	2.63 (1.48–4.69)**	0.000
	Fruits	0.94 (0.54–1.65)	1.1 (0.63–1.92)	2.11 (1.22–3.64)**	0.006
Foods	Tofu & fried tofu	0.95 (0.53–1.68)	1.17 (0.67–2.04)	2.07 (1.19–3.58)**	0.005
	Green leaf vegetable	1.7 (0.95–3.03)†	1.96 (1.11–3.47)*	2.27 (1.28–4.04)**	0.005
	Root vegetables	0.91 (0.52–1.59)	1.15 (0.66–2)	1.82 (1.06–3.11)*	0.018
	Tomato	0.82 (0.46–1.45)	1.41 (0.82–2.41)	1.57 (0.92–2.68)†	0.028
	Mushrooms	1.21 (0.69–2.12)	1.29 (0.73–2.26)	2.15 (1.24–3.7)**	0.007
	Coffee	1.63 (0.91–2.91)	1.55 (0.87–2.76)	2.24 (1.26–3.97)**	0.011
	Rice	0.87 (0.52–1.45)	0.94 (0.56–1.59)	0.45 (0.25–0.81)**	0.018
Energy-producing nutrients	Protein	1.03 (0.58–1.83)	1.54 (0.89–2.66)	2.02 (1.15–3.56)*	0.006
	Fat	1.13 (0.64–1.98)	1.31 (0.75–2.27)	1.71 (0.98–3)†	0.049
	Carbhydrates	1.03 (0.61–1.75)	0.96 (0.56–1.66)	0.51 (0.28–0.93)*	0.038
	Animal protein	1.02 (0.58–1.78)	1.25 (0.72–2.15)	1.76 (1.03–3.03)*	0.028
	Animal fat	1.23 (0.71–2.15)	1.18 (0.68–2.07)	1.84 (1.07–3.17)*	0.038

Table 3. Food groups, Foods, and Nutrients associated with SHS score. *Indicates $p < 0.05$. **indicates $p < 0.01$. †indicates $p < 0.1$.

intake of beans and vegetables and a lower grain intake. For other foods, a higher SHS score was associated with a higher intake of mushrooms and coffee, and a lower intake of rice.

Based on these results and from previous reports, which are assumed to be related to physical and mental health[42,43], four nutrients and foods: proteins[42,43], fat[42,43], carbohydrates[42,43], and vegetable intakes[44] were used for graphical modeling.

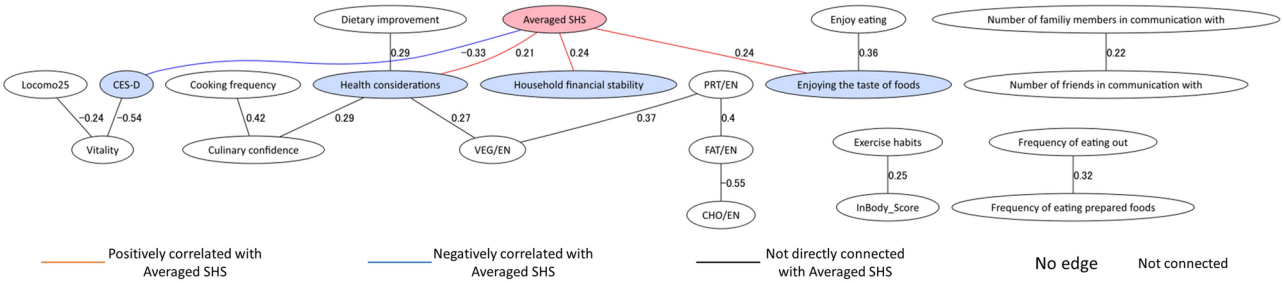


Fig. 2. Red circle indicates Averaged SHS. Blue circles indicate variables directly correlated with Averaged SHS. Numbers on the right side of the edges indicate the partial correlation coefficients between the variables connected by edges. Red lines indicate the edges positively correlated with Averaged SHS. Blue line indicates the edge negatively correlated with Averaged SHS. Black lines indicate the edge not directly connected with Averaged SHS. Variables not connected by edges had a partial correlation coefficient of 0 according to the covariance selection criteria. This indicates that variables not connected by edges are conditionally independent.

Category	Subgroups	Count	Percentage
Age	< 45	181	34.9
	45–64	199	38.3
	≧65	139	26.8
Gender	Male	215	58.6
	Female	304	41.4
Marital status	With partner	378	72.8
	Without partner, unmarried, or divorced	118	22.7
	Without partner bereavement	23	4.4
Job category	Primary Industry	98	18.9
	Non-primary Industry	331	63.8
	Unemployed	90	17.3
Final educational background	High school diploma or less	323	62.2
	Graduated from a vocational school or a junior college	125	24.1
	Bachelor's degree or higher	65	12.5
	Others	6	1.2

Table 4. Number of participants divided by subgroups.

The relationship between Averaged SHS and various factors by graphical modeling in all participants

To clarify the relationship between the selected variables and SWB, an undirected graph was created using data from 519 participants in the 2021 IHPP. Four of the 20 variables were directly related to Averaged SHS. This graph is presented in Fig. 2. The graph did not indicate causation but indicated a partial correlation coefficient between the variables. Heat maps of the partial correlation coefficients before and after covariance selection are shown in Supplementary Fig. 1. The relationship between the variables and Averaged SHS is described below.

