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Fine particulate matter and depressive symptoms in children: A mediation model of physical activity and a moderation model of family poverty

Young Sun Joo [a], Jisun Kim [b], Jungae Lee [c], Ick-Joong Chung [d,*]

[a] Myongji University, Department of Social Welfare, 34 Geobukgol-ro, Seodaemoon-gu, Seoul, 03674, South Korea
[b] Korea Social Security Information Service, 173, Toegye-ro(Chungmuro 3-ga), Jung-Gu, Seoul, 04554, South Korea
[c] National Center for the Rights of the Child, G Tower, 71, Sambong-ro, Jongno-gu, Seoul, 03150, South Korea
[d] Ewha Womans University, Department of Social Welfare, 52, Ewhayeodae-gil, Seodaemun-gu, Seoul, 03760, South Korea

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ABSTRACT

Rationale: Exposure to fine particulate matter has adverse effects on mental health outcomes. However, no empirical study has yet been conducted on mechanisms of how and why exposure to fine particulate matter can affect mental health outcomes, especially focusing on children. In addition, children living in poverty may be more vulnerable to fine particulate matter.
Objective: This study aims to examine whether physical activity can explain the impact of ambient fine particulate matter on depressive symptoms among Korean children and whether family poverty moderates the associations between fine particulate matter, physical activity, and children's depressive symptoms.
Methods: Children and their primary caregiver data were drawn from the Children's Happiness Life Time Survey data collected by Child Fund Korea, and fine particulate matter data were derived from Air Korea, collected by the Korea Environment Corporation. Individual-level data were linked to a nationwide neighborhood-level data on air quality. Multilevel structural equation modeling was used to consider the hierarchical data structure. The analytical sample consisted of 4,161 children living in 79 neighborhoods.
Results: The findings suggest that living in neighborhoods with higher levels of fine particulate matter is associated with a decrease in physical activity, which in turn increases children's depressive symptoms. Physical activity fully mediates the association between fine particulate matter and children's depressive symptoms. However, family poverty does not have a significant moderating role for the associations between fine particulate matter, physical activity, and children's depressive symptoms.
Conclusions: The results of this study indicate the importance of physical activity in relation to fine particulate matter and children's depressive symptoms.

1. Introduction

Growing attention is being paid to the consequences of exposure to fine particulate matter on mental health outcomes, including the adverse impacts of depression and suicide attempts (Kim et al., 2016; Kioumourtzoglou et al., 2017; Lim et al., 2012). Fine particulate matter refers to a mixture of solid particles and liquid droplets formed as a result of chemical reactions between pollutants, including PM_{10}, particles with diameters 10 μm and smaller, and $PM_{2.5}$, particles with diameters 2.5 μm and smaller (United States Environmental Protection Agency, 2021). Exposure to fine particulate matter harms physical health and promotes cardiovascular, lung, and respiratory diseases, and it has adverse effects on mental health outcomes as well (Bakian et al., 2015; Kim et al., 2016; Lim et al., 2012). Previous studies have consistently found significant impacts of exposure to fine particulate matter on depressive symptoms (Buoli et al., 2018; Kim et al., 2016; Kioumourtzoglou et al., 2017; Lim et al., 2012; Zhao et al., 2020). However, few empirical studies have been conducted on the mechanisms through which exposure to fine particulate matter can affect mental health outcomes. Respiration of high levels of fine particulate matter may discourage people from physical activity (An & Xiang, 2015; Jung et al., 2019; Yu et al., 2017), which could be a possible mechanism for this effect.

In particular, few studies have focused on mental health outcomes

* Corresponding author.
E-mail addresses: ysjoo@mju.ac.kr (Y.S. Joo), praise5908@naver.com (J. Kim), drama7004@naver.com (J. Lee), ichung@ewha.ac.kr (I.-J. Chung).

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among children and adolescents or examined how their mental health outcomes could be negatively affected by exposure to fine particulate matter. Children tend to be restricted to passive responses and reactions to fine particulates, whereas adults can actively protect themselves against high levels of fine particulate matter. For example, decision not to attend school due to high levels of fine particulate matter may depend on the parents, not on the children themselves (Leliveld et al., 2018). Children are also more vulnerable to environmental hazards, such as fine particulates, because their bodies are growing, and pollutants can impair their healthy development (Kulkarni & Grigg, 2008). A study by Woo et al. (2019) focused on South Korean children in out-of-home placements and found that fine particulate matter had negative impacts on their mental health. A descriptive study by Sang Jung Lee (2019) that examined the children and parents' behaviors related to fine particulate matter found that about 31% of parents did not allow their children to do outdoor activities, and 42% canceled outdoor events, such as leisure activities and family-and-friends gatherings, due to high levels of fine particulate matter. Because the desire for active outdoor activity is especially high in childhood (Han & Kim, 2017), limited physical activity due to fine particulate matter may have a negative effect on both physical and mental health. Evidence has suggested that physical activity in children affects mental health in various ways, including outcomes of anxiety, depression, stress, and happiness (Biddle & Asare, 2011; Korczak et al., 2017; McPhie & Rawana, 2015; Strong et al., 2005; Yoo & Kim, 2014). When regular and active physical activity is properly performed in childhood, it is associated with improvements in future depressive symptoms, although the effect size was small (Korczak et al., 2017).

