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Analysis of direction of association between radiation risk perception and relocation using a random-intercept and cross lagged panel model: The Fukushima Health Management Survey

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A R T I C L E I N F O

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A B S T R A C T

In the aftermath of a nuclear disaster, a person's radiation risk perception can harm their sociopsychological health. Although there are reports of an association between radiation risk perception and relocation, the direction of this association has not been clarified yet. In this study, we used a random-intercept and cross lagged panel model (RI-CLPM) to investigate the association and its direction between radiation risk perception and the prefectural-level relocation (i.e., inside/outside of Fukushima Prefecture). We did this by using five waves of longitudinal surveys between 2011 fiscal year and 2015 fiscal year among the people affected by the Fukushima disaster in 2011. We included 90,567 participants aged ≥15 years during the time of the disaster who responded to the questionnaire at least once. RI-CLPM was applied to examine the reciprocal relationship between radiation risk perception and locations. We used two radiation risk perception indicators (i.e., genetic effect and delayed effect) and two handling methods on missing data (i.e., listwise deletion and full information maximum likelihood estimation) as sensitive analyses. The effects of radiation risk perception on relocation were found to be negligibly small. Living inside Fukushima Prefecture reduced radiation risk perception irrespective of the difference of indicators or methods, highlighting that radiation risk perception did not dominantly govern whether people were living inside Fukushima Prefecture, but that the locations also affected radiation risk perception. This was the first study to reveal the direction of the association between radiation risk perception and relocation in the aftermath of nuclear disasters.

1. Introduction

A person's radiation risk perception can harm their sociopsychological health. As observed in the Chernobyl nuclear disaster in 1986 (Bromet, 2012), severe psychological distress was found among people who had a high perception of radiation risk after the Fukushima nuclear disaster in 2011 (Maeda et al., 2019; Suzuki et al., 2015). After the Fukushima disaster, several researchers reported that radiation risk perception was associated with food avoidance, a hesitancy to visit for sightseeing, a low safety view on the environment, employment turnover, discrimination, and social divisions, eventually resulting in a decline in the population's well-being (Murakami et al., 2018, 2019; Sawano et al., 2018; Shirai et al., 2019; Suzuki et al., 2018; Takebayashi et al., 2017). Although there is a scientific consensus that there are no discernible increases in heritable effects and cancer among the people affected by the Fukushima disaster (United Nations Scientific Committee on the Effects of Atomic Radiation, 2014; 2017), 36% of the affected people in the 2016 fiscal year (FY; April to March) still had concerns for the next generation's health due to radiation (Radiation Medical Science Center for the Fukushima Health Management Survey Fukushima

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Medical University, 2020).

The radiation risk perception of those affected was also reported to be associated with individuals' relocation or willingness to return to their hometown (Do, 2019; Matsunaga et al., 2019; Orita et al., 2013). After the Fukushima disaster, approximately 150,000 people were relocated to other areas, including outside of Fukushima Prefecture under a governmental evacuation order (The National Diet of Japan, 2012). As of April 2019, approximately 23,000 mandatory evacuees still live outside of Fukushima Prefecture, although the evacuation order has been lifted in several areas (Reconstruction Agency, 2019). In addition to economic status and life environments being affected by the disaster and associated evacuation, a high radiation risk perception is one of major reasons that evacuees have hesitated to return to their hometown (Murakami, Takebayashi, & Tsubokura, 2019; Reconstruction Agency, 2020). The people with a high risk perception were likely to evacuate farther away from the affected area (Do, 2019) and less likely to return their hometown (Orita et al., 2013). These results suggest radiation risk perception affects relocation.

There is also a possibility of an opposite direction of causality between radiation risk perception and locations. The people who lived in the Fukushima Prefecture have lower radiation risk perception than those in Tokyo (Shirai et al., 2019). Risk perception depends on several factors, including what they know, trust, and experience (Ferrer et al., 2016; Murakami et al., 2016; Shirai et al., 2019; Visschers & Siegrist, 2013). The experience of living in the Fukushima Prefecture possibly affects people's radiation risk perception.

There is a possible bidirectionality between radiation risk perception and relocation; however, there are no studies to reveal the direction. If the causal direction was that radiation risk perception caused hesitation of reallocation to inside Fukushima Prefecture, reduction of radiation risk perception among people outside Fukushima Prefecture would encourage relocation to inside Fukushima Prefecture. On the other hand, if the causal direction was opposite, the key for radiation risk perception would be present in the living environment in Fukushima Prefecture. Understanding the direction will enhance effective measures in mitigation of radiation risk perception and relevant sociopsychological issues.

In this study, we analyzed a bidirectionality between radiation risk perception and relocation using five waves of longitudinal surveys between 2011FY and 2015FY among the people affected by the Fukushima disaster. First, we overviewed age- and gender-specific yearly changes of radiation risk perception and the proportion of people who live inside/outside of Fukushima Prefecture. We then clarified an association and its direction between radiation risk perception and the prefectural-level relocation (i.e., inside/outside of Fukushima Prefecture) by using random-intercept and cross lagged panel model (RI-CLPM). It should be noted that we did not analyze the return to the hometown and instead looked at the prefectural-level relocation, and that the participants in this study included those whose hometowns were under evacuation orders during the survey period.