Averaged SHS was negatively correlated with "CES-D". This result indicated a relationship between depression and a lower Averaged SHS. Averaged SHS was positively correlated with "Enjoying the taste of foods", "Health considerations" and "Household financial stability". As an indirect relationship between Averaged SHS and other variables, "CES-D" was negatively correlated with "Vitality" and "Health considerations" was positively correlated with "VEG/EN" indicating vegetable intake (weight/1000 kcal) and "Culinary confidence". "Enjoying the taste of foods" was positively correlated with "Enjoy eating".

The relationship between averaged SHS and various factors based on participants' backgrounds

As shown in Table 4, participants were divided into subgroups based on age, gender, job category, final educational background, and marital status. Averaged SHS was obtained for each subgroup to confirm the differences. The results are shown in Fig. 3. Moreover, undirected graphs were created for each subgroup to clarify the differences in the relationships between Averaged SHS and each variable across the subgroups.

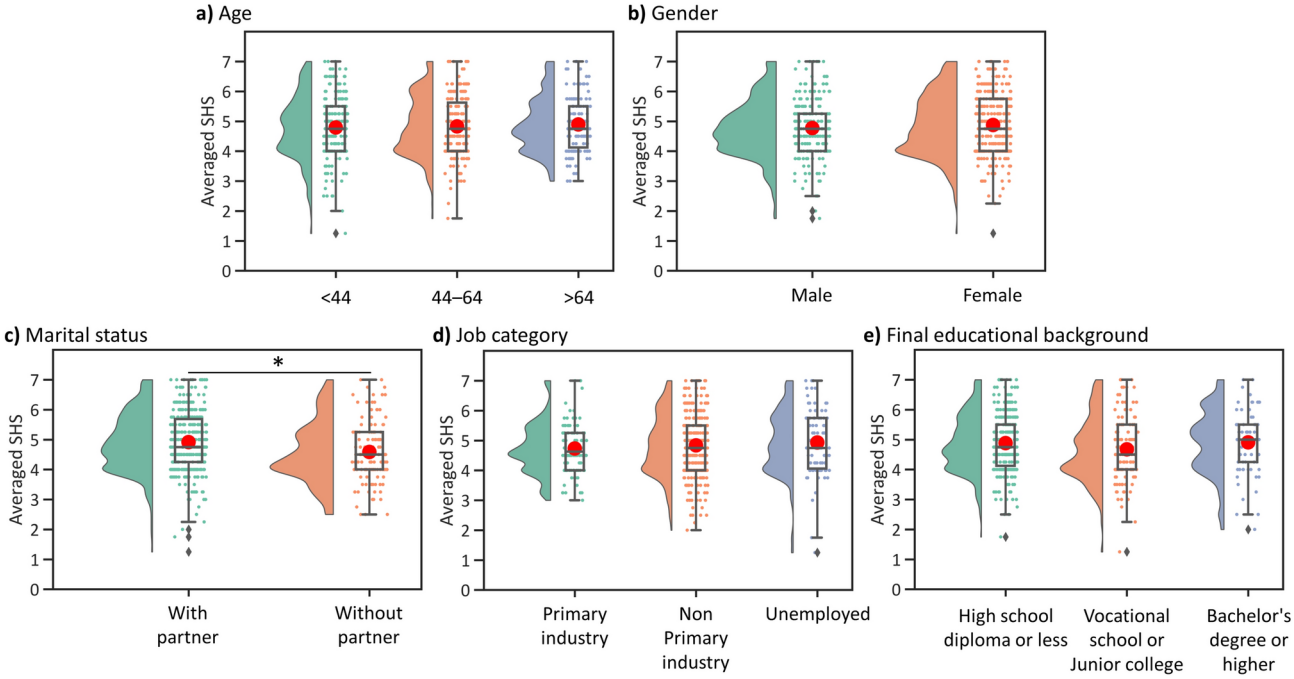


Fig. 3. Histogram of SHS average on the left side of the figure. The box-and-whisker diagram on the right, the red dots are the average values, the black solid line is the median, the top of the box indicates the top 75% and the bottom indicates the bottom 25% of the data. The whiskers indicate the upper end + 1.5 × interquartile range, and the lower end − 1.5 × interquartile range. The dscf test was used. *Indicates $p < 0.05$.

Groups		Positively correlated with Averaged SHS	Negatively correlated with Averaged SHS
Gender	Male	Household financial stability, Number of friends communication with	CES-D
	Female	Enjoying the taste of foods, Health considerations, Household financial stability	CES-D
Age	< 45	Enjoying the taste of foods, Health considerations, Number of friends communication with	CES-D
	45–64	Household financial stability, Number of family members communication with, Number of friends communication with	CES-D
	> 64	Enjoying the taste of foods, Household financial stability	CES-D
Marital status	With partner	Enjoying the taste of foods, Household financial stability, Number of friends communication with	CES-D
	Without partner	Enjoying the taste of foods, Health considerations, Household financial stability, Number of friends communication with, vitality	CES-D
Jobs	Primary industry	Enjoying the taste of foods, Number of friends communication with	–
	Non primary industry	Enjoying the taste of foods, Health considerations, Household financial stability, Number of friends communication with	CES-D
	Unemployed	Health considerations, Household financial stability, Locomo25, Vitality	CES-D
Final educational background	High school diploma or less	Enjoying the taste of foods ,Health considerations, Household financial stability, Number of friends communication with	CES-D
	Vocational school or Junior college	Health considerations, Household financial stability, Number of family members communication with, Number of friends communication with, vitality	CES-D
	Bachelor or higher	Cooking frequency, Frequency of eating out, Health considerations, Locomo25, Number of family members communication with, PRT/EN, VEG/EN, Vitality	CES-D, Culinary confidence, Enjoy eating

Table 5. Edges correlated with Averaged SHS sub-grouped by participant's status.