Moreover, environmental risks, such as that of fine particulate matter, can have greater adverse impacts on children in poverty due to the insufficient economic resources of their families. Recent evidence has suggested that higher-income families tend to lessen outdoor activities, wear masks, and use air purifiers to actively minimize the negative influence of fine particulate matter more than lower income families (Eom & Oh, 2019). Previous studies have consistently found that long-term and chronic exposure to poverty is associated with negative influence on children's mental health outcomes, such as anxiety and depression (Kim, 2010; Najman et al., 2010). This association can be partially explained as a result of negative parenting behaviors. Parents who are poor are more likely to abuse and/or neglect their children than those who are not (McLeigh et al., 2018), and the impact of such abusive behaviors on children's depression tends to be greater when the levels of family poverty are high (Cho et al., 2019). In addition, children's levels of physical activity differ between those in high- and low-income families. Children in low-income families are more likely to watch television or DVDs at home, and children in high-income families are more likely to engage in physical activity with their parents (Kang & Park, 2013; Tandon et al., 2012).

Although there may be other possible mediating mechanisms for how fine particulate matter can affect children's mental health, such as through parenting behaviors and physical health, this study focused on physical activity as a mediator because the South Korean government recommends that the public not go out and allows schools to close when the levels of fine particulate matter are high, which can limit children's physical activity. In addition, the impact of fine particulate matter on children's physical activity and depressive symptoms can be greater for children living in poverty due to the insufficient economic resources of their families. Therefore, this study examined whether reduced physical activity mediates the association between exposure to fine particulate matter and children's depressive symptoms and whether family poverty moderates the associations between fine particulates, physical activity, and children's depressive symptoms. Fig. 1 displays the analytic model of this study.

2. Methods

2.1. Data and sample

The data were derived from the Children's Happiness Life Time Survey, Air Korea data, and Statistics Korea data in 2017. Children's Happiness Life Time Survey data were collected by Child Fund Korea from a nationally representative sample of 4704 children in elementary, middle, and high school and their primary caregivers through sample distribution by age and neighborhood nationwide. Approximately 83% of the primary caregivers were the mother, 16% were the father, and 1% were the grandparents, siblings, or other type of caregiver. The children's survey items included the actual time of physical activity, study time, sleeping time, and times of various daily routines. Primary caregiver survey items included the actual time of work, education, caregiving practice, household chores, hobbies, and primary caregiver's socio-demographic characteristics.

Air Korea data were collected by the Korea Environment Corporation, which measures air quality data on an hourly basis from 398 monitoring sites located in 112 cities and counties throughout Korea. These data are often used by administrative governments for implementing environmental policy and by researchers for analyzing the

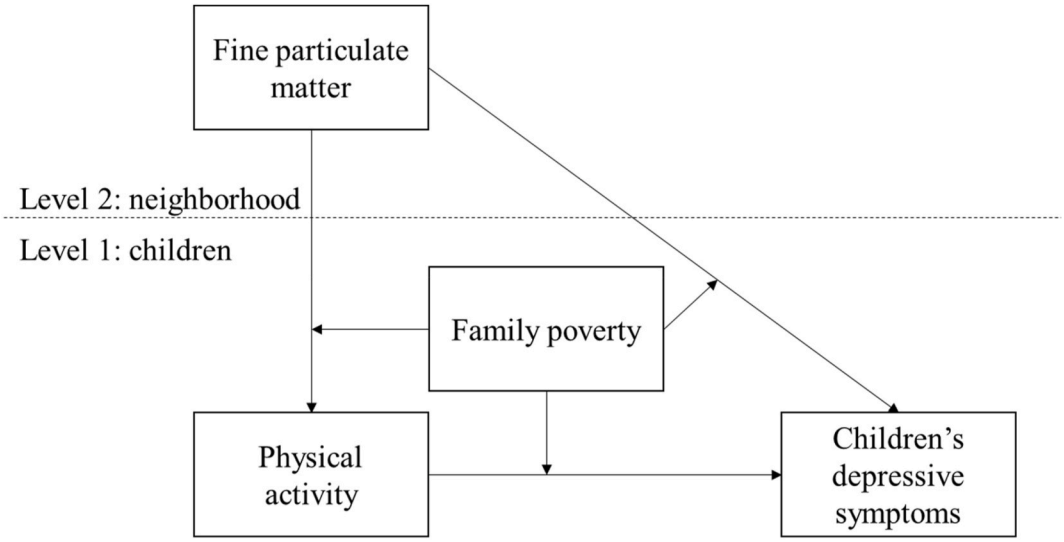

Fig. 1. Analytic model.

negative effects of fine particulate matter on health outcomes. This study merged the Children's Happiness Life Time Survey data and Air Korea data by neighborhood code. In addition, this study merged Statistic Korea data to take into account for neighborhood poverty rate. The analytical sample consisted of 4161 children living in 79 neighborhoods. Fig. 2 shows the spatial distribution of 79 neighborhoods, in South Korea as a whole and for Seoul, which is the biggest city in South Korea.