2. Method

2.1. Study sites

This study was performed as a part of the Fukushima Health Management Survey (FHMS) (Yasumura et al., 2012). This is a large cohort survey targeting residents in 13 municipalities spanning evacuation order areas: Tamura City, Kawamata Town, Iitate Village, Minamisoma City, Katsurao Village, Namie Town, Futaba Town, Okuma Town, Tomioka Town, Naraha Town, Hirono Town, Kawauchi Village, and hot-spot areas in Date City (Fig. 1). The target residents were defined in accordance with the registration data in the Basic Resident Register in 13 municipalities. The Japanese government designated a 20 km radius from the Fukushima Daiichi Nuclear Power Station and a 10 km radius from the Fukushima Daini Nuclear Power Station as evacuation order areas on 12 March 2011. The government updated the evacuation order areas to be a 20 km radius from the Fukushima Daiichi Nuclear Power Station and where an additional effective dose exceeded 20 mSv/year on 22 April 2011. Hirono Town and some areas in Kawauchi Village were outside the evacuation order areas, but the municipal office issued its own evacuation order for the residents. The municipal evacuation order was lifted on 31 January 2012 in Kawauchi Village and on 31 March 2012 in Hirono Town. The governmental evacuation order has started to lift since 1 April 2014. Details were described elsewhere (Ministry of the Environment, 2019; Reconstruction Agency, 2019).

2.2. Participants

We used data from FHMS questionnaire surveys performed in 2011FY–2015FY. The questionnaires were distributed to residents in 13 municipalities in January 2012, February 2013, February 2014, February 2015, and February 2016. The number of adult participants in 2011FY–2015FY was 73,431 (valid response rate: 40.7%), 55,061 (29.8%), 46,372 (25.0%), 43,811 (23.4%), and 43,970 (23.8%), respectively. This study targeted 100,353 respondents aged ≥15 years at the time of the disaster who responded to the questionnaire at least once. We excluded 9786 proxy respondents. The total number of participants was 90,567.

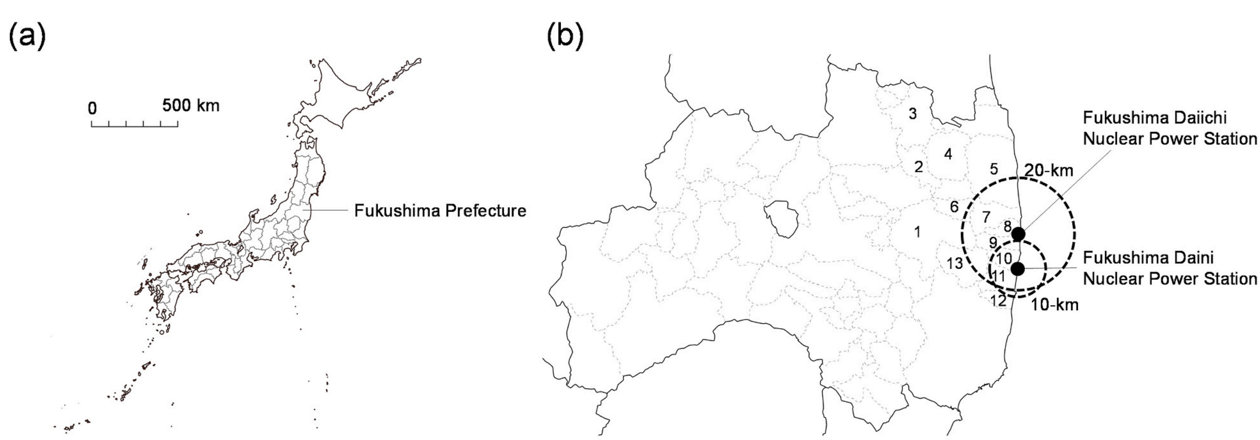

Fig. 1. Study sites. (a) Japan, (b) Fukushima Prefecture. 1. Tamura City, 2. Kawamata Town, 3. Date City, 4. Iitate Village, 5. Minamisoma City, 6. Katsurao Village, 7. Namie Town, 8. Futaba Town, 9. Okuma Town, 10. Tomioka Town, 11. Naraha Town, 12. Hirono Town, 13. Kawauchi Village.

2.3. Questionnaire items

Post-disaster residential locations were defined by the current addresses, which participants stated. If they were not available, the mailing addresses were used instead. The locations were classified into two categories: inside of Fukushima Prefecture and outside of Fukushima Prefecture.

Two types of radiation risk perceptions based on Lindell's indicators (Lindell & Barnes, 1986) were asked in all the survey years: (1) 'What do you think is the likelihood of damage to your health (e.g. cancer onset) in later life as a result of your current level of radiation exposure?' (delayed effect); (2) 'What do you think is the likelihood that the health of your future (i.e. as-yet unborn) children and grandchildren will be affected as a result of your current level of radiation exposure?' (genetic effect). There were four ways for the participants to respond: 1 = very unlikely, 2 = unlikely, 3 = likely, or 4 = very likely. Since a person's risk perception of genetic effect is the most sensitive indicator of their mental health (Suzuki et al., 2015), we mainly used this indicator. The risk perception of delayed effect was used as a sensitive analysis.

We considered items reported to be a risk factor of radiation risk perception as covariates (Suzuki et al., 2015). Self-rated health conditions and histories of mental illness were also added as covariates because they were considered to associate with radiation risk perception: we confirmed their significant associations in 2011FY (Welch's *t*-test or chi-squared test: $P < 0.001$). Covariates were age at the time of the disaster, gender, educational attainment, nuclear power plant accident experience, house damage, bereavement, unemployment status, income status, self-rated health condition, and history of mental illness. The data of age at the time of the disaster and gender were available from all the participants. Apart from these two factors, the data in the 2011FY survey were used as covariates in the statistical analysis. The classification or cutoff of variables followed the previous studies (Suzuki et al., 2015). We used Welch's *t*-test or chi-squared test to confirm associations between locations in 2011FY and radiation risk perception (genetic effect) or covariates with IBM SPSS Statistics 24 software (Table 1). Welch's *t*-test was used instead of *t*-test or Mann–Whitney *U* test, as it was recommended as a standard test (Rasch et al., 2011).

