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Impacts of Streetscape Features on Individual Social Capital: Applying Korea's Neighborhood Data to Street View Images to Improve Lives of the Socially Vulnerable

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Abstract: Neighborhood social vulnerability is a dimension of vulnerability that influences society's response to external factors, encompassing various social factors tied to socioeconomic and demographic attributes at the neighborhood level. While previous studies have explored the associations between vulnerable neighborhoods and stressors like environmental hazards, understanding of their impact on residents' social capital remains limited. Moreover, the role of built environments in mitigating these effects is uncertain. This study investigates the impact of neighborhood social vulnerability, alongside streetscape features, on individual social capital in Seoul, South Korea. Using a stratified random sampling method, we surveyed 1000 Seoul residents, assessing their social capital and demographics. In particular, six questionnaires based on a four-point Likert scale were used to measure the individual level of social capital: two questions for social networks, three questions for social participation, and one question for sense of community. Additionally, we employed a deep learning-based model to analyze Google Street View images for detailed streetscape features. Our analysis, utilizing multiple and ordinal logistic regression models, reveals that walkable environments and neighborhood prosperity, indicated by factors like income, education, and street greenery, are linked to higher social capital. Moreover, less urbanized areas with lower land prices and greater openness to the sky also show positive associations. These findings underscore the potential of improving streetscape features to mitigate the negative impacts of neighborhood vulnerability, particularly in neighborhoods where low-income and less-educated residents are concentrated, offering insights for urban planners and community leaders.

Keywords: neighborhood social vulnerability; streetscape features; social capital; deep learning-based computer vision

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1. Introduction

Social capital is a vital resource that reflects the communal contexts of various communities, encompassing residents' willingness to establish networks and engage in social activities [1,2]. This resource, which plays a significant role in community health and safety, is viewed as a key factor in enhancing individual quality of life and fostering community sustainability. For instance, residents' active participation in community enhancement initiatives can bolster resident networks and foster social and recreational activities, thereby improving both physical and mental well-being [3,4]. Furthermore, an enhanced social network can cultivate residents' sense of community and encourage their engagement and cooperation in social endeavors for mutual benefit in neighborhoods [5,6]. As a result, planners and policymakers in both developed and developing nations, striving to create socially sustainable communities, prioritize the cultivation of social capital for its multifaceted advantages.

The neighborhood social vulnerability index is a quantitative measure that estimates the degrees of social vulnerability in neighborhoods [7]. In particular, the index has been widely employed to identify contextual social environments that represent the potential for vulnerability in neighborhoods [8]. Contextual social factors are often related to neighborhoods' socioeconomic and demographic characteristics, particularly in terms of income, gender, education, employment, deteriorated housing, and population characteristics within neighborhoods. Because of contextual clarity and data availability, the concept of neighborhood social vulnerability has substantially been used in disaster research to examine the effects of environmental hazards on socially vulnerable neighborhoods [9–11]. However, it is less certain that neighborhood social vulnerability affects residents' social capital.

Social and built environment attributes in neighborhoods serve as a crucial factor in either fortifying or undermining social capital. Given the link between diverse social frameworks and built environments, and residents' access to services and amenities [4,6,12], various opportunities to build social capital can vary based on neighborhood characteristics. Individuals residing in socio-environmentally disadvantaged neighborhoods, for instance, may encounter limited access to diverse socioeconomic opportunities, constraining their ability to expand social connections. Conversely, neighborhoods with socio-environmental advantages can facilitate access to a wide array of services and amenities, fostering the development of social capital [13]. In this vein, previous studies have focused on the relationships between the levels of neighborhood social vulnerability and individual social capital [14,15]. Additionally, due to the importance of environmental features, some studies have accounted for built environment attributes when identifying the levels of social vulnerability in neighborhoods [16–19].

Along with social environments in neighborhoods, the quality of built environments may affect individual social capital. For instance, walkable environments encourage residents to walk and engage in physical activities, increasing face-to-face interactions among residents and thereby enhancing social capital [20,21]. In particular, given that most face-to-face interactions supporting social capital formation occur on streets [6,22], the quality of streetscapes plays a crucial role in influencing social capital. It is essential to simultaneously consider the social environments of neighborhoods (i.e., neighborhood social vulnerability) and streetscape features to identify the impacts of social vulnerability features in neighborhoods on individual social capital. Despite the significance of streetscape environments in neighborhoods, prior studies have relied on field audits and surveys to identify the quality of built environments and their relations to individual social capital. This study fills this gap by employing deep learning-based models to identify detailed streetscape features in neighborhoods.

This study addresses the following research question: Do streetscape features accounting for neighborhood social vulnerability affect residents' social capital? We hypothesize that higher quality streetscape features encourage individual social capital after taking into account social environments. Additionally, this study hypothesizes that the effects of these attributes may vary across different domains of social capital (i.e., structural and cognitive social capital). To test these hypotheses, we examine the relationship between individual social capital and neighborhood social vulnerability, including streetscape features, in Seoul, South Korea.

We empirically measured the quality of streetscape features through Google Street View (GSV) panoramic images and deep learning-based semantic segmentation techniques, which are advanced computer vision tasks. By comprehensively considering the social contexts and streetscape features of the neighborhoods where survey respondents reside, this study contributes to extending the interrelationships among various environmental attributes and examining the effects of neighborhood environments, in terms of vulnerability, on social capital. Based on an online survey of 1000 adults residing in Seoul aiming to identify the levels of individual social capital, this study employs multiple regression and ordinal logistic regression models to examine the effects of neighborhood environmental

vulnerability on individual social capital. This study provides empirical insights into enhancing the understanding of neighborhood social vulnerability through the application of deep learning technologies. These insights are valuable for planners, researchers, community leaders, and policymakers in both developed and developing countries who aim to enhance residents' social capital in neighborhoods. Furthermore, the findings serve as a reference for understanding detailed environmental characteristics to be considered in developing tailored guidelines to improve social capital in various domains.