2.2. Measures

2.2.1. Children's depressive symptoms

Depressive symptoms were assessed using a subscale of the Symptom Checklist-90-Revised (SCL-90-R) questionnaire. The original depression scale developed by Derogatis (1977) consists of 13 self-reported items to evaluate depressive symptoms. This study used the Korean version of the SCL-90-R, modified for Korean children (Kim et al., 1984), which is widely used in the Korean Children and Youth Panel Survey, consisting of 10 items, all of which are related to depressive symptoms. Sample items include: "I don't have much energy," and "I think I am unhappy or feel sad and depressed," with responses on a 4-point Likert scale from 1 = not true to 4 = very true. An average score was created as a composite score for depressive symptoms, with higher scores indicating greater depressive symptoms. In our sample, the average score was 1.91 (SD = 0.62) (see Table 1 and Fig. 3 for descriptive results).

2.2.2. Fine particulate matter

Exposure to fine particulate matter was measured at the neighborhood level by averaging particulate levels with an aerodynamic diameter ≤2.5 μm, $PM_{2.5}$. If one neighborhood had more than one air quality monitoring site, then the average level of fine particulate matter was determined by taking a total of the values and dividing it by the number of sites. The average level of fine particulate matter was 129.98 μg/m^3 (SD = 28.03).

2.2.3. Physical activity

Physical activity was assessed at the children's level with actual activity and leisure time measured in minutes per week. The Children's Happiness Life Time Survey used a retrospective survey method to measure physical activity by asking children to record how many minutes they committed to activity and leisure each week, which could also include indoor forms of physical activity. Higher scores indicated greater physical activity. The average minutes for physical activity in our analytic sample was 29.23 min (SD = 45.38). According to Tremblay et al. (2016), who analyzed the level of physical activity of children in 38 countries, the level of physical activity among South Korean children is among the lowest in the world. The WHO (2020) recommends that children engage in active exercise for at least 60 min per a day, but the

Table 1
Summary statistics for all variables.

Variables	M/%	SD	Min	Max	N
Community Level					
Independent Variable					
Fine particulate matter (μg/m^3)	129.98	28.03	78	218	79
Standardized fine particulate matter	0	1	−1.84	3.02	79
Individual Level					
Dependent Variable					
Child's depressive symptoms	1.91	0.62	1	4	4704
Standardized depressive symptoms	0	1	−1.50	3.33	4704
Mediator					
Physical activity (minutes)	29.23	45.38	0	600	4607
Standardized physical activity	0	1	−0.64	12.68	4607
Moderator					
Family poverty	14%				4546
Covariates					
Children					
Girl	53%				4704
Age					4704
Elementary school child	27%				
Middle school child	32%				
High school child	41%				
Self-reported grades at school	5.99	2.15	1	10	4582
Primary caregiver					
Types of primary caregiver					4704
Mother	83%				
Father	16%				
Others	1%				
Age	45.49	4.66	23	79	4416
Married	87%				4704
Number of family members	4.14	0.92	2	15	4703
Graduated college	58%				4646
Homeowner	67%				4677
Urbanicity					4704
Live in urban area	48%				
Live in suburban area	37%				
Live in rural area	15%				
Neighborhood poverty rate	3.66	0.68	2.10	4.65	79