As shown in Fig. 3, there were no significant differences in Averaged SHS according to age, gender, job category, or final educational background. On the other hand, there was a significant difference in Averaged SHS according to the marital status. Averaged SHS was higher in "With partner" compared to "Without partner" ($p < 0.05$).

For each subgroup of the undirected graphs, the number of variables, and those directly connected to Averaged SHS are listed in Table 5. The undirected graphs for each subgroup are shown in Figs. 4, 5, 6, 7 and

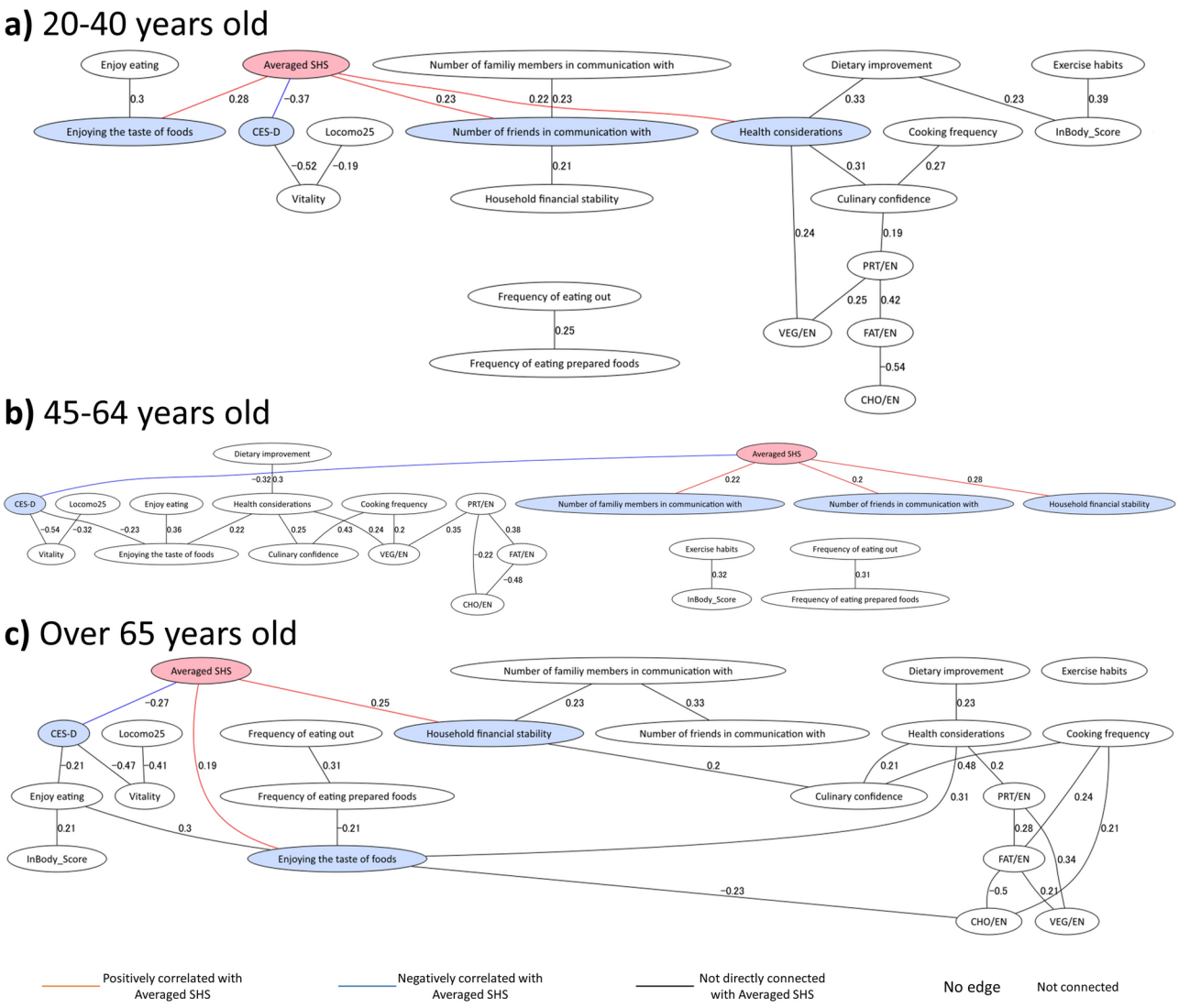


Fig. 4. Red circle indicates Averaged SHS. Blue circles indicate variables directly correlated with Averaged SHS. Numbers on the right side of edges indicate the partial correlation coefficients. Red lines indicate the edges positively correlated with Averaged SHS. The blue line indicates the edge negatively correlated with Averaged SHS. Black lines indicate the edge not directly connected with Averaged SHS. Variables not connected by edges had a partial correlation coefficient of 0 according to the covariance selection criteria. This indicates that variables not connected by edges are conditionally independent. (**a**) Undirected graph of participants between 20 and 44 years of age (n = 181), (**b**) Undirected graph of participants between 45 and 64 years of age (n = 199), (**c**) Undirected graph of participants over 65 years of age (n = 139).