2. Literature Review

2.1. Multidimensional Domains of Social Capital

Social capital is a combination of actual and potential resources that are expressed through the interactions between society components: individuals, families, and residents [1,2,22]. Such social interactions facilitate the effective exchange of information and resources and encourage residents to extend their social networks and participate in community activities [23]. In addition, as improved social activities promote comfort and attachment to a community, they make a positive contribution in promoting social sustainability in the neighborhood [6]. Considering such conditions, previous studies have examined the relationship between the provision of community spaces and individual social capital. However, their findings are somewhat mixed. Regarding service facilities, several studies have reported that community facilities and open spaces, such as parks and community centers, can enhance residents' sense of community and social trust [6,24]. Nonetheless, case studies in Norfork, Virginia, and St. Louis, Missouri, U.S., indicated that the provision of community facilities supporting social and leisure activities may not have significant relationships with social capital [25,26]. Such inconsistent correlations of social capital may be related to a limited understanding of the multifaceted and complex nature of social capital and imply that the quality of the overall neighborhood environment (e.g., streetscapes and built environments) may be important in creating social capital beyond the provision of specific facilities.

Despite various approaches to social capital, its multidimensional feature can be explained by typological and hierarchical approaches. In terms of a typological approach, social capital can be classified into two categories: "structural social capital", which complements social participation, and "cognitive social capital", associated with individual values and attitudes [6,22,27]. Structural social capital appears through participation in individual and social behaviors with mutual benefits, and it is associated with better access to and availability of socioeconomic opportunities, such as jobs, education, and safety [2,22,24,27]. Cognitive social capital appears as individual perceptions, such as social networks, trust, and a sense of community, which motivate mutually cooperative social behavior based on shared individual and community values [6,22]. The structural and cognitive patterns of social capital are interconnected and reinforced; however, such an interconnected feature can bring mixed results when measuring social capital by focusing on a single aspect [6,23].

In terms of a hierarchical approach, the measurement of social capital should simultaneously consider individual and collective attributes. Individual-level social capital is associated with an individual's potential to build and facilitate mutually cooperative social connections [2,22]. Previous studies have emphasized the active role of individuals regarding individual-level social capital while assuming that access to resources and information depends on their availability for maintaining connections among individuals [22,28]. Collective-level social capital is defined as community-, neighborhood-, and region-level goods, and it is considered a collection of resources that accelerates individual cooperation and collective behavior [29,30]. In particular, surrounding environments are assumed to facilitate social activities for mutual benefit and the spread of a sense of community. From a socioecological perspective, such concepts provide important insights into the connection between social capital and the environmental contexts of neighborhoods. In this vein, this study considers the multidimensional area of social capital, particularly

focusing on both structural and cognitive social capital, to examine relationships between the socio-environmental attributes of a neighborhood and a resident's social capital.

2.2. Considering Environmental Contexts in Social Vulnerability

Vulnerability, defined as the erosion of resilience in the face of social and environmental risks, has been a key concept in understanding how different social and environmental contexts affect health and quality of life. Previous research has demonstrated that vulnerability can manifest in the internalization of social and environmental disadvantages, leading to adverse effects on residents' health, resilience, and quality of life [9,12,16]. For instance, socially vulnerable groups such as low-income households, single-parent families, and individuals with disabilities may experience ongoing exposure to risks in their disadvantaged neighborhoods due to limited opportunities for building social capital and moving residences [8,9,20], resulting in further declines in health and well-being. It is crucial to identify and address areas of social vulnerability to develop effective policies aimed at enhancing the health and quality of life for community members.

Qualitative research on social capital emphasizes that key parameters of social vulnerability, such as education levels, income levels, and unemployment rates in a region, are linked to social capital formation [5,14,15]. Additionally, housing stability is a crucial social context within neighborhoods that affects social capital. It can affect the stable expansion of social networks and foster a stronger sense of belonging [5,31]. In neighborhoods with a high proportion of renter households, residents may be less motivated to invest in their communities, leading to reduced participation in social activities and a diminished sense of belonging.

The socioeconomic characteristics of a neighborhood are an important vulnerability parameter associated with social capital. Previous studies have explored the link between vulnerability and social capital in terms of various socioeconomic factors but have produced inconsistent results. Some research has indicated that neighborhoods with a high concentration of socially vulnerable households (such as single-parent households, low-income households, and older adult households) may see a decrease in social capital [4,32]. However, other studies have suggested that individuals in low-income neighborhoods benefit from the ability to make decisions that impact their communities through collective social capital, with their social networks compensating for their lack of material and human resources [4,33]. These contrasting findings highlight the importance of taking into account the environmental characteristics of a community in order to fully comprehend the relationships between resident's social capital and neighborhood social vulnerability. The environmental contexts are closely tied to access to and availability of various neighborhood opportunities, which play a significant role in shaping social capital formation [8,34].

Existing social vulnerability frameworks provide empirical evidence on individual health and community resilience in relation to various socioeconomic and demographic factors, either individually or in combination. Along with socioeconomic and demographic factors to identify neighborhood social vulnerability, recent studies have shifted their focus towards streetscapes, which better reflect the social context of neighborhoods and the quality of their design [20,35–37]. Design elements influenced by New Urbanism and Smart Growth principles have been shown to promote physical activity and walking among residents, resulting in a range of health and environmental benefits [36,38,39]. In particular, pedestrian-friendly environments in neighborhoods facilitate social interactions by offering easy access to a variety of destinations such as shopping areas, workplaces, schools, cafes, and restaurants for leisure and social endeavors [6,40]. Despite the importance of built environmental contexts, there is limited understanding of whether neighborhood social vulnerability, particularly considering streetscape features within a vulnerability framework, affects individual social capital. Visual and perceptual factors, including the distribution of green spaces, sidewalks, and the skyline, that individuals encounter while walking in a neighborhood are crucial in shaping their environmental perception, thereby affecting overall well-being [20,36].

Poorly designed streetscapes can lead to negative environmental perceptions among residents and hinder outdoor activities that contribute to the formation of social capital. Additionally, since walking is a primary mode of transportation for marginalized populations [20,39], evaluating streetscape walkability can provide valuable insights into whether a neighborhood offers economically disadvantaged households the opportunity for social interactions. This study aims to empirically account for streetscape features to identify neighborhood social vulnerability and explore how the environmental context of a neighborhood affects social capital formation by integrating them within a vulnerability framework.

2.3. Measuring Streetscape Features Using Deep Learning Models

Over the past few decades, there has been a growing interest in the fields of public health and urban planning regarding walkability as an indicator of neighborhood quality in terms of built environments. This interest stems from the recognition that pedestrian-friendly environments support social sustainability by encouraging walking, a fundamental physical activity in daily life [16,36–40]. Consequently, the promotion of design guidelines that incorporate walking and cycling into daily routines is advocated in both developing and developed countries seeking to establish healthy and sustainable urban settings [35].