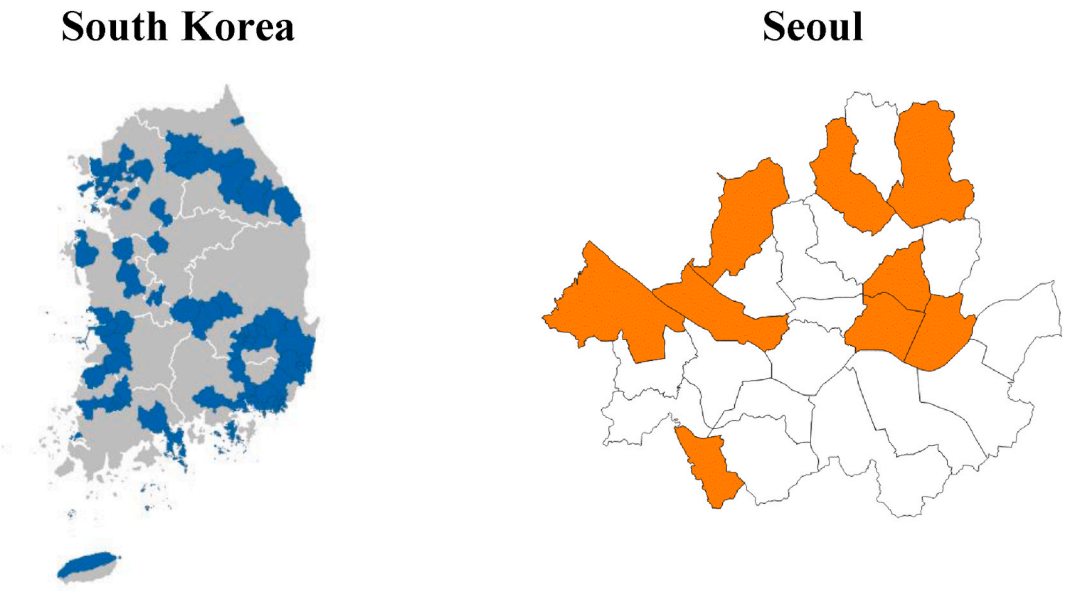

Fig. 2. Spatial distribution of the sample neighborhood.

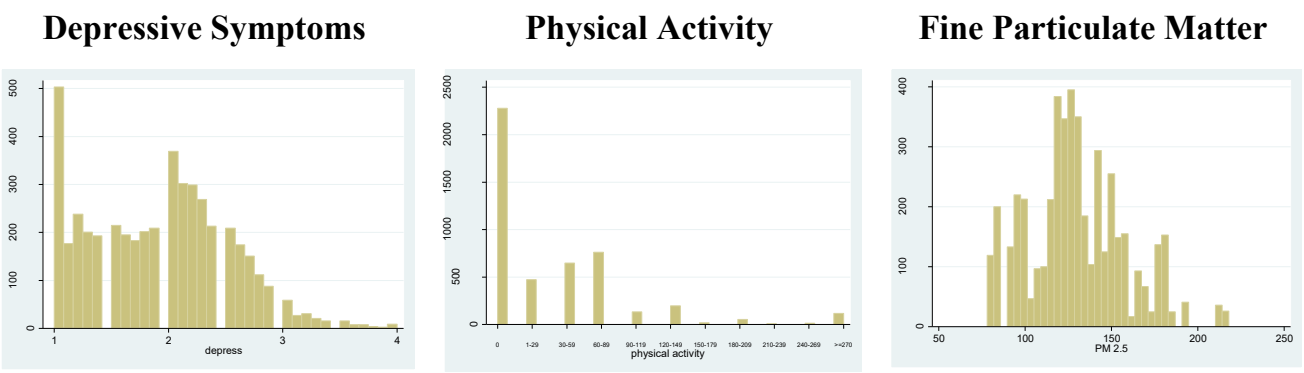

Fig. 3. Distribution of depressive symptoms, physical activity, and fine particulate matter.

average level of physical activity among South Korean children is well below the average (Lee & Kang, 2016). Due to low levels of time spent in physical activity, this study rescaled physical activity to 30 min in the analyses.

2.2.4. Family poverty

Family poverty was assessed as a dichotomous measure, using the primary caregiver survey questionnaire. This survey asked whether the given family was a recipient of the Basic Livelihood Security Program, a public assistance program in South Korea for low-income households. If the primary caregiver's household received a benefit from the Basic Livelihood Security Program, they were coded as 1 (living in poverty). In our sample, approximately 14% of respondents were living in poverty.

2.2.5. Covariates

To analyze the associations among fine particulate matter, physical activity, family poverty, and depressive symptoms, this study controlled for children's demographic characteristics (gender, age, and grade point average), family background characteristics (primary caregiver type, age, marital status, educational attainment, and number of family member, homeownership), and regional characteristics, including living in a city, a suburb, or a rural area, as well as the neighborhood poverty rate, all of which are associated with children's physical activity and depressive symptoms (Goodwin & Gotlib, 2004; Huang, 2015; Lee, 2020; Najman et al., 2010).

2.3. Analytic strategies

This study used Stata 14.0. for all analyses. First, we tested intra-class correlations (ICC) from the unconditional mean model prior to conducting multilevel modeling. The ICC values used were between 0 and 1, where higher values indicated greater similarity between neighborhoods (Raudenbush & Bryk, 2002). Our ICC values were, however, all small in magnitude (Table 2). Of the total variance, the neighborhood level accounted for 2.6% of physical activity and 6.4% of children's depressive symptoms, showing little between-neighborhood variation in our data. The difference between 2.6% and 6.4% are from the lower standard deviation (SD) for children level rather than from the difference in SD constants for neighborhood effect. However, because random effects at the neighborhood level were statistically significant, the use of a multilevel modeling approach was justified (Raudenbush & Bryk, 2002). In addition, some scholars have argued against relying on ICC values, favoring instead a hierarchical data structure for use in multilevel modeling (Nezlek, 2008; Robson & Pevalin, 2015). A lack of between-group variance does not imply that the associations between measures are the same across all groups (Nezlek, 2008; Robson & Pevalin, 2015), and our data clearly have a nested structure (children nested in neighborhoods), so the multilevel modeling approach was used for our mediation analyses.