8. As presented in Table 5, the variables directly linked to Averaged SHS were different for each subgroup. In other words, the factors related to Averaged SHS differed depending on the background of the participants. Interestingly, although Averaged SHS was comparable for each subgroup in terms of age, gender, job category, and final educational background, the variables associated with Averaged SHS differed.

Discussion

The relationship between averaged SHS and various factors in all participants

Findings overview

As shown in Fig. 2, Associations between SWB and variables from various domains such as "Mental health", "Physical health", "Social Situations", and "Eating behaviors" were found among Japanese people. This result will be useful in understanding the complex relationship between SWB and various influencing factors. Furthermore, we have provided an interpretation of how Averaged SHS relates to the surrounding variables.

Regarding mental and physical health, "Vitality" and "Locomo25" were indirectly related to Averaged SHS via "CES-D". Mental and physical health are considered closely related[45], and they affect SWB. For "Vitality" and

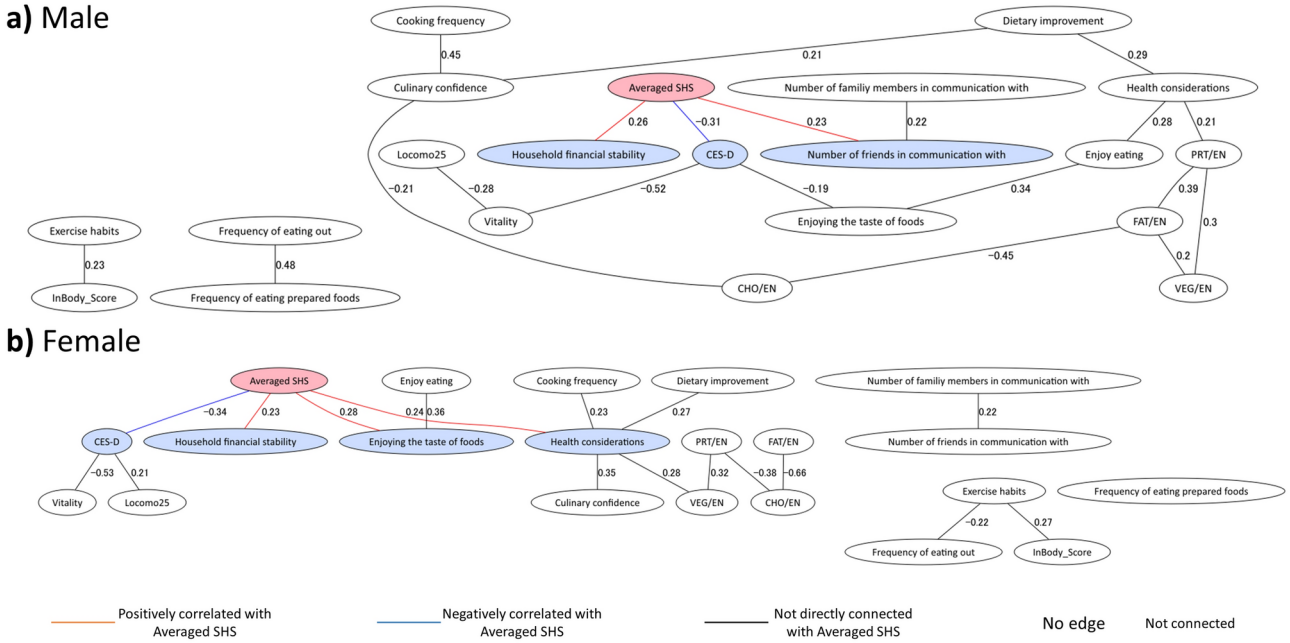


Fig. 5. Red circle indicates the Averaged SHS. Blue circles indicate variables directly correlated with Averaged SHS. Numbers on the right side of the edges indicate the partial correlation coefficients. Red lines indicate the edges positively correlated with Averaged SHS. Blue line indicates edges negatively correlated with Averaged SHS. Black lines indicate the edge not directly connected with Averaged SHS. Variables not connected by edges had a partial correlation coefficient of 0 according to the covariance selection criteria. This indicates that variables not connected by edges are conditionally independent. (**a**) Undirected graph of males (n = 215), (**b**) Undirected graph of females (n = 304).

"Locomo25", it was difficult to find a one-to-one relationship with Averaged SHS because the partial correlation coefficients were close to 0. However, the undirected graphs confirmed an indirect association with Averaged SHS via "CES-D". This result suggests that graphical modeling is suitable for considering indirect relationships among multiple variables.

Averaged SHS was positively correlated with "Health considerations", which was positively correlated with vegetable intake and "Culinary confidence" and indirectly correlated with "Cooking frequency" through "Culinary confidence". These relationships seem reasonable, because previous studies[46,47] have shown similar relationships that vegetable and fruit consumption lead to improved SWB[22,44,48]. In this study, we found indirect relationships between SWB and vegetable intake or cooking behavior through "Health considerations". Therefore, we inferred that one of the psychological important factors of these relationships is "Health considerations".

Averaged SHS was positively correlated with "Enjoying the taste of foods". Various studies[49–51] have reported relationships between enjoying eating and health conditions, such as depression. In this study, there was no relationship between "CES-D" and "Enjoying the taste of foods"; thus, we inferred that having a tasty food is important for SWB independent of mental health in Japanese people.