The increased focus on pedestrian-friendly environments has led to the creation of various tools for evaluating neighborhood design quality. Tools based on field audits offer valuable insights into understanding and quantifying the environmental factors that contribute to design quality [35,37]. However, the requirement for significant time, resources, and surveyors limits the assessment of vast urban areas [20,37]. Recent advancements in computer vision technology and the availability of street image data through map services have captured the interest of planning professionals and researchers as potential solutions to the restrictions of field audits [36,37]. Semantic segmentation techniques leveraging neural network algorithms allow for reliable object classification and data extraction from streetscape images, such as those obtained from GSV data. These techniques streamline the processing of large image datasets, facilitating the assessment of design quality across a wide spectrum of spaces [36,40].

Despite the demonstrated utility of semantic segmentation techniques in analyzing travel behavior and enhancing environmental awareness, only a few studies have explored their effectiveness in evaluating the impact of interconnected variables on social capital within the vulnerability framework. This study seeks to unravel the intricate dynamics of social capital by examining the vulnerability associated with streetscape design quality alongside various socioeconomic and demographic factors linked to social vulnerability.

3. Methodology

3.1. Study Area

This study empirically analyzes the relationship between social capital and social vulnerability in Seoul, the capital city of the Republic of Korea, with a population of approximately 10 million people (refer to Figure 1) [41]. Seoul experienced extensive urbanization, rapid economic growth, and industrialization from the 1970s to the 2000s [20]. Since the rapid urbanization in the 1960s, large-scale redevelopment projects have been a representative planning strategy in Seoul. While these projects have increased the number of housing units, they have faced criticism from planners and scholars for frequently leading to the displacement of current residents and the depletion of distinct social assets within neighborhoods [6]. To address this concern, Seoul's urban development administrators have prioritized the enhancement of social capital and the promotion of community sustainability on their agenda [6].

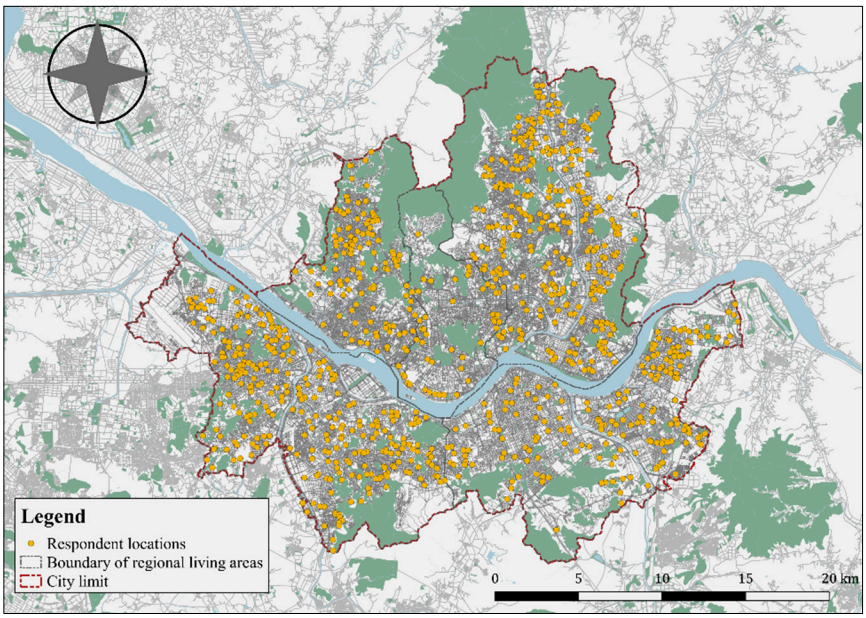

Figure 1. Spatial distribution of survey respondents in Seoul.

In addition, the uneven distribution of socioeconomic services and amenities, driven by spatially imbalanced redevelopment approaches, has resulted in social and health inequality among its citizens. For instance, the suicide and mortality rates were found to be 7.3 times and 5.3 times higher, respectively, for individuals with a high school diploma or less compared to those with a university degree or higher education [42]. Given that socioeconomically disadvantaged populations are concentrated in specific areas [20,39], social and health disparities in Seoul are likely exacerbated. The rates of recipients of basic living benefits and single-person households in Seoul were discovered to be 1.7 times and 1.5 times higher, respectively, in areas with the highest rates compared to those with the lowest rates [42]. In light of social capital's potential contribution to social and health resilience, it is essential to examine the correlations between social capital and neighborhood social vulnerability to reverse the detrimental trend of these inequalities. The empirical findings from the case of Seoul could have significant implications for other developing countries and cities experiencing the erosion of social capital as well as for finding ways to preserve community social sustainability in response to these spatial inequalities.

3.2. Data Set of Korean Neighborhoods

The unit of analysis to identify the social contexts of neighborhoods is the spatial unit of "dong", which is similar to the "census tract" in the U.S. Seoul consists of 425 dongs, which are administrative neighborhoods.

Based on the spatial unit, this study used a wide range of publicly available data to estimate social vulnerability in neighborhoods (refer to Table 1). Household median income data were obtained from K-atlas to account for the levels of household median income in neighborhoods. Regarding land prices in neighborhoods, this study used Korea Appraised Land Price data, obtained from the National Spatial Data Infrastructure. The variables of education, being aged 65 or older, being aged 9 or younger, and being female in neighborhoods were obtained from the Korea Statistical Information Service. In addition, the levels of elderly living alone, population with physical disability, population with mental disability, and basic livelihood were identified by Data Seoul. Finally, Ministry of the Interior and Safety data were used to measure the numbers of public housing in neighborhoods. These variables were utilized as principal determinants to measure the levels of social vulnerability in "dong" areas in Seoul.

Table 1. Neighborhood socioeconomic data descriptions and sources.