Second, this study used path analysis with generalized structural equation model (GSEM) to examine whether reduced physical activity mediates the association between fine particulate exposure and children's depressive symptoms. Because physical activity can be both a predictor and an outcome variable, this study used path analysis, as a subset of GSEM, to consider all associations simultaneously in a multilevel data structure. In particular, GSEM extends the standard SEM approach because GSEM accommodates multilevel data structure, while SEM can only be used for single-level data (Huber, 2013). Because fine particulate matter was measured at the neighborhood level (level 2), and physical activity and depressive symptoms were measured at the individual level (level 1), this study used the 2-1-1 multilevel mediation model as described below.

$$\text{Level 1}: \ M_{ij} = \beta_{M0j} + e_{ijM}$$

$$\text{Level 2}: \ \beta_{M0j} = \gamma_{00M} + aX_j + u_{0jM},$$

which represents the effect of the level 2 X_j (fine particulate matter) on the level 1 M_{ij} (physical activity); i refers to individual children, j refers to the neighborhood, γ_{00} is the intercept for M_{ij}, a is the effect X_j on M_{ij}, and e_{ij} and u_{0j} are the level 1 and level 2 residuals, respectively. The multilevel mediation model regarding the dependent variable depressive symptoms is given in the following equations.

$$\text{Level 1}: \ Y_{ij} = \beta_{Y0j} + \beta_{Y1j}M_{ij} + e_{ijY}$$

$$\text{Level 2}: \ \beta_{Y0j} = \gamma_{00Y} + cX_j + u_{0jY}$$

$$\text{Level 2}: \ \beta_{Y1j} = \gamma_{10} + u_{ij}.$$

Table 2
Unconditional mean model.

Outcomes	Fixed Effect		Random Effect				ICC
	Intercept		Neighborhood-level		Children-level		
	Coef.	SE	SD	Variance Component	SD	Variance Component	
Physical activity	0.006	0.022	0.161	0.026*	0.986	0.977*	0.026
Depressive symptoms	−0.004	0.030	0.255	0.065*	0.972	0.944*	0.064

The coefficient b indicates the effect of M_{ij} on Y_{ij}at level 2 only, while the coefficient γ_{10} indicates the effect of M_{ij} on Y_{ij}at level 1 only. In addition, u_{ij} is the residual of level 2 slope, and β_{Y1j} is a random slope. Next, this study decomposed the direct, indirect, and total effects using the delta method, which expands a function of a random variable about its mean and takes the variance (Preacher & Hayes, 2008). We relied on the size and significance of the coefficient estimates to examine the model fit because in Stata, GSEM does not allow the derivation of fit statistics, including the root mean square error of approximation or the comparative fit index (StataPress, 2019; Wright et al., 2018), and all of the variables used in our study were observed variables.

Third, this study examined the moderating effects of family poverty on the association between fine particulate matter, physical activity, and children's depressive symptoms, taking the nested structure of the data into account. The interaction terms between the fine particulate matter and family poverty, and between physical activity and family poverty were included in our analytic models.

The amount of missing data ranged from 0% to 6%. We used Little's MCAR test (Li, 2013) to test whether missing values were missing at random. The test results showed that the missing data were not missing completely at random at a significance level of 0.05 ($\chi^2 = 68.5928$, $p < .001$). The missing cases were more likely to live with an unmarried mother, with a mother without a college degree, or with a primary caregiver who was not the mother. To retain as many observations as possible and reduce missing data bias, we used the full information maximum likelihood estimation (Myrtveit et al., 2001; Newman, 2003).

3. Results

Table 3 and Fig. 4 show the mediation effects of physical activity from our GSEM models. As hypothesized, living in neighborhoods with higher levels of fine particulate matter was associated with decreased physical activity, which in turn was associated with a decrease in children's depressive symptoms. A 10 μg/m^3 increase in fine particulate matter was associated with a statistically significant reduction in physical activity by 0.05. In addition, 30 min increase in physical activity was associated with decrease in depressive symptoms by 0.01 point, which was 0.33% reduction in depressive symptoms respectively.

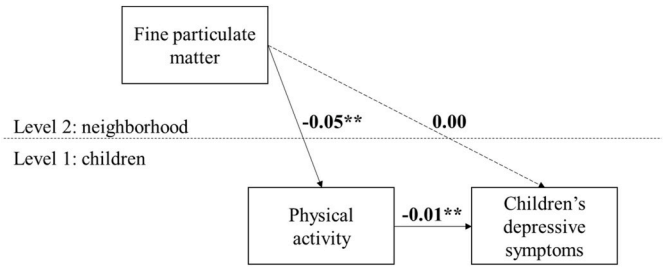

Fig. 4. Direct, indirect, and total effects (N = 4161).

The decomposition of the direct, indirect, and total effects of fine particulate matter on children's depressive symptoms suggests that physical activity fully mediated the association between fine particulate matter and children's depressive symptoms (indirect effect = 0.001, $p < .05$, see Table 4). However, fine particulate matter was not directly associated with children's depressive symptoms.