Comparison with previous studies

In summary, the structure of Averaged SHS and "Physical health" via "Mental health" was consistent with findings from previous studies[24,25]. However, the relationship between Averaged SHS and "Enjoying the taste of foods" without the involvement of "Mental health" was a novel finding and not confirmed by previous studies. Dietary intake was related neurotransmitters such as dopamine[52], which are also related to mental health[53]. However, no association between tasty meals and mental health was found. As it has been reported that cooking behavior increases self-efficacy and contributes to SWB[47], we suggest that the direct association observed in this study is due to the satisfaction or self-affirmation derived from consuming a tasty meal, which are independent of mental health. Therefore, it may be preferable to design culinary experiences for SWB that consider not only mental health and health considerations but also preferences and cooking ability for experiencing tasty food.

Additionally, regarding the relationship between Averaged SHS, "Culinary confidence", and vegetable intake, we found "Health considerations" as one of the indicators mediating the relationships. Furthermore, the structure and interpretation of the complex relationships between SWB and various factors across different domains have not been summarized in the previous literature[3].

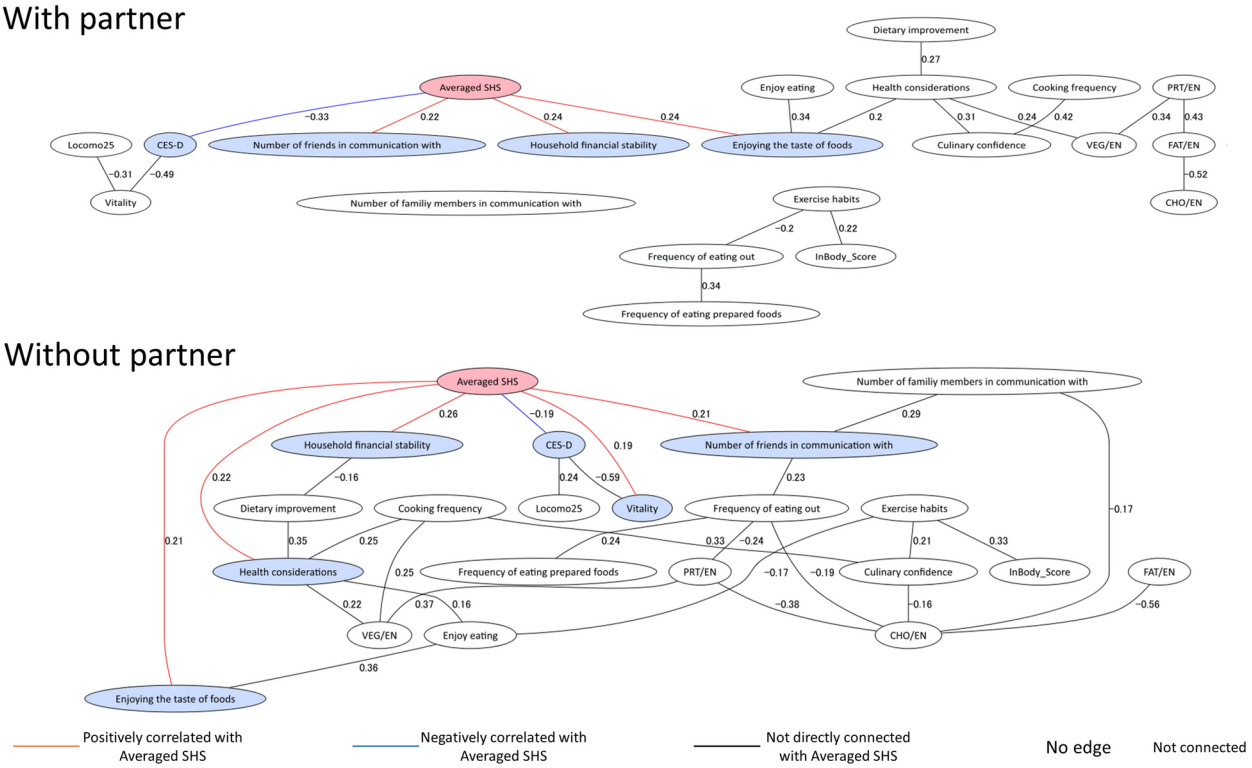


Fig. 6. Red circle indicates Averaged SHS. Blue circles indicate variables directly correlated with Averaged SHS. Numbers on the right side of the edges indicate the partial correlation coefficients. Red lines indicate the edges positively correlated with Averaged SHS. Blue line indicates edges negatively correlated with Averaged SHS. Black lines indicate the edge not directly connected with Averaged SHS. Variables not connected by edges had a partial correlation coefficient of 0 according to the covariance selection criteria. This indicates that variables not connected by edges are conditionally independent. (**a**) Undirected graph with partner (n = 378), (**b**) Undirected graph without partner, excluding bereavement (n = 118).

Implications for practice

Supporting the improvement of these factors can enhance SWB among Japanese people. In terms of eating behavior, a guideline has been established[54] in Japan. This guideline proposes several lifestyle changes to increase health-conscious eating behaviors, such as "increasing cooking frequency", "enhancing culinary knowledge and skills", and "increasing vegetable intake". These behaviors align closely with those associated with SWB. Thus, our results indicated that this guideline contributes to improving both SWB and health condition. Additionally, we believe that these findings are valuable for understanding the mechanisms behind changes in SWB, particularly when shifts in the living environment or interventions occur.