Variables	Description	Sources
Income	Median annual income (10M KRW)	K-atlas
Land price	Average land price (1M KRW)	NSDI [a]
Education	% with a bachelor's degree or more	KOSIS [b]
Aged 65 or older	% of aged 65 or older populations	
Aged 9 or younger	% of aged 9 or younger populations	
Female	% of female populations	
Elderly living alone	% of elderly living alone	Data Seoul
Population with physical disability	% of populations with physical disability	
Population with mental disability	% of populations with mental disability	
Basic livelihood	% of basic livelihood recipients	
Public housing	% of public housing units	MOIS [c]

[a]: National Spatial Data Infrastructure; [b]: Korea Statistical Information Service, [c]: Ministry of the Interior and Safety.

3.3. Data for Analysis and Variable Setting

We utilized an online survey and spatial data to examine the influence of neighborhood social vulnerability on the formation of social capital. This study employed Hankook Research (www.hrc.co.kr, accessed on 21 April 2024), a specialized survey firm, to conduct an online survey from February to March 2021. The company has been a reliable survey firm, conducting several public and periodic surveys, such as the Seoul Public Housing Panel Survey, the Korea Housing Survey, the Korea Welfare Panel Survey, the Korean Labor and Income Panel Study, and public opinion polls for presidential elections. Based on their million-survey panel lists, stratified random sampling was employed to collect specific information regarding respondents' home addresses, socio-demographic information, and responses to social capital questionnaires. The survey sample was stratified by three factors: gender, age, and the five Living Zones of Seoul (refer to Figure 1). In addition, the survey only targeted adults aged 19 years and older who had resided in Seoul for over a year for the following reasons. First, young respondents under the age of 19 tend to spend most of their time in schools or institutes in Korea, which may lead to biased answers and distortions when examining the effects of environmental contexts on individual social outcomes. Second, this study excluded residents who had lived in Seoul for less than one year to avoid drawing conclusions based on short-term fluctuations and distortions in social capital. All participants who completed the online survey were given a $10 online gift certificate as a gesture of appreciation to enhance response rates. Despite an initial response rate of 46.7% in the first survey, the online survey reached a sample size of 1000 respondents. Out of the 1000 samples gathered, three were excluded due to missing analytical information or inaccurate addresses, resulting in 997 samples being utilized for the final analysis. Among these, one respondent was missing a home address, and two respondents were missing social capital questionnaires. The survey was approved by the Institutional Review Board of Hanyang University to ensure ethical clearance (Ref. No. HYUIRB202203005).

Figure 2 shows the framework of the research to estimate the variables of individual social capital, socio-demographic attributes, and neighborhood social vulnerability. To measure neighborhood social vulnerability, this study used the home addresses of the survey respondents; we empirically estimated the levels of social vulnerability, including streetscape features, in the neighborhoods where respondents reside. In particular, as the unit of analysis identifying the environmental contexts of respondents, this study uses the neighborhood unit of "dong".

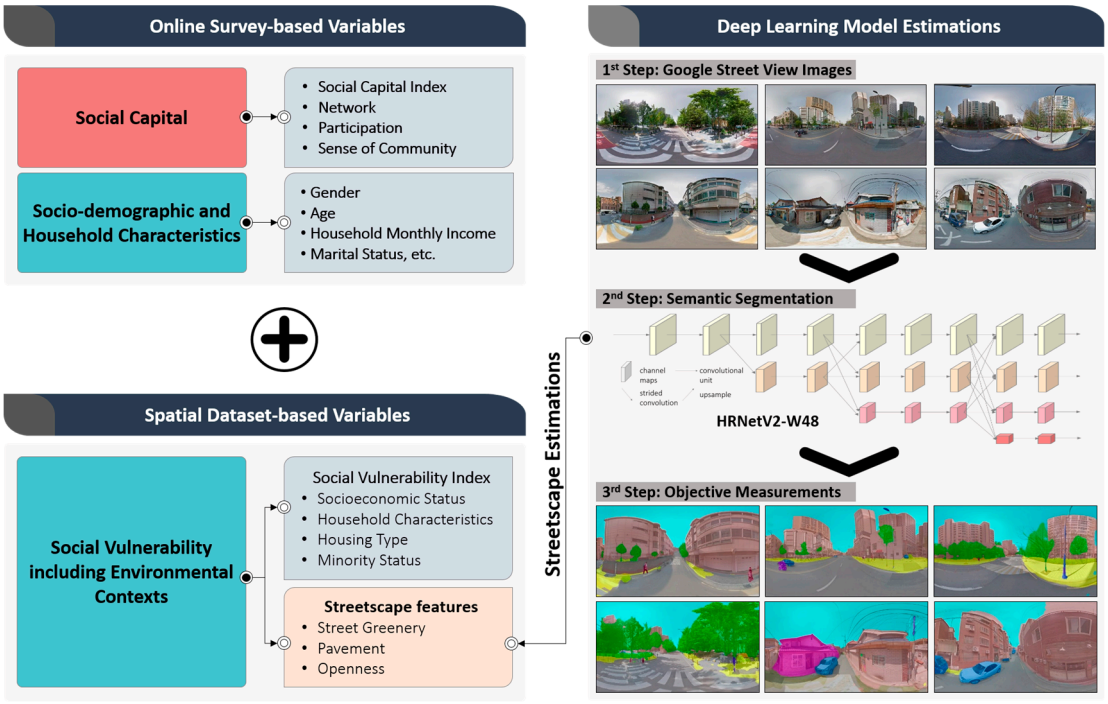

Figure 2. Workflow of data processing and the deep learning model.

To identify the levels of individual social capital, the online survey includes questions about respondents' socioeconomic and demographic characteristics as well as questions related to multidimensional social capital. Specifically, the social capital section covers three domains and six questions: social network ("I know many of my neighbors in the neighborhood" and "My neighbors are friendly with each other"), participation ("I am actively involved in neighborhood organizations (e.g., neighborhood meetings and resident meetings)", "I actively participate in neighborhood gatherings (e.g., athletic, educational, cultural, religious, social, and community meetings)", and "I am actively involved in volunteer activities in my neighborhood"), and sense of community ("I feel like a member of my neighborhood"). All the questions were measured on a four-point Likert scale, ranging from 1 (Strongly disagree) to 4 (Strongly agree).