2.4. Random-intercept and cross lagged panel model (RI-CLPM)

To investigate the reciprocal relationship between radiation risk perception and locations, RI-CLPM (Hamaker et al., 2015) was applied to the five waves of longitudinal data. The RI-CLPM in this study is depicted in Fig. 2. CLPM can estimate the autoregressive (path a1 for radiation risk perception, a2 for location) and cross lagged (path b1 for effect of radiation risk perception on location, b2 for effect of residential location on risk perception) effect between two variables. RI-CLPM adds a latent random-intercept factor onto CLPM to control between-person stability (which reflects stable individual differences between participants) for each indicator. Adding random-intercept to the CLPM can estimate the pure within-person autoregressive and cross lagged effects controlling for the between-person stability. In other words, including a random-intercept in the CLPM reduces the overestimation bias (caused by uncontrolled between-person stability) of autoregressive and cross lagged effects. RI-CLPM is recognized as one of the most suitable models to estimate within-person reciprocal relationships between variables over time (Hamaker et al., 2015; Keijsers, 2016).

A latent variable was set to each of the observed variables, and the variances of the observed variables were constrained to zero to shift the interpretation of the parameters from a between-person level to a within-person level. The autoregressive effect (path a) reflects the degree that the individuals' prior deviations from their own scores can predict their deviations from their own expected scores. Similarly, the cross lagged effect (path b) reflects the degree that the individuals' deviations from their own expected scores in a variable at $t-1$ (i.e., a previous time point) can predict their deviations from their own expected scores in another variable at t (i.e., a next time point) (Hamaker et al., 2015; Keijsers, 2016).

Table 1
Association between radiation risk perception (genetic effect) or covariates and locations in the 2011 fiscal year. SD: standard deviation.

		Total	Outside Fukushima Prefecture	Inside Fukushima Prefecture	P
Radiation risk perception (genetic effect)	1. Very unlikely	9174	1848 (20.1%)	7326 (79.9%)	<0.001[a]
	2. Unlikely	14,827	2583 (17.4%)	12,244 (82.6%)	
	3. Likely	15,241	2858 (18.8%)	12,383 (81.2%)	
	4. Very likely	20,976	4328 (20.6%)	16,648 (79.4%)	
	Arithmetic mean ± SD		2.83 ± 1.10	2.79 ± 1.07	
Age at disaster	15–49	23,502	6179 (26.3%)	17,323 (73.7%)	<0.001[b]
	50–64	20,402	3298 (16.2%)	17,104 (83.8%)	
	≥65	20,282	2758 (13.6%)	17,524 (86.4%)	
Gender	Female	36,233	7458 (20.6%)	28,775 (79.4%)	<0.001[b]
	Male	27,953	4777 (17.1%)	23,176 (82.9%)	
Educational attainment	Elementary, junior high or high school	45,570	7625 (16.7%)	37,945 (83.3%)	<0.001[b]
	Vocational college, junior college or more	16,052	4175 (26.0%)	11,877 (74.0%)	
Nuclear power plant accident experience	No	30,420	4885 (16.1%)	25,535 (83.9%)	<0.001[b]
	Yes	33,766	7350 (21.8%)	26,416 (78.2%)	
House damage	Less than partial collapse of the house	50,325	8557 (17.0%)	41,768 (83.0%)	<0.001[b]
	Partial collapse and worse	9496	2348 (24.7%)	7148 (75.3%)	
Bereavement	No	49,883	9247 (18.5%)	40,636 (81.5%)	<0.001[b]
	Yes	12,470	2722 (21.8%)	9748 (78.2%)	
Became unemployment	No	50,759	8283 (16.3%)	42,476 (83.7%)	<0.001[b]
	Yes	13,427	3952 (29.4%)	9475 (70.6%)	
Income has decreased	No	52,181	9876 (18.9%)	42,305 (81.1%)	0.069[b]
	Yes	12,005	2359 (19.7%)	9646 (80.3%)	
Self-rated health situation	1. Very good	2667	498 (18.7%)	2169 (81.3%)	<0.001[a]
	2. Good	8533	1563 (18.3%)	6970 (81.7%)	
	3. Fair	39,970	7452 (18.6%)	32,518 (81.4%)	
	4. Poor	10,499	2206 (21.0%)	8293 (79.0%)	
	5. Very poor	1116	274 (24.6%)	842 (75.4%)	
	Arithmetic mean ± SD		3.02 ± 0.76	2.97 ± 0.73	
History of mental illness	No	58,364	11,094 (19.0%)	47,270 (81.0%)	<0.001[b]
	Yes	3079	668 (21.7%)	2411 (78.3%)	

[a] Welch's *t*-test.
[b] Chi-squared test.