We found that girls, older age, and higher academic achievement led to lower likelihood of engaging in physical activity. In addition, children

Table 4
Decomposition of direct, indirect, and total effects (N = 4161).

Model path	Direct		Indirect			Total	
	β	[95% CI]	β		[95% CI]	β	[95% CI]
Fine particulate → Physical activity → Depressive symptoms	0.003	[-0.01, 0.01]	0.001	*	[0.00, 0.00]	0.004	[-0.01, 0.01]

*p < .05.

Table 3
Mediation effect of physical activity (N = 4161).

Predictors	Direct effect							
	Physical activity				Depressive symptoms			
	Unstandardized			Standardized	Unstandardized			Standardized
	b		[95% CI]	β	b		[95% CI]	β
Level 2								
Fine particulate matter (10 μg/m^3)	−0.05	**	[-0.09, −0.02]	−0.07	0.00		[-0.01, 0.01]	0.01
Level 1								
Physical activity (30 min)	-			-	−0.01	**	[-0.02, −0.01]	−0.05
Covariates								
Girl	−0.45	***	[-0.58, −0.31]	−0.20	0.21	***	[0.18, 0.25]	0.34
(Elementary school child = 0)								
Middle school child	−0.41	***	[-0.61, −0.22]	−0.19	0.18	***	[0.13, 0.23]	0.30
High school child	−0.74	***	[-0.94, −0.54]	−0.33	0.24	***	[0.18, 0.29]	0.38
Self-reported grades at school	−0.04	*	[-0.07, −0.01]	−0.04	−0.06	***	[-0.07, −0.05]	−0.21
(Mother is a primary caregiver = 0)								
Father is a primary caregiver	0.04		[-0.14, 0.23]	0.02	−0.02		[-0.07, 0.03]	−0.03
Other person is a primary caregiver	−0.82		[-0.12, 1.77]	0.37	0.00		[-0.25, 0.26]	0.00
Primary caregiver's age	0.01		[-0.01, 0.03]	0.02	0.01	**	[0.00, 0.01]	0.05
Primary caregiver is married	−0.08		[-0.29, 0.13]	−0.04	−0.03		[-0.09, 0.02]	−0.06
Number of family member	0.01		[-0.06, 0.09]	0.01	−0.01		[-0.03, 0.01]	−0.01
Primary caregiver has a college degree	−0.10		[-0.24, 0.03]	−0.05	0.02		[-0.02, 0.05]	0.02
Primary caregiver is a homeowner	−0.10		[-0.25, 0.04]	−0.05	−0.03		[-0.06, 0.01]	−0.04
(Live in urban area = 0)								
Live in suburban area	0.25	*	[0.04, 0.46]	0.11	0.04		[-0.01, 0.09]	0.06
Live in rural area	0.04		[-0.21, 0.28]	0.02	0.05		[-0.01, 0.11]	0.08
Neighborhood poverty rate	−0.01		[-0.23, 0.03]	−0.03	−0.03		[-0.06, 0.00]	−0.03
ICC	0.017				0.015			

*p < .05; **p < .01, ***p < .001.

Table 5
Moderation effect of family poverty.

Predictors	Physical activity				Depressive symptoms			
	Unstandardized			Standardized	Unstandardized			Standardized
	b		[95% CI]	β	b		[95% CI]	β
Level 2								
Fine particulate matter	−0.05	**	[-0.08, −0.01]	−0.06	0.00		[-0.01, 0.01]	0.02
Level 1								
Poverty	0.36		[-0.52, 1.24]	0.01	0.09		[-0.15, 0.33]	0.04
Fine particulate × Family poverty	−0.03		[-0.09, 0.04]	−0.03	−0.00		[-0.02, 0.01]	−0.02
Physical activity	-			-	−0.02	**	[-0.02, −0.01]	−0.05
Physical activity × Family poverty	-			-	−0.01		[-0.02, 0.02]	−0.00
Covariates								
Girl (Elementary school child = 0)	−0.46	***	[-0.60, −0.33]	−0.21	0.21	***	[0.17, 0.24]	0.33
Middle school child	−0.39	***	[-0.58, −0.21]	−0.18	0.19	***	[0.14, 0.24]	0.31
High school child	−0.71	***	[-0.90, −0.51]	−0.32	0.24	***	[0.19, 0.29]	0.39
Self-reported grades at school	−0.04	*	[-0.07, −0.00]	−0.03	−0.06	***	[-0.07, −0.05]	−0.21
(Mother is a primary caregiver = 0)								
Father is a primary caregiver	0.07		[-0.12, 0.25]	0.03	−0.01		[-0.06, 0.04]	−0.02
Other person is a primary caregiver	0.74		[-0.22, 1.70]	0.33	−0.03		[-0.29, 0.23]	−0.05
Primary caregiver's age	0.01		[-0.01, 0.03]	0.02	0.01	*	[0.00, 0.01]	0.04
Primary caregiver is married	−0.08		[-0.30, 0.14]	−0.04	−0.01		[-0.07, 0.05]	−0.02
Number of family member	0.01		[-0.07, 0.09]	0.00	−0.01		[-0.03, 0.01]	−0.02
Primary caregiver has a college degree	−0.08		[-0.22, 0.06]	−0.04	0.02		[-0.02, 0.05]	0.03
Primary caregiver is a homeowner	−0.10		[-0.24, 0.05]	−0.04	−0.02		[-0.06, 0.02]	−0.04
(Live in urban area = 0)								
Live in suburban area	0.20		[-0.00, 0.40]	0.09	0.04		[-0.02, 0.09]	0.06
Live in rural area	0.04		[-0.20, 0.27]	0.02	0.05		[-0.01, 0.12]	0.08
Neighborhood poverty rate	−0.10		[-0.23, 0.03]	−0.03	−0.02		[-0.06, 0.01]	−0.02
ICC			0.015				0.018	