This study utilized two types of dependent variables, continuous and ordinal scales, to determine comprehensive social capital and social capital in the three specific domains. The continuous scale is a score normalized from 0 to 100, calculated by the following index [6,43]:

$$SCI = \left(\sum_{i=1}^{n} \frac{y_i}{Y_i} \right) \times 100. \quad (1)$$

In the equation above, the Social Capital Index (SCI) represents the respondents' overall social capital that has been standardized by social capital-related questions. "n" denotes the total number of respondents used to calculate the composite social capital, "y_i" indicates the actual score of the "i-th" respondent's overall social capital, and "Y_i" is the maximum potential score for social capital attainable by the "i-th" respondent. Higher scores on this index indicate greater overall social capital within networks, participation, and sense of community. Furthermore, this study analyzed each aspect of social capital using ordinal scales, which were assessed using an average Likert scale for networks, participation, and sense of community as dependent variables. Thus, this study utilized both multiple regression analysis and ordinal logistic models to establish the relationship between social capital and social vulnerability, while taking into account these dependent variables.

This research considered a diverse range of variables at both individual and neighborhood levels to explore their impact on the formation of social capital. Table 2 presents descriptive statistics and empirical measurements related to social capital and sociodemo-

graphic characteristics of the survey respondents, including gender, age, marital status, and household monthly income, as well as household attributes such as residence length, number of household members, homeownership, and living in an apartment.

Table 2. Descriptive statistics for research variables.

Variables	Measurements	Mean	SD [a]	Min	Max
Dependent variables					
Social Capital Index	A normalized continuous score based on six items related to social capital	52.93	15.36	25	100
Network	Average Likert scale of two items for network	2.15	0.70	1	4
Participation	Average Likert scale of three items for participation	1.97	0.73	1	4
Sense of community	Likert scale of the item for sense of community	2.50	0.77	1	4
Independent variables					
Socioeconomic characteristics					
Gender	1 = female; 0 = male	0.52	0.50	0	1
Age	1 = 19–29; 2 = 30–39; 3 = 40–49; 4 = 50–59; 5 = 60 or more				
Household monthly income	1 = less than 1M KRW [b]; 2 = 1M to 2M KRW; 3 = 2M to 3M KRW; 4 = 3M to 4M KRW; 5 = 4M to 5M KRW; 6 = 5M to 6M KRW; 7 = 6M to 7M KRW; 8 = 7M to 8M KRW; 9 = 8M to 9M KRW; 10 = 9M to 10M KRW; 11 = 10M KRW or more	5.34	2.49	1	11
Marital status	1 = yes; 0 = no	0.55	0.50	0	1
Residence period	Years	9.73	9.05		
Number of households	1 = single-family households; 2 = 2; 3 = 3; 4 = 4; 5 = 5 or more household members	3.07	1.14	1	5
Homeownership	1 = yes; 0 = no	0.58	0.49	0	1
Apartment living	1 = yes; 0 = no	0.48	0.50	0	1

[a] SD: Standard deviation. [b] 1M KRW = 751 USD.

3.4. Empirical Measurement of Neighborhood Social Vulnerability

This study incorporates socioeconomic characteristics as well as environmental attributes related to streetscape design quality, in order to assess neighborhood social vulnerability. Taking into account the varying availability of data, this study utilized data from 2018 to ensure that all time points could be aligned. Table 3 presents descriptive statistics for the 14 principal determinants used to empirically measure the social vulnerability of 421 neighborhoods in Seoul, with a final sample size of 997 respondents.

Table 3. Descriptive statistics for the principal components.

Variables	Mean	SD	Min.	Max.
Income	3.92	1.45	2.76	15.86
Land price	3.11	1.92	0.89	16.9
Education	57.35	15.86	3.03	95.27
Aged 65 or older	7.23	1.69	3.34	20.29
Aged 9 or younger	3.50	1.16	0.61	11.09
Female	50.52	1.98	39.72	60.71

Table 3. *Cont.*

Variables	Mean	SD	Min.	Max.
Elderly living alone	2.00	1.04	0.36	11.11
Population with physical disability	1.95	1.72	0.51	6.73
Population with mental disability	0.27	0.18	0.08	1.66
Basic livelihood	1.60	1.27	0.01	9.58
Public housing	5.05	8.72	0.00	69.79
Street greenery	7.86	3.86	2.22	26.39
Pavement	8.98	1.78	2.88	18.19
Openness	26.99	2.95	19.28	39.83

This study utilized GSV panoramic images and semantic segmentation techniques to generate environmental variables related to neighborhood streetscape design quality. By inputting coordinate data with 20 m interval points along the street network of Seoul into the GSV metadata API, a total of 319,493 street panoramic images were obtained (Figure 3). Due to the temporal distribution of these images ranging from 2009 to 2020, this study excluded 25,511 GSV images to focus on streetscapes captured in 2018. Additionally, this study excluded 2590 images taken in winter to prevent bias in street greenery measurements. Furthermore, 36,479 images captured at locations with prohibited pedestrian access, such as tunnels, overpasses, and roads exclusively for motor vehicles, were excluded to focus on streetscapes experienced by residents while walking. Therefore, this study utilized 254,913 images taken in 421 neighborhoods in Seoul from March to November 2018 to assess neighborhood streetscape design quality.

Figure 3. Sample retrieval of Google Street View panorama images.

Street panoramic images often exhibit distortions at the edges of the image [40,44]. Since these distortions can potentially affect the accuracy of inferences made during the image classification process, this study followed the criteria outlined in the existing literature [20,45] and employed a cropping algorithm to eliminate the highly distorted edges within the human field of view (Figure 4).

Figure 4. Example of a cropped image from the original panoramic image.