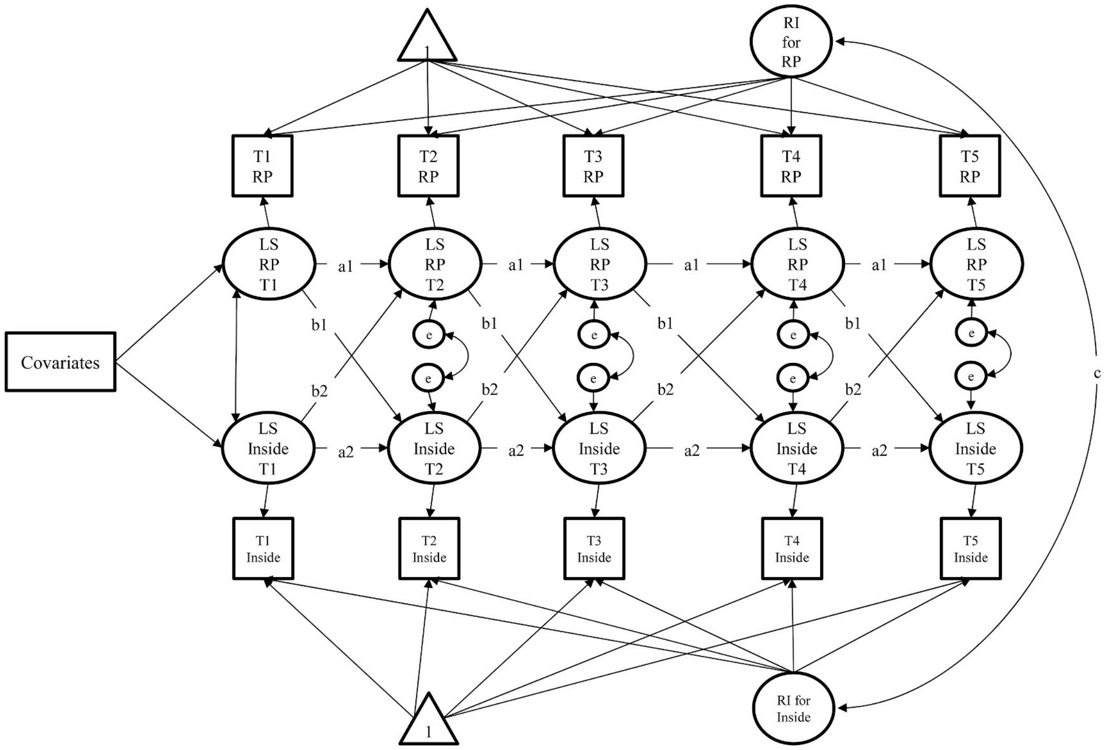

Fig. 2. Model structure. T1–T5: time step (2011FY–2015FY); RI: random-intercept; LS: latent score; RP: risk perception; Inside: inside Fukushima Prefecture; e: error term; a: auto regression; b: cross lag effect; c: correlation between RIs. Covariates included age at disaster, gender, educational attainment, nuclear power plant accident experience, house damage, bereavement, unemployment status, income status, self-rated health situation, and history of mental illness.

To investigate whether autoregressive and cross lagged effects varied across time, a series of nested models with increasing constraints were tested (Selig & Little, 2012, pp. 265–278): an unconstrained model (freely estimated autoregressive, cross lagged path, and residual covariance at a different time point) (Model 1), followed by the constrained autoregressive path model (Model 2), then the constrained autoregressive and cross lagged path model (Model 3). Finally, the model constrained cross-sectional residual correlation between contract add on Model 3 (Model 4) was tested. To select the model, comparative fit index (CFI), standardized root mean squared residual (SRMR), and root mean square error of approximation (RMSEA) were used. Based on past research (Kline, 2015), CFI should be ≥ 0.90 for acceptable fit and >0.95 for good fit, SRMR should be <0.10 for acceptable fit and <0.08 for good fit, and RMSEA should be <0.10 for acceptable fit and <0.06 for good fit. If a difference of less than 0.01 is found in the ΔCFI index between nested models, it is indicated the less parameterized model is supported (Cheung & Rensvold, 2002).

Scores of radiation risk perception (genetic effect) ranged from 1 to 4. Radiation risk perception (delayed effect) was also used as a sensitive analysis. Regarding locations, outside and inside Fukushima Prefecture was regarded as 0 and 1, respectively. The following variables were included in the model as covariates to control baseline participants' characteristics: age at the time of the disaster, gender, educational attainment, nuclear power plant accident experience, house damage, bereavement, unemployment status, income status, self-rated health situation, and history of mental illness. These variables regressed on latent variables of radiation risk perception and locations at T1 (2011).

For non-normal nature of included variables, the robust Maximum Likelihood Estimator (MLR) was used. Missing data was handled with listwise deletion. For the purpose of sensitivity analysis, the same model was tested with different methods for dealing with missing observation (full information maximum likelihood (FIML) estimation). While listwise deletion excludes participants with any missing data, FIML estimation means all participants are included by using a model-based parameter estimation method based on all available information. In addition, the RI-CLPM model was examined by changing only the risk perception indicator from genetic effect to delayed effect. Since gender and age were related to risk perception based on the previous study (Suzuki et al., 2015), the model was tested stratified by gender (female or male) and age group (15–49, 50–64, ≥65).

RI-CLPM was estimated with a lavaan package (Rosseel, 2012), which can conduct structural equation modeling in R (R Development Core Team, 2020).

3. Results

3.1. Yearly changes of radiation risk perception and locations

Among all participants, the radiation risk perception (genetic effect) was 2.80 (95% confidence interval (CI): 2.79–2.81) in 2011FY and gradually reduced to 2.25 (2.24–2.26) in 2015FY (Fig. 3a). Similar decreasing trends of radiation risk perception (genetic effect) were observed irrespective of age group (Fig. 3b) or gender (Fig. 3c). While there was little difference in the radiation risk perception (genetic effect) among age groups (e.g., 2015FY: ≤ 49 y at the disaster, 2.24 (95% CI: 2.23–2.26); 50–64 y, 2.24 (2.23–2.26); ≥65 y, 2.26 (2.24–2.28)), radiation risk perception (genetic effect) among females was higher than among males (e.g., female, 2.30 (2.28–2.31); male, 2.19 (2.17–2.21)).