*p < .05; **p < .01, ***p < .001.

who live in suburban areas were more likely to engage in physical activity than children living in urban areas. However, the type of primary caregiver, primary caregiver's age, the primary caregiver's marital status and educational attainment, the number of family members in the household, homeownership, and neighborhood poverty rate were not associated with physical activity.

Th associations between covariates and children's depressive symptoms showed that girls and children in middle school and high school were more likely to have depressive symptoms than boys and elementary school students. Children with higher grades were less likely to have depressive symptoms than children with lower grades. The primary caregiver's age was positively associated with depressive symptoms. However, the type of primary caregiver, the primary caregivers' marital status, the number of family members, the primary caregiver's educational attainment, homeownership status, the urbanization level, and the poverty rate of the neighborhoods were not associated with children's depressive symptoms.

This study also examined the moderating role that family poverty plays in the association between fine particulate matter, physical activity, and children's depressive symptoms. Unexpectedly, family poverty did not have a significant moderating effect on any pathway between fine particulates, physical activity, and children's depressive symptoms. As shown in Table 5, the interaction terms between fine particulate matter and poverty and between physical activity and poverty were not statistically significant. In terms of the study covariates, children's gender, age, and academic achievement were associated with physical activity and children's depressive symptoms, and primary caregiver's age was associated with children's depressive symptoms.

4. Discussion

Environmental pollution is being taken more seriously worldwide, and it has drawn growing attention and concern in relation to the risk to human health. To the best of our knowledge, this study is the first to empirically analyze the effects of fine particulate matter on children's mental health risk and on depressive symptoms in particular, through the mediating mechanism of physical activity and the moderating role of family poverty. Although fine particulate matter can have a severe impact on children's health (Kulkarni & Grigg, 2008), children's responses and reactions to exposure to fine particulate matter may be passive, as they must rely on their parents' decision-making. In addition, children's desire for active movement may be strong, but the high levels of fine particulate matter may limit their physical activity, which may indirectly increase their depressive symptoms. Moreover, the impact of fine particulate matter on children's physical activity and depressive symptoms can be greater for children living in poverty due to their insufficient household resources. Therefore, this study examined the mediating effects of physical activity and the moderating effects of family poverty on the associations between exposure to fine particulate matter and depressive symptoms among children in South Korea.

Our first hypothesis investigated whether reduced physical activity can explain the association between fine particulate exposure and children's depressive symptoms. Our results suggest that reduced physical activity fully mediated the association between fine particulate matter and children's depressive symptoms. The significant association between fine particulate matter and physical activity that we established is similar to the findings of previous studies (An & Xiang, 2015; Bae & Hong, 2018; Baek & Park, 2014; Kim et al., 2020; Song et al., 2009; Yu et al., 2017). Warning people not to go out when levels of fine

particulate matter are high may affect decisions regarding physical activity (Wen et al., 2009), which in turn may have an adverse impact on children's depressive symptoms. There may be other physical mechanisms at play, such as decreased lung function and increased cardiovascular and respiratory symptoms, which may have adverse impacts on actual performance (Cutrufello et al., 2011; Rundell & Caviston, 2008). Our results, which indicate a significant mediating effect through physical activity, however, suggest several important practice and policy implications for protecting children's mental health outcomes, even in the presence of severe fine particulates. First, children and their parents may need to reconsider the importance of physical activity even in the presence of fine particulate matter. The government alerts the public not to go out or at least to wear a mask when out in under high levels of fine particulates. However, these recommendations may not be the best solution with respect to mental health risks among children. Encouraging indoor physical activity, even in the presence of severe fine particulates, may be more beneficial for both physical and mental health, including reducing depressive symptoms. Therefore, the government may need to educate people on and promote the importance of physical activity for children and their parents, even in the presence of fine particulates. For example, including a description of the importance of physical activity through media, news, and social network services may be an effective strategy for informing people and promoting the importance of physical activity. In addition, contents related to fine particulate matter and physical activity may need to be included in parenting programs and counseling services to inform parents regarding the importance of physical activity for promoting positive mental health outcomes for children. This active effort may encourage parents to ensure that their children have the chance to have physical activity time regardless of the level of fine particulate matter, which may ultimately promote mental health outcomes.