The HRNetV2-W48 model, trained with the ADE20K dataset, processed approximately 255,000 images, each annotated with 150 categories, to determine the number of pixels in each category per image (see Figure 5) [46,47]. The model exhibited an accuracy of 82.5% during validation testing. Out of the 150 categories, this study specifically focused on key categories associated with neighborhood streetscape design quality, including street greenery, pavements, and openness to the sky along streets [36,37,40]. These categories were quantified based on previous research and calculated individually for each image. Street greenery was estimated by the percentage of tree, plant, and grass pixels to the total number of pixels in the GSV images. This variable refers to various forms of plants along streets, which provide a sense of comfort for pedestrians [48]. Pavements were measured as the percentage of sidewalk pixels relative to the total pixels of sidewalks and roads. This measure is related to pedestrian safety when they walk on streets [20]. Lastly, openness to the sky was determined by calculating the percentage of sky pixels in the GSV images. Pedestrians can visually experience pleasure from streets with a high sense of openness [49]. In the final analysis, each value was aggregated at the neighborhood level, which served as the unit of analysis. More specifically, the average environmental attributes related to neighborhood streetscape design quality were calculated using the streetscape images from each neighborhood.

$$\text{Street greenery} = \frac{\text{number of greenery pixels}}{\text{number of total pixels}} \times 100(\text{greenery} = \text{tree, plant, and grass}) \quad (2)$$

$$\text{Pavement} = \frac{\text{number of sidewalk pixels}}{\text{number of road pixels} + \text{number of sidewalk pixels}} \times 100 \quad (3)$$

$$\text{Openness} = \frac{\text{number of sky pixels}}{\text{number of total pixels}} \times 100 \quad (4)$$

This study utilized a dimensionality reduction technique to analyze the contribution of 14 environmental factors to social vulnerability, which were derived from public data and semantic segmentation. By examining the complex interactions among these factors, this study aimed to identify the specific dimensions that influence vulnerability. The methodology employed in this study involved principal component analysis with Varimax rotation, a widely accepted factor reduction method. This approach helped to determine how the

various vulnerability factors were grouped into distinct components [8]. The exploratory analysis revealed that the 14 variables could be reorganized into four components: special needs, less urbanization, walkability and urban prosperity, and household composition and housing type. These components provided a comprehensive overview of how different environmental factors in neighborhoods contribute to social vulnerability (refer to Table 4).

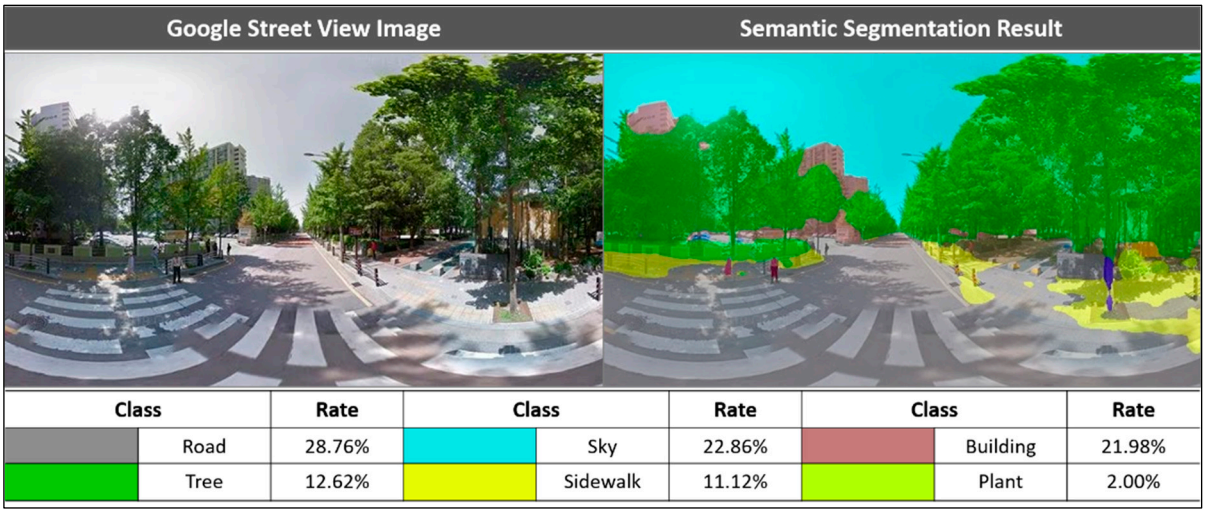

Figure 5. Example of semantic segmentation results using HRNetV2-W48.

Table 4. The results of principal component analysis.

	Rotated Component Matrix			
	Special Needs (+) [a]	**Less Urbanization (+)**	**Walkability and Urban Prosperity (−)**	**Household Composition and Housing Type (+)**
Population with physical disability	0.922	0.138	−0.245	0.026
Basic livelihood	0.894	0.060	−0.164	−0.043
Population with mental disability	0.833	0.158	−0.034	0.175
Aged 65 or older	0.793	0.022	−0.045	−0.151
Elderly living alone	0.751	−0.130	−0.030	−0.428
Pavement	0.033	−0.853	0.106	−0.053
Openness	−0.157	0.823	−0.108	0.000
Land price	0.111	−0.685	−0.519	0.149
Income	−0.218	−0.051	0.823	0.033
Street greenery	−0.028	0.211	0.785	0.198
Education	−0.514	−0.006	0.641	0.142
Female	−0.160	−0.239	0.143	0.735
Public housing	0.415	0.332	0.076	0.566
Aged 9 or younger	−0.233	0.394	0.260	0.526

[a] The plus (+) and minus (−) signs in parentheses signify the relationship between each component and social vulnerability. Extraction was performed via Kaiser Normalization Varimax. Shaded cells signify parameters that make up each component.

Overall, the components demonstrated a strong model fit, explaining 72.07% of the variance in the input variables and showing that the Kaiser–Meyer–Olkin value was 0.77. This analysis sheds light on the interconnected nature of environmental attributes and their impact on vulnerability.

4. Results

4.1. Results of Overall Social Capital

Table 5 shows the results of the multiple regression models that investigate the relationships between neighborhood social vulnerability and overall social capital. All regression coefficients were estimated using White's robust standard errors to address the issue of heteroscedasticity in the samples utilized for the analysis. Additionally, in order to identify unobserved regional characteristics and account for the spatial autocorrelation problem, this study incorporated the x and y coordinates of the centroids of neighborhoods, which were normalized by the distance to the CBD, into the analysis.

Table 5. The results of multiple regression model for overall social capital.

	Overall Social Capital			
	Coef.	**Robust Std. Err.**	**t**	***p***
Socio-demographic and household characteristics				
Gender	−1.128	0.937	−1.20	0.229
Age	0.080 *	0.044	1.84	0.066
Household monthly income	0.108	0.240	0.43	0.669
Marital status	4.043 ***	1.282	3.15	0.002
Residence period	1.759 ***	0.523	3.37	0.001
Number of households	−0.169	0.516	−0.33	0.744
Homeownership	3.238 ***	1.121	2.89	0.004
Apartment living	0.713	1.075	0.66	0.507
Neighborhood social vulnerability				
Special needs	0.905 *	0.491	1.85	0.065
Less urbanization	1.003 **	0.508	1.98	0.049
Walkability and urban prosperity	1.273 **	0.622	2.05	0.041
Household composition and housing type	−0.602	0.542	−1.11	0.266
Locational characteristics				
X, Y coordinates	Included			

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$.