Graphical modeling based on background

Findings overview

An undirected graph of subgroups based on age, gender, job category, final educational background, and partners was created. Although Averaged SHS was comparable for each subgroup according to age, gender, job category, and final educational background (Fig. 3), the variables associated with Averaged SHS differed (Figs. 4, 5, 6, 7, 8 and Table5). The results indicated that, even though the degree of SWB was equal, the mechanisms behind SWB differed depending on the participants' attributes. The interpretation of feature paths of subgroups is described below.

Comparison with previous studies based on background

In the age-based subgroups, among participants aged over 65 years (Fig. 4C), "Enjoying the taste of foods" was positively correlated with Averaged SHS and negatively correlated with "Frequency of eating prepared foods." A related study[55] found that values around food vary by age; older adults prioritize safety and organic food over convenience. Based on these findings and our results, we inferred that self-prepared, tasty meals improved SWB among older adults.

Regarding gender, among the females (Fig. 5B), "Enjoying the taste of foods" and "Health considerations" were positively correlated with Averaged SHS. In contrast, no correlation was observed between eating behaviors and Averaged SHS among the males. This finding may be related to the fact that home economics

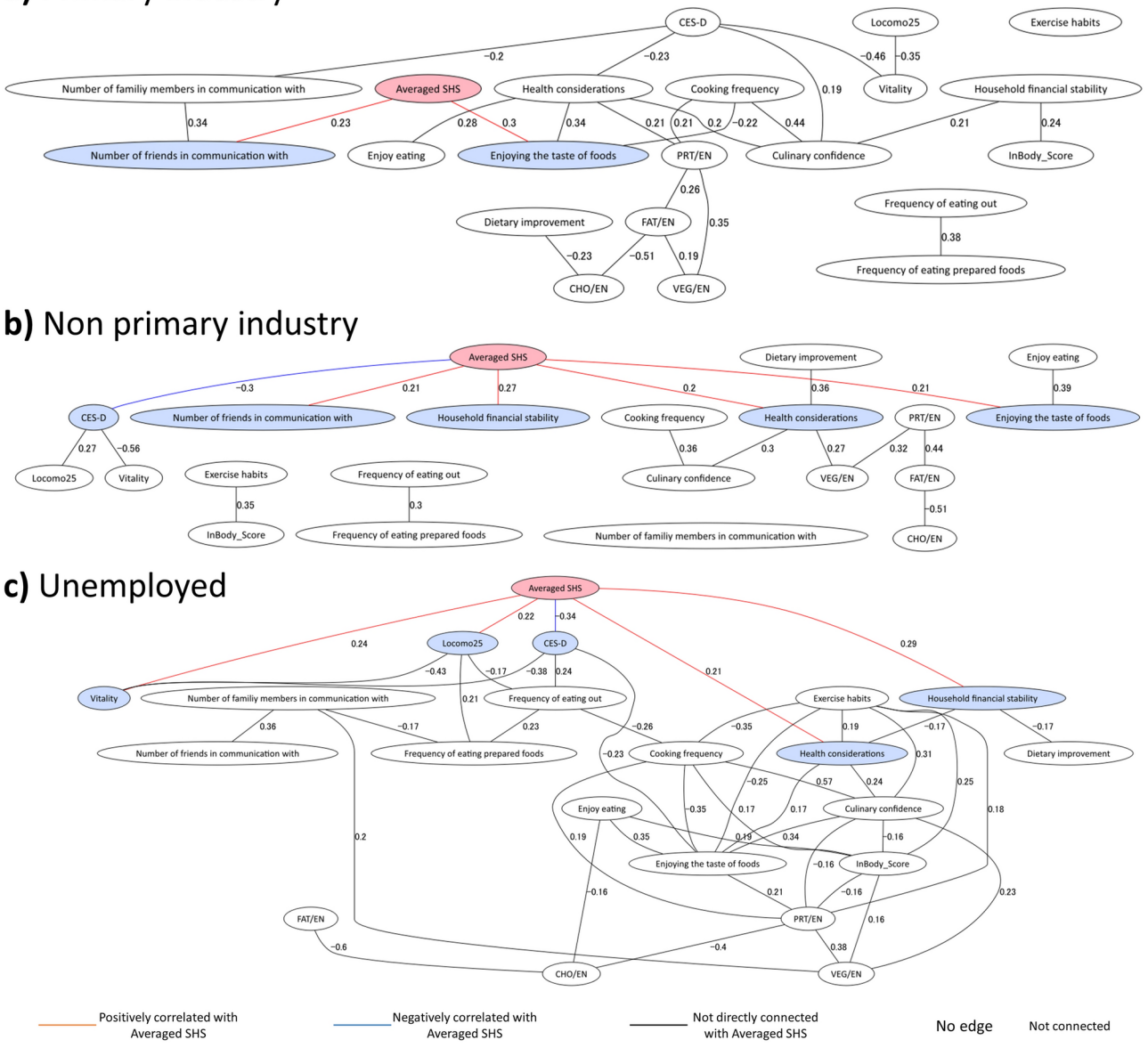
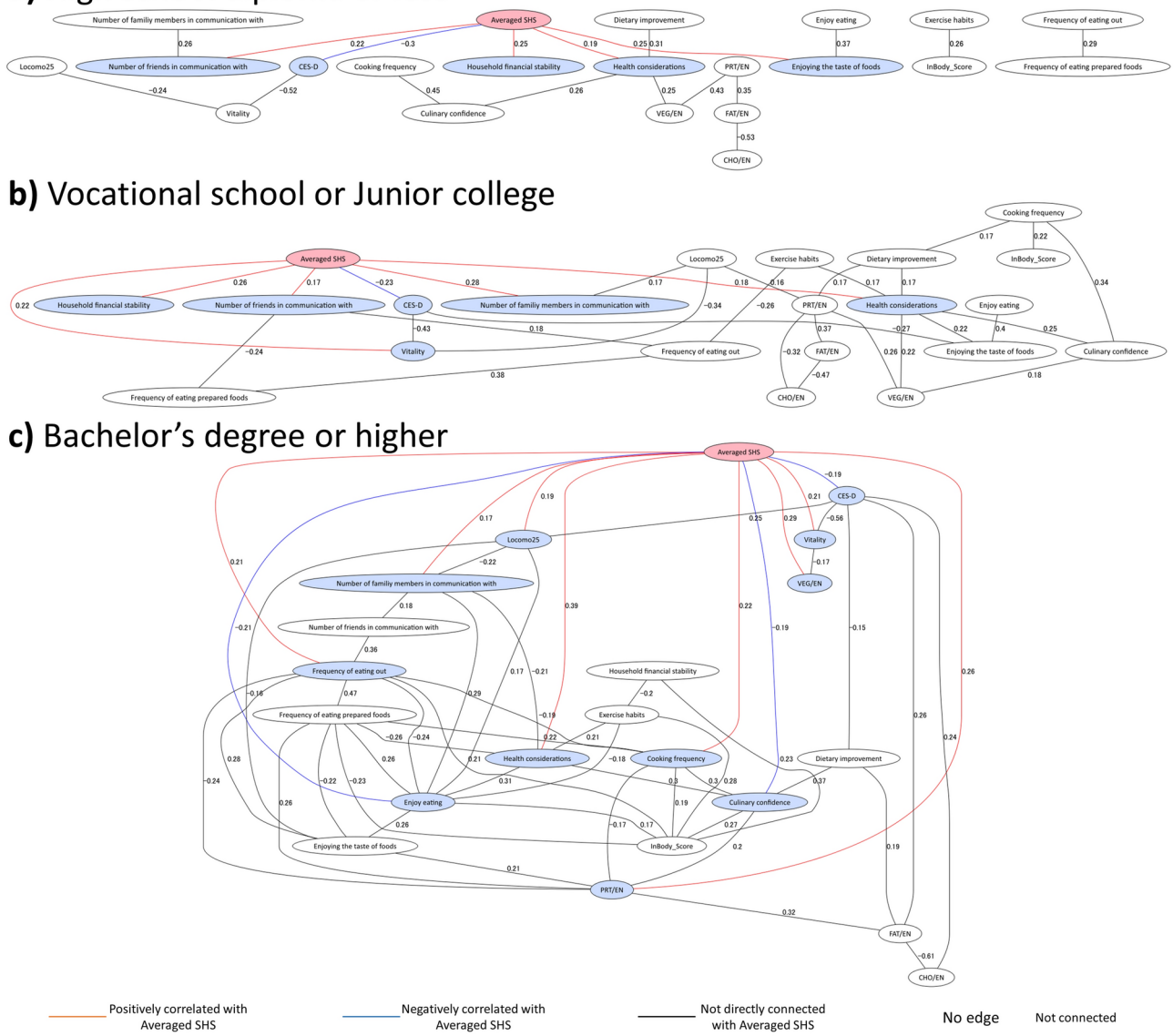