Among all participants, the proportions of those who lived inside Fukushima Prefecture were 80.9% (80.6%–81.2%) in 2011FY and slightly increased to 84.8% (84.5%–85.2%) in 2015FY (Fig. 3d). Among 13,684 participants who responded to all the questionnaires from 2011FY to 2015FY, the proportion of those who have lived inside Fukushima Prefecture for 5 years were 78.6%. Those who have lived outside Fukushima Prefecture for 5 years were 12.3%. A total of 2.2% of participants have relocated from inside to outside Fukushima Prefecture, whereas 6.1% have relocated from outside to inside Fukushima Prefecture. It was noted that 0.7% of participants have experienced the

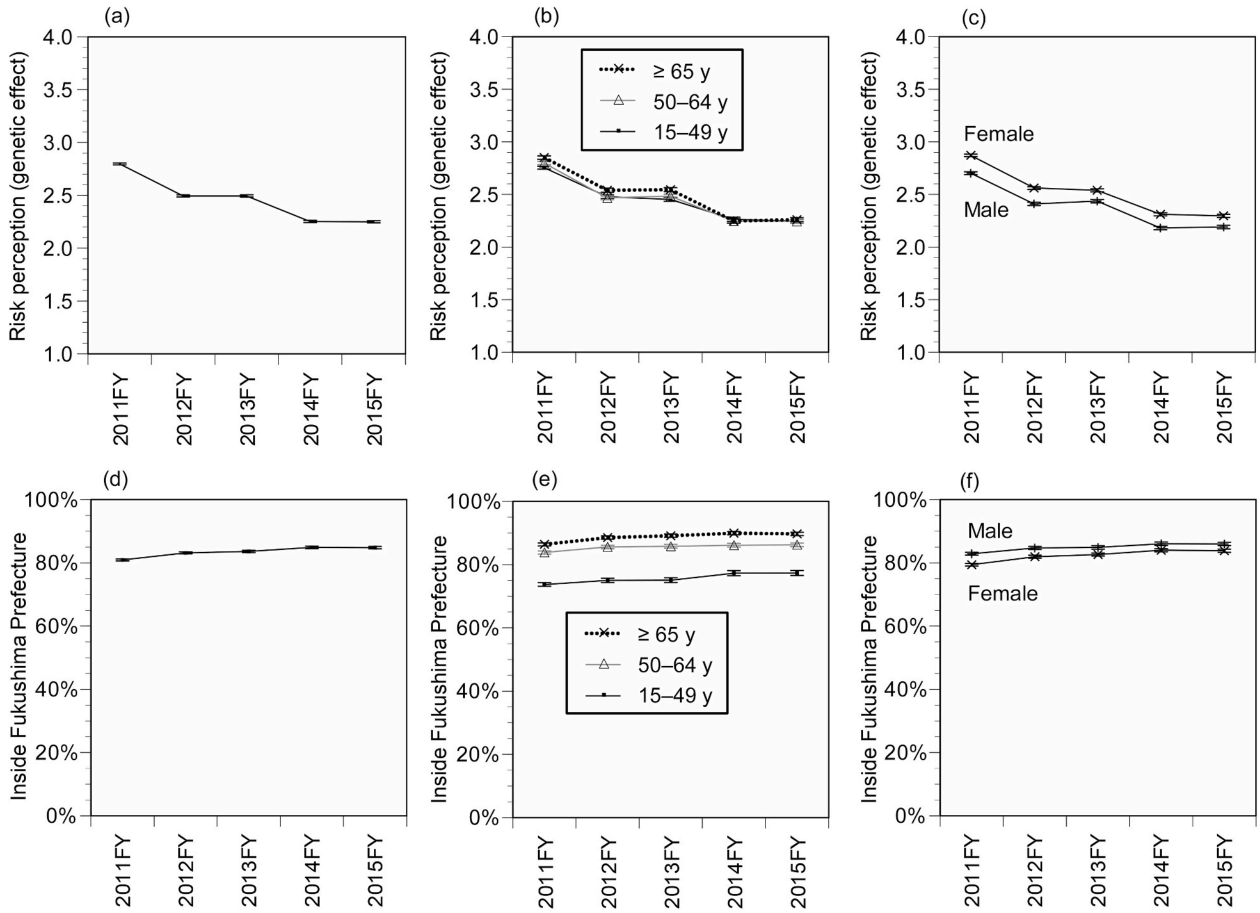

Fig. 3. Yearly changes of radiation risk perception (genetic effect) and proportion of people who lived inside Fukushima Prefecture. (a–c) Risk perception (genetic effect), (a) all participants, (b) age at the disaster, (c) gender; (d–f) proportion of people who lived inside Fukushima Prefecture, (d) all participants, (e) age at the disaster, (f) gender. Error bars represent 95% confidence intervals.

Table 2
Results of model fit. CFI: comparative fit index; SRMR: standardized root mean squared residual; RMSEA: root mean square error of approximation. FIML: full information maximum likelihood estimation.