Second, the government needs to expand the indoor spaces available for children to participate in physical activity. In South Korea, various indoor facilities are available for young children, including kids cafes and indoor playgrounds; however, fewer indoor facilities are available to older children and adolescents. Because all children and adolescents are equally in need of active exercise for their healthy development, both physically and mentally, the government should target neighborhoods with insufficient indoor facilities for children and expand them. Children and adolescents who use these facilities could also benefit from physical activity programs and emotional support programs to prevent depressive symptoms.

It is easy to understand and recognize the negative effects of fine particulate matter on human physical health, but it is difficult to know (or experience) their adverse impacts on mental health outcomes. In particular, it is important to examine whether exposure to fine particulate matter can affect children's mental health risk because their mental health outcomes can affect children through adulthood and because children are more vulnerable to air pollutants. This study found that exposure to fine particulate matter is associated with depressive symptoms in children through reduced physical activity, and the importance of this should be emphasized and publicized.

Our second study hypothesis investigated the moderating role of family poverty on the association between fine particulate matter, physical activity, and children's depressive symptoms. Unexpectedly, we found no significant moderating role for family poverty on the associations between fine particulate matter, physical activity, and children's depressive symptoms. This unexpected finding may be due to the low level of variation found in the amount of physical activity according to family poverty. WHO (2016) examined the cross-country comparisons on the amount of physical activity and found that 94.2% of children in South Korea lacked physical activity, the highest rate of inactivity among all 146 countries surveyed. This result may be due to the greater emphasis on study time in South Korea. According to the OECD Program for International Student Assessment (2019), South Korean children spend approximately 49.43 h on study per week, while children in OECD countries, on average, spent 33.92 h. In addition, Soo Jin Lee (2019) found that Korean children in non-poor families tended to spend the most time on studying, while children in poor families tended to spend the most time watching media. As a result, regardless of their poverty status, Korean children in general tended to engage in static activities rather than in physical activities.

This study is not without its limitations. First, our study is a cross-sectional study, which cannot infer causality. To infer causality, exposure to fine particulate matter should occur before physical activity, and a lack of physical activity should occur before depressive symptoms, however, the cross-sectional design of this study is limited in this regard, which may also limit the ability to establish a mediating effect. In addition, because long-term exposure to fine particulate matter may have a severe impact on human behaviors and pose mental health risks, future research should extend our work by using longitudinal survey data. Second, examining the effects of fine particulate matter on physical activity and mental health outcome raises the questions of the omitted variable bias and endogeneity. Higher physical activity can affect better mental health and vice versa. Additionally, unmeasured family and neighborhood characteristics likely influence physical activity and mental health outcomes. Third, the measurement used in this study to examine children's depressive symptoms is not a diagnostic measure and does not include a cutoff point to distinguish severely from moderately depressed children. For severely depressed children, targeting depressive symptoms directly, such as by providing medication or counseling, may be more effective than encouraging physical activity. Future study may need to collect children's diagnostic data on depression to examine the different patterns regarding the mechanisms of the impact of fine particulate matter on children's mental health outcomes. Fourth, the measure of physical activity does not distinguish between indoor and outdoor physical activity, thus future study may need to collect more in-depth data to establish the precise amount of physical activity that could be affected by the exposure to fine particulate matter. Fifth, because the sample neighborhoods were not equally distributed across South Korea, thus our findings may not be generalizable to South Korean children in general. Lastly, there may be other possible mediating and moderating factors that link the fine particulate matter and children's mental health outcomes, such as through parenting behaviors and physical health. Thus, it is necessary to continuously explore these black box associations and recommend proactive interventions against fine particulate matter for children.

Ethical Statement

Hereby, I/Ick-Joong Chung/consciously assure that for the manuscript/Fine Particulate Matter and Depressive Symptoms in Children: A Mediation Model of Physical Activity and a Moderation Model of Family Poverty/the following is fulfilled:

1) This material is the authors' own original work, which has not been previously published elsewhere.
2) The paper is not currently being considered for publication elsewhere.

3) The paper reflects the authors' own research and analysis in a truthful and complete manner.
4) The paper properly credits the meaningful contributions of co-authors and co-researchers.
5) The results are appropriately placed in the context of prior and existing research.
6) All sources used are properly disclosed. Literally copying of text must be indicated as such by using quotation marks and giving proper reference.
7) All authors have been personally and actively involved in substantial work leading to the paper, and will take public responsibility for its content.

I agree with the above statements and declare that this submission follows the policies as outlined in the Guide for Authors and in the Ethical Statement.

CRediT authorship contribution statement

Young Sun Joo: Methodology, Software, Formal analysis, Writing-Original Draft.

Jisun Kim: Writing-Original Draft, Project administration.

Jungae Lee: Writing-Original Draft, Visualization.

Ick-Joong Chung: Conceptualization, Resources, Supervision, Writing-Original Draft.

Declaration of competing interest

The authors of this paper have no competing interest, financial or otherwise, in any of the programs or interventions included in this study.

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