Fig. 7. Red circle indicates Averaged SHS. Blue circles indicate variables directly correlated with Averaged SHS. Numbers on the right side of edges indicate the partial correlation coefficients. Red lines indicate the edges positively correlated with Averaged SHS. The blue line indicates the edge negatively correlated with Averaged SHS. Black lines indicate the edge not directly connected with Averaged SHS. Variables not connected by edges had a partial correlation coefficient of 0 according to the covariance selection criteria. This indicates that variables not connected by edges are conditionally independent. (**a**) Undirected graph of primary industry (n = 98), (**b**) Undirected graph of non-primary industry (n = 331) and (**c**) Undirected graph of unemployed (n = 90).

was not included in the educational curriculum for men until 1993[56], whereas women still tend to bear primary responsibility for cooking and, likely, grocery shopping[57]. Providing tasty and highly nutritious foods to the females was considered important for improving SWB.

In terms of the participants' final educational background, among those with a bachelor's degree or higher (Fig. 8C), 11 variables correlated with Averaged SHS the highest among all subgroups. Individuals with higher educational levels tend to engage in a variety of activities, including professional work, their children's education[58], and social engagements[59]. They are also likely to be aware of the relationship between these activities and their well-being. In a bachelor's degree or higher group, "Enjoy eating" and "Culinary confidence" were negatively correlated with Averaged SHS. This group had different associations between SWB and the eating behaviors than



Graphical modeling grouped by Highest educational background

Fig. 8. Red circle indicates Averaged SHS. Blue circles indicate variables directly correlated with Averaged SHS. Numbers on the right side of the edges indicate the partial correlation coefficients. Red lines indicate the edges positively correlated with Averaged SHS. Blue lines indicate edges negatively correlated with Averaged SHS. Black lines indicate the edge not directly connected with Averaged SHS. Variables not connected by edges had a partial correlation coefficient of 0 according to the covariance selection criteria. This indicates that variables not connected by edges are conditionally independent. (**a**) Undirected graph of high school diploma or less (n = 323), (**b**) Undirected graph of a vocational school or a junior college (n = 125) and (**c**) Undirected graph of bachelor or higher (n = 65).

those observed for the other groups. Therefore, dietary interventions to improve SWB may need to consider the educational background of the target population.