Model	Radiation risk perception	Model	Participants	CFI	SRMR	RMSEA
Model 1	Genetic effect	Listwise	All participants	0.970	0.039	0.039
Model 2	Genetic effect	Listwise	All participants	0.965	0.045	0.041
Model 3	Genetic effect	Listwise	All participants	0.965	0.046	0.040
Model 4	Genetic effect	Listwise	All participants	0.964	0.046	0.039
Model 4	Delayed effect	Listwise	All participants	0.969	0.044	0.037
Model 4	Genetic effect	FIML	All participants	0.960	0.041	0.024
Model 4	Genetic effect	Listwise	Age at disaster: 15–49	0.975	0.042	0.037
Model 4	Genetic effect	Listwise	Age at disaster: 50–64	0.964	0.051	0.041
Model 4	Genetic effect	Listwise	Age at disaster: ≥ 65	0.957	0.052	0.042
Model 4	Genetic effect	Listwise	Gender: Female	0.964	0.047	0.041
Model 4	Genetic effect	Listwise	Gender: Male	0.965	0.049	0.038

prefectural-level relocation twice or more within 5 years.

The stratified analyses also showed the increasing trends of each age and gender group (Fig. 3e and f). The higher proportions of people living inside Fukushima Prefecture were observed among older groups: e.g., 2015FY: ≤ 49 y, 77.3% (95% CI: 76.6%–78.1%); 50–64 y, 86.2% (85.7%–86.8%); ≥65 y, 89.7% (89.2%–90.2%)). The proportion of males living inside Fukushima Prefecture was slightly higher than the proportion of females (e.g., female, 83.9% (83.4%–84.4%); male, 86.0% (85.5%–86.5%)).

3.2. Random-intercept and cross lagged panel model: analysis of direction of association between radiation risk perception and relocation

We first confirmed the model fit (Table 2). CFI, SRMR, and RMSEA were similar among Models 1–4 (listwise) that analyzed radiation risk perception (genetic effect) among the participants. These indexes were judged as good model fits (Kline, 2015). ΔCFI indexes between nested models were <0.01, showing Model 4 was applicable (Cheung & Rensvold, 2002). Model 4 (listwise) using risk perception of delayed effect instead, Model 4 (FIML), or targeting age- and gender-subgroups also showed similar indexes. We therefore demonstrate results based on Model 4 hereinafter.

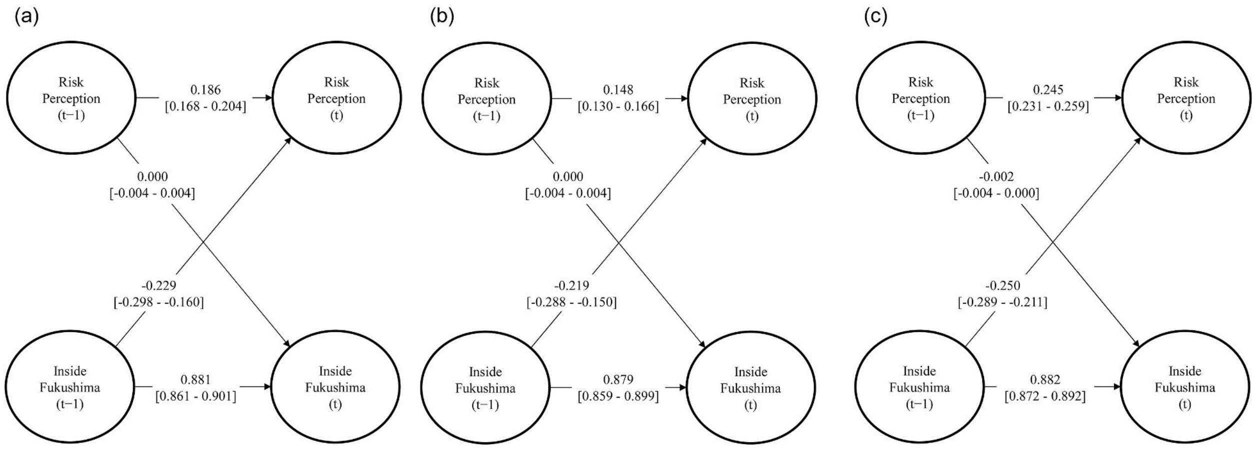

Fig. 4. Relationships between radiation risk perception and locations (all participants). (a) Genetic effect (listwise), (b) delayed effect (listwise), (c) genetic effect (FIML). Values represent unstandardized regression coefficients [95% confidence interval]. t = T2–T5 (2012FY–2015FY). FIML: full information maximum likelihood estimation.

In radiation risk perception (genetic effect), a significant positive association was found between two time periods (unstandardized regression coefficient: 0.186 [95% CI: 0.168–0.204]), and there was a strong significant positive association in the locations (0.881 [0.861–0.901]) (Fig. 4a). The effect from the locations (inside Fukushima Prefecture) at t−1 on radiation risk perception (genetic effect) at t was significantly negative (−0.229 [−0.298 to −0.160]). Contrary to this, the effect from radiation risk perception (genetic effect) at t−1 on the locations (inside Fukushima Prefecture) at t was not significant and negligibly small (0.000 [−0.004–0.004]). The models using radiation risk perception (delayed effect) or the FIML method showed a similar result (Fig. 4b and c).

The stratified analyses regarding age or gender groups also showed consistent results, despite the exception that there was a relatively weak association in the locations between two time periods among people aged ≥65 y at the disaster (0.573 [0.479–0.667]) (Fig. 5a–e).