The results of the respondents' socioeconomic attributes indicate that older respondents exhibit higher levels of overall social capital; this finding was statistically significant at 10%. Additionally, married respondents demonstrate a higher level of overall social capital. However, the gender and income levels of individuals did not show statistical significance. Respondents who have resided for a longer period and own a house exhibit higher levels of overall social capital.

Regarding the statistical results for neighborhood social vulnerability, the main focus of this study, neighborhoods with high special needs show a positive correlation with overall social capital; this finding was statistically significant at 10%. Furthermore, respondents residing in neighborhoods with high tendencies of less urbanization and walkability and urban prosperity exhibit high levels of overall social capital. Household composition and housing type did not show statistical significance with overall social capital.

4.2. Results of Social Capital in Diverse Domains

This study examined the influence of neighborhood social vulnerability on various aspects of social capital. Table 6 presents the ordinal logistic regression results for network, participation, and sense of community.

Table 6. The results of ordered logistic regression models for each domain of social capital.

	Network			Participation			Sense of Community		
	Coef.	**OR**	**z**	**Coef.**	**OR**	**z**	**Coef.**	**OR**	**z**
Socio-demographic and household characteristics									
Gender	−0.202 ***	0.817	−1.76	−0.080 ***	0.923	−0.70	0.109	1.115	0.89
Age	0.005	1.005	0.89	0.015 ***	1.015	2.78	0.012 **	1.012	2.19
Household monthly income	0.023	1.023	0.83	−0.033	0.967	−1.23	0.322 **	1.379	3.94
Marital status	0.413 ***	1.511	2.66	0.554 ***	1.740	3.55	−0.152	0.859	−2.14
Residence period	0.333 ***	1.394	5.06	0.061	1.063	0.94	0.109	1.115	0.89
Number of households	0.008	1.008	0.13	−0.031	0.970	−0.51	0.012	1.012	2.19
Homeownership	0.079	1.082	0.59	0.591 ***	1.806	4.38	0.072 ***	1.075	2.51
Apartment living	−0.012	0.989	−0.09	−0.002	0.998	−0.02	−0.036 *	0.965	−0.22
Neighborhood social vulnerability									
Special needs	0.125 **	1.134	2.04	0.087	1.090	1.45	0.056	1.058	0.84
Less urbanization	0.079	1.082	1.24	0.143 **	1.153	2.22	0.088	1.091	1.26
Walkability and urban prosperity	0.035	1.035	0.46	0.125 *	1.133	1.66	0.322 ***	1.379	3.94
Household composition and housing type	−0.073	0.929	−1.10	0.005	1.005	0.08	−0.152 **	0.859	−2.14
Locational characteristics									
X, Y coordinates	Included								

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$.

Regarding socioeconomic characteristics, gender was found to have a negative correlation with participation in social capital. Females displayed lower odds of participation. Meanwhile, age was positively correlated with participation and sense of community. Therefore, older respondents exhibited a greater tendency to be involved in social capital domains, such as participation and sense of community. Furthermore, respondents with higher income levels demonstrated a stronger sense of community. Married respondents also showed higher levels of social capital in areas such as networks and participation. The odds ratios for married respondents were estimated at 1.511 for networks and 1.740 for participation, indicating that the odds of having a higher level of network and participation increased by 51.1% and 74.0%, respectively, for married individuals.

The length of residence showed a positive correlation with networks, although this was not statistically significant for participation and sense of community. Similarly, homeownership was positively associated with participation and sense of community but not with networks. It was found that respondents living in apartments had a reduced sense of community, with a significance level of 10%.

The results suggest that different components of social vulnerability have varying correlations with social capital formation across different domains. Each component appears to be linked to distinct social domains. Respondents living in neighborhoods with high special needs exhibited higher levels of networks. Additionally, neighborhoods with lower levels of urbanization were linked to increased participation among residents. However, these associations were not statistically significant in relation to the other two social capital domains. Walkability and urban prosperity as well as household composition and housing type were all significantly correlated with a sense of community. Respondents residing in neighborhoods with high walkability and urban prosperity, as well as those with diverse household composition and housing types, demonstrated higher levels of sense of community.

5. Discussion and Conclusions

In order to develop effective plans and policies that promote social sustainability and healthy urban development, it is crucial to establish correlations with the social capital of a neighborhood through the use of social vulnerability indicators that take into account the environmental contexts of those neighborhoods. This study empirically investigates the influence of a community's social vulnerability on social capital, while also considering the environmental context. The research employs a deep learning model and streetscape images to measure the quality of neighborhood streetscape design features and estimate the social vulnerability of a community. By comprehensively identifying various social capital domains, this study delves into the impact of social vulnerability on social capital.

Regarding the socioeconomic characteristics, the variables of marital status, household monthly income, residence period, and home ownership have shown positive relationships with various domains of social capital, consistent with previous studies. However, the variable of age has yielded contradictory results compared to previous studies; our findings indicated positive relationships between age and social capital. Previous studies have shown that individual age is negatively associated with social capital because older individuals may have fewer information-based bonds and could be at risk of losing emotion-based bonds, such as close friendships [28,50]. These conflicting results may be attributed to social structural changes in South Korea, which has transitioned into an aging society since 2000. The country has implemented a range of policies aimed at enhancing the health and quality of life of older adults. Training programs and employment opportunities have provided older adults with access to new social resources, encouraging their engagement in social activities [51,52]. Meanwhile, our findings raised concern regarding the lower levels of social capital for young adults. Recent studies have also highlighted the increase in young single-person households in Seoul with limited economic stability, consequently leading to the accelerated social isolation of younger individuals [53]. Therefore, it is essential for planners and policymakers to develop comprehensive and tailored strategies that encompass the entire family life cycle, aimed at alleviating the social isolation of young people and fos-

tering social capital. For example, the U.K. government has taken steps to address the issue of social isolation for young adults. The Civil Society and Youth Directorate, a department responsible for this area, introduced the "A Connected Society: A Strategy for Tackling Loneliness" in 2018. This strategy outlines specific objectives and plans to combat social isolation and enhance social capital among young people, and it has been systematically implementing tailored policies in collaboration with various government departments.