Concerning the subgroups based on the marital status (Fig. 6), Averaged SHS was higher in the "With partner" group compared to the "Without partner" group ($p < 0.05$). This trend was also reported in a prior study[7] in Japanese. However, most variables correlated with Averaged SHS across both groups. Considering this point, previous studies that have investigated why marriage makes people happier were helpful. Marriage and SWB are related to closeness with the partner. This study's model does not incorporate these psychological factors. Another study reported an increase in health awareness with marriage. In this study, Averaged SHS was not directly related to "Health considerations" in the "With partner" group; however, "Health considerations" was indirectly related to Averaged SHS through "Enjoying the taste of foods". This difference between "With

partner" group and "Without partner" group was inferred to be the change in health awareness associated with marriage.

Implications for practice

The representation of the complex structure of the SWB in graphical modeling and the interpretation of the structure of each graph provides important insights for improving SWB in Japanese people. As mentioned above, we observed distinct features of "Eating behaviors" and SWB among the elderly and women, and differences in the structure of SWB based on educational background. Thus, we can simplify and interpret complex models by identifying factors unique to specific subgroups that are directly or indirectly linked to Averaged SHS, providing interpretations for each pathway. This process will allow us to uncover the characteristics of various backgrounds.

Generalizability of the results and limitations of the study

The generalizability of the results and limitations of this study are as follows. In this study, graphical modeling was conducted using correlations and simple rules[31–33]. It was considered effective to search for associations without prior hypotheses other than variable selection. However, it was difficult to identify causal relationships because of the lack of direction and use of cross-sectional data. Efforts to improve the validity of these associations, such as comparisons with other studies, are necessary to develop effective recommendations for improving SWB among Japanese adults.

The p-value < 0.30 was used as the threshold to stop repetition in the covariance selection process. This threshold was set with reference to values used in experiments in the literature[32]. However, in this literature, it was stated that there is no defined threshold and not only one correct model. In addition, AIC and BIC are sometimes used[34,60]. Thus, it is necessary to consider that the model was obtained under the specified conditions.

It is also important to consider that the IHPP data were obtained from Hirosaki City[30], a single region in Japan. Therefore, it is necessary to carefully consider generalization, because the mental and physical health conditions as well as social situations used in this study cannot be determined to be representative of the Japanese population. However, as indicated in Table 4, this study targeted participants with diverse backgrounds. Moreover, regarding the intake of nutrients used in the modeling—such as protein, fat, and carbohydrates—and body composition—such as height, weight, and BMI—no large effect sizes (Cohen's $d \geq 0.5$) were observed between the participants of this study and a nationally representative sample of individuals over 20 years old[61]. Results are presented in Supplementary Tables 1 and 2.

Confounding variables may arise because of subgrouping, and it cannot be inferred that individual groups directly influenced the model. To account for confounding, each group and its associated indicators are presented in the Supplementary Table 8.

Conclusion

In this study, an undirected graph was created using covariance selection to clarify the relationship between SWB and various factors, such as nutrient intake, eating behaviors, mental and physical health, and social situations among Japanese people. The undirected graph shown in Fig. 2 revealed the relationship between Averaged SHS and various variables across domains.

Furthermore, by comparing graphs divided into subgroups, it was found that the mechanisms behind Averaged SHS differed depending on the participants' attributes (Figs. 4, 5, 6, 7 and 8).

The model developed in this study can be utilized to connect well-being research across different domains. Our findings contribute to a deeper understanding of SWB and help identify key areas for enhancing SWB among Japanese people. For instance, the relationship between SWB and variables from various domains will play a crucial role in designing effective interventions to enhance SWB and in proposing policies aimed at improving SWB among Japanese people from diverse backgrounds.

Data availability

The data that support the findings of this study are available from the Hirosaki University COI Institutional Data Access / Ethics Committee (contact via e-mail: coi@hirosaki-u.ac.jp), but restrictions apply to the availability of these data, which were used under license for the current study, and so are not publicly available. The IHPP dataset is managed by the data management office of Hirosaki University. Further queries can be directed to corresponding author.

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Author contributions
SS, AO, EH, IK, GI, YT, and CF contributed to the design of this research. SS, AO, and EH analyzed the data. SS, IK, GI, and CF wrote the manuscript. SN, KM, KI, YT, and TM contributed to the creation of the database of IHPP and organizing and management of IHPP. All authors reviewed the manuscript.

Declarations

Competing interests
SS, AO, EH, IK, GI, and CF are employees of Ajinomoto Co., Inc., at the time of research. The specific roles of these authors are articulated in the Author contributions statement. The Department of Digital Nutrition and Health Science is a joint research department supported by Ajinomoto Co., Inc. The other authors declare that they have no competing interests.

Additional information
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