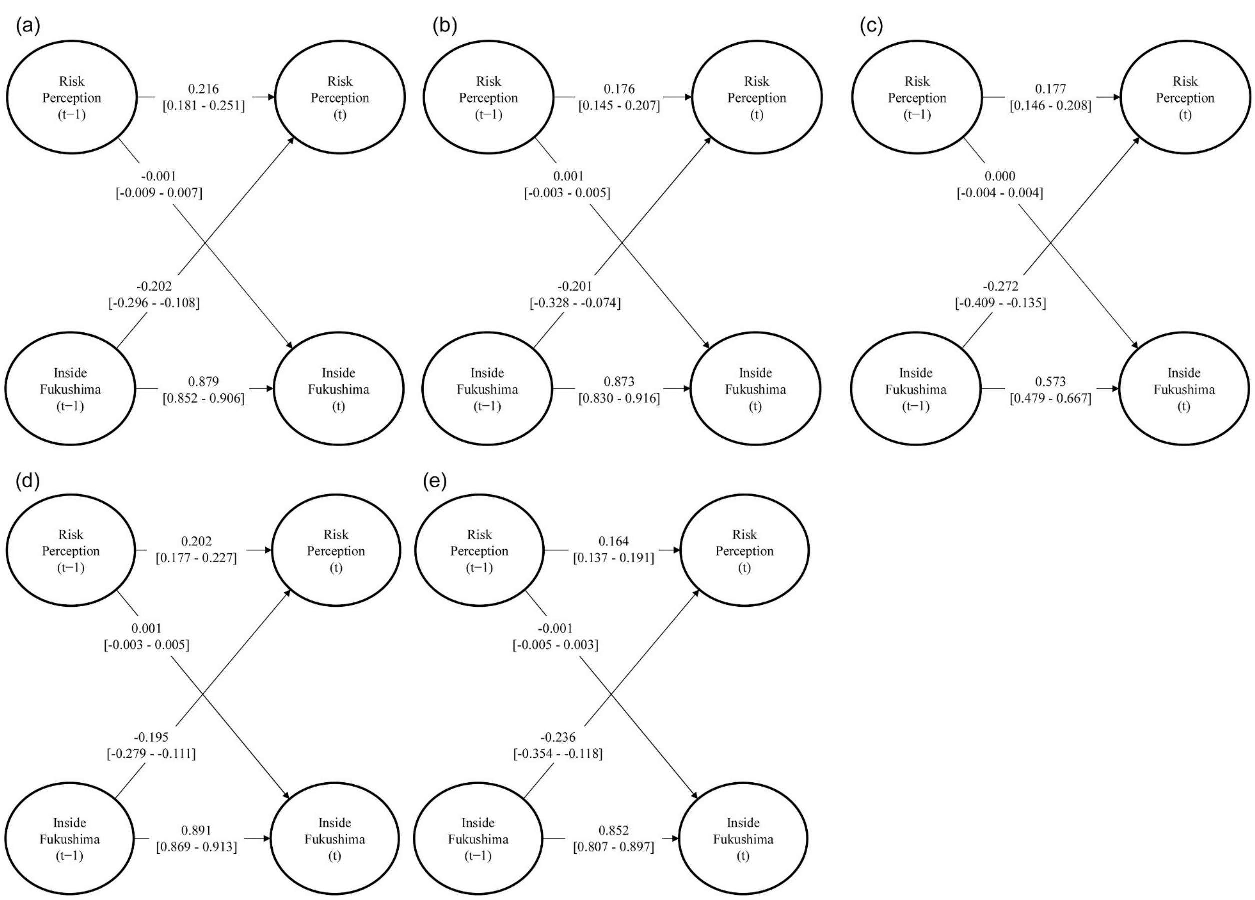

Fig. 5. Stratified analyses: relationships between radiation risk perception (genetic effect, listwise) and locations. (a) 15–49 y at the disaster, (b) 50–64 y at the disaster, (c) ≥ 65 y at the disaster, (d) female, (e) male. Values represent unstandardized regression coefficients [95% confidence interval]. t = T2–T5 (2012FY–2015FY). FIML: full information maximum likelihood estimation.

4. Discussion

In this study, we investigated five-year changes of radiation risk perception and the relocation among the people who lived in the municipalities, including evacuation order areas after the Fukushima disaster, and analyzed the direction of their associations using the RI-CLPM.

Radiation risk perception (genetic effect) gradually decreased within five years in the aftermath of the Fukushima disaster, irrespective of age and gender groups. This reduction was consistent with other indicators of radiation risk perception (i.e., radiation anxiety regarding living spaces) (Suzuki et al., 2018). Further, the proportion of people who were living inside Fukushima Prefecture had gradually increased. Older people were more likely to live inside Fukushima than younger, which was consistent with the finding that aged people were abundant among returnees (Murakami, Takebayashi, & Tsubokura, 2019).

The RI-CLPM showed a good fit, irrespective of model types. This suggested that degrees of associations between radiation risk perception and the locations were similar among the survey periods.