This study empirically demonstrates that social vulnerability factors within a community can affect the formation of social capital. The findings suggest that individuals in neighborhoods characterized by high levels of walkability and urban prosperity, indicative of low vulnerability, exhibit higher levels of overall social capital and a stronger sense of community. The presence of diverse green spaces (i.e., street trees and vegetation) within neighborhoods can encourage residents to engage in more walking and can serve as focal points for leisure and social activities [25]. Introducing such environmental interventions in neighborhoods with high social vulnerability may prove vital in promoting social interactions among residents and strengthening social capital within the community. Therefore, it is essential for planning practitioners and policymakers to prioritize the creation of green spaces along street networks within neighborhoods and to offer educational opportunities to low-income households. These efforts can help to enhance social capital within neighborhoods that lack sufficient green spaces and face socioeconomic challenges.

Neighborhoods with high levels of urbanization, reflecting the interconnected nature of the neighborhood's economic and physical environment, are positively correlated with overall social capital and diverse social domains, particularly participation. This finding is unexpected as previous studies have shown a positive correlation between social capital and urbanized areas. However, this result can be interpreted within the context of social structural changes aligned with rapid urbanization. The dynamics of rapid urbanization can enhance physical infrastructure and create job opportunities, but it may weaken traditional social cohesion by bringing together 'unfamiliar' individuals in a neighborhood and weakening connections with family and neighbors [54,55]. Given that high housing costs due to rapid urbanization can marginalize vulnerable groups [55,56], residents in relatively less urbanized neighborhoods may increase their social capital through participation in local gatherings and interactions [57]. Nevertheless, deteriorated infrastructure and amenities in these areas can negatively affect their residents' quality of life and health. Therefore, it is crucial to propose tailored strategies to uphold social cohesion and enhance living conditions. For instance, conserving social assets through urban regeneration projects could be an effective approach to improving resilience and bolstering social capital, unlike large-scale redevelopment which raises property values and leads to the involuntary displacement of current residents.

The findings also indicate that other components of social vulnerability (such as special needs as well as household composition and housing type) are significantly correlated with various social capital domains. Special needs are positively associated with social networks. Previous studies have demonstrated that similar groups can strengthen bonds in order to access external resources [4,58]. In essence, residents in neighborhoods with high special needs can enhance their social connections to access external resources, including public health care, welfare, humanitarian aid institutions, non-local donations, and welfare benefits, thereby expanding their social networks. However, groups with special needs (such as people with physical or mental disabilities, those in need of basic livelihood assistance, individuals aged 65 years or older, or older adults living alone) may face limitations in terms of in-person contact or opportunities for mutual exchange, which can hinder the formation of social capital due to reduced physical and cognitive abilities. Hence, planners, transportation experts, and urban designers should collaborate to develop design guidelines and mobility services that promote accessibility for these marginalized populations. For instance, in the U.S., the Americans with Disabilities Act (ADA) sets forth "Accessibility Standards" that offer guidance on creating buildings, travel routes, sites, and

public transportation systems that allow disadvantaged populations to access amenities safely and conveniently, thereby enhancing their social interactions [59].

This study identified that neighborhoods characterized by high household composition and housing type, factors contributing to vulnerability, exhibited a negative correlation with sense of community. Individuals residing in these neighborhoods, such as occupants of public rental properties, often encounter frequent conflicts with their neighbors, who reside in non-public housing, primarily due to social exclusion and stigma [60]. This results in exposure to external stressors that detrimentally affect their emotional well-being. Establishing community centers and parks within these neighborhoods can facilitate neighborhood interactions and serve as practical strategies to enhance the sense of community and promote emotional stability [6,61]. In addition to the provision of such facilities, it is recommended that community empowerment initiatives be implemented to assist residents in engaging with their neighbors, offering support, and reinforcing social connections [61].

This study empirically explores the impact of neighborhood social vulnerability, accounting for streetscape features, on social capital formation. We utilized deep learning-based semantic segmentation models to identify detailed streetscape features in neighborhoods. By incorporating these neural network measurements into the conventional social vulnerability index, this study aimed to fill the gap left by previous studies that relied on subjective field audits or surveys to identify neighborhood, built environments and their relationships with individual social capital. The findings imply that planners and policymakers should monitor and improve the quality of streetscape features in neighborhoods to enhance residents' social capital, rather than solely focusing on socio-demographic attributes when addressing social vulnerability.

Our key findings highlight the importance of enhancing environmental contexts, particularly streetscape features, to mitigate the negative impacts of social vulnerability on residents' social capital. Specifically, we found that neighborhoods characterized by walkable environments and greater prosperity, as indicated by factors such as neighborhood income, education, and street greenery, are significantly associated with higher levels of social capital among residents. Additionally, less urbanized neighborhoods, characterized by lower land prices and greater openness to the sky, show a positive association with individual social capital. These results suggest that improving streetscape features, such as street greenery and openness, can mitigate the negative influences of socioeconomically vulnerable neighborhoods (i.e., lower land prices, income, and education) on residents' social capital.

The close collaboration of a wide range of stakeholders, including planners, architects, community leaders, and policymakers, is necessary to improve the quality of streetscape features, especially in neighborhoods where low-income and less-educated residents are concentrated. For instance, planners need to work with community leaders and residents to identify streets with poor streetscape quality, particularly in terms of greenery and openness to the sky. In addition, planners and landscape architects should make efforts to provide design and maintenance guidelines for improving streetscape features in socially vulnerable neighborhoods. For instance, landscaping to enhance street greenery and incorporating building setbacks and street furniture design to ensure street openness should be considered. These policy interventions and collaborations can play a pivotal role in fostering social capital and well-being for marginalized neighborhoods.

This study has some limitations. First, the findings of this study may not be generalizable to other countries and cities as this study only focused on the case of Seoul. We suggest that future studies extend the scope of the impacts of neighborhood social vulnerability accounting for streetscape features across other countries and cities. Second, this study did not consider respondents' home environments, which may affect individual social capital. More research is needed to investigate such micro-environments and their impacts on individual social capital.

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Data Availability Statement: The data presented in this study are available upon request from the corresponding author. The data are not publicly available due to privacy restrictions.

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