Importantly, the RI-CLPM revealed that the effects of radiation risk perception on relocation were negligibly small, and living inside Fukushima Prefecture reduced radiation risk perceptions irrespective of the difference of indicators (i.e., genetic effect and delayed effect) or methods (i.e., listwise deletion and FIML estimation). Furthermore, the direction and degree of associations were almost consistent among age or gender groups. These results highlight that radiation risk perception does not dominantly govern the decision of whether to live inside Fukushima Prefecture, but that the locations still affect radiation risk perception. The former finding was inconsistent with the previous reports that an evacuee's return to their hometown or their willingness to do so was associated with high radiation risk perception (Matsunaga et al., 2019; Orita et al., 2013). This gap can be explained by three possibilities. First, our study distinguished the locations between inside and outside Fukushima Prefecture, whereas the previous study (Orita et al., 2013) assessed return hometowns where people had originally lived. The people with a high radiation risk perception in this study might have relocated to places outside of the evacuation order areas in Fukushima Prefecture. Second, the actual return behavior of evacuees differs from their willingness, which is known as an intention-behavior gap (Sheeran, 2002). The previous survey (Matsunaga et al., 2019) assessed the participants' intentions to return to their hometowns rather than their actual behaviors. The actual return behavior is complex and governed by other factors (e.g. medical services, economic factors, convenience to daily education, and employment (Reconstruction Agency, 2020)). In fact, the gender ratios were similar among returnees (Murakami, Takebayashi, & Tsubokura, 2019), despite the differences in the willingness between genders (Matsunaga et al., 2019). Third, the participants in this study included those whose hometowns' evacuation orders were not lifted. Since people can live in Fukushima Prefecture even under evacuation orders, they could relocate to Fukushima Prefecture if they wanted to. However, the residents whose hometowns were under evacuation orders during the survey period might hesitate to relocate to Fukushima Prefecture till the lifting of the evacuation order, even though they could relocate. Therefore, the effects of radiation risk perception on locations might be underestimated.

There are some reasons why living inside Fukushima Prefecture reduces radiation risk perception. First, Shirai et al. reported a person's health and social knowledge regarding radiation could slightly reduce their radiation risk perception, and the knowledge depended on the type of available information (Shirai et al., 2019). There was a media information gap in quantity and quality between locations inside and outside Fukushima Prefecture (Meissner, 2018). People living inside Fukushima possibly have more opportunities to access the knowledge that mitigated radiation risk perception. Second, various risk communication activities have been implemented among stakeholders, including residents, medical professionals, radiation experts, governmental staff, and non-profitable organization members mainly in Fukushima Prefecture (Lochard, 2016; Schneider et al., 2019). Risk perception is strongly affected by personal experience and trust rather than knowledge (Ferrer et al., 2016; Murakami et al., 2016). Risk communication activities involving stakeholders did not only provide knowledge regarding radiation but also worked to improve radiological protection measures, which support decision making, the sharing of experiences, and the enhancement of trust via cooperation with each other, possibly resulting in the decline of radiation risk perception as well as the promotion of resilience (Murakami et al., 2017; Takebayashi et al., 2020).

A high radiation risk perception can harm sociopsychological health in various ways. In particular, depression, stigma, and discrimination are likely to occur in communities with different cultures or identities when the people move outside Fukushima Prefecture (Kobayashi et al., 2019; Sawano et al., 2018). It is important that affected people can cope with such social issues and people living outside can share the current circumstances of Fukushima Prefecture. People generally overestimate the radiation risk (Murakami et al., 2016) and are not extensively familiar with social and health issues regarding radiation and its mitigation measures after the Fukushima disaster (Shirai et al., 2019). Scientific findings regarding radiation health effects (i.e., no discernible increases in heritable effects and incidences of cancer (United Nations Scientific Committee on the Effects of Atomic Radiation, 2014; 2017)) and living experiences in the Fukushima Prefecture are expected to be shared among all the people, including those who were not affected by the Fukushima disaster.

This study had some limitations. First, the response rates were not very high (from 23.4% to 40.7%). To reduce selection biases, we targeted those who responded to the questionnaire survey at least once and confirmed the results were consistent between two different handling methods on missing data (listwise deletion and FIML estimation). Second, we only distinguished the locations between inside and outside Fukushima Prefecture due to data availability. The detailed analyses, especially regarding returns to hometowns, were expected. Third, we did not include variables such as job status or family members of the nuclear power station workers. The radiation risk perception among nuclear power station workers is different from that of the public (Kivimäki & Kalimo, 1993). Although the number of full-time Tokyo Electric Company employees at the Fukushima Daiichi and Daini Nuclear Power Stations at the time of the disaster was about 1800 (Shigemura et al., 2014), the number of affiliated company employees and their families would be much larger. Further, employment opportunities due to the presence of the nuclear power stations could have generated potential economic benefits among the local population. Radiation risk acceptance is governed by trust via risk perception and benefit perception (Visschers & Siegrist, 2013). Although changes in annual income and unemployment status due to the disaster were considered covariates in this study, detailed variables such as nuclear-related occupations or their family, which were not considered, might have influenced the associations between radiation risk perception and relocation. Therefore, there are prospects for future studies that will take these variables into account. Furthermore, since the number of nuclear industry-related workers and their families, and the economic benefits, are considered to be larger in municipalities where nuclear power stations are located, detailed analysis of associations between radiation risk perception and relocation by municipalities is promising for assessing the effects of the nuclear industry.

Despite such limitations, this study was the first to reveal the direction of the association between radiation risk perception and relocation based on five waves of longitudinal surveys.

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Ethics statement

Ethical approval for this study was granted by the Fukushima Medical University Ethics Committee (approval number: 1316 and 2148).

CRediT authorship contribution statement

Michio Murakami: Conceptualization, Formal analysis, Methodology, Visualization, Writing - original draft. **Yoshitake Takebayashi:** Formal analysis, Methodology, Visualization, Writing - review & editing. **Mayumi Harigane:** Writing - review & editing. **Rie Mizuki:** Writing - review & editing. **Yuriko Suzuki:** Writing - review & editing. **Tetsuya Ohira:** Writing - review & editing. **Masaharu Maeda:** Writing - review & editing. **Seiji Yasumura:** Writing - review & editing.

Declaration of competing interest

None.

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