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Housing, street and health: a new systemic research framework

SYNTHESIS

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ABSTRACT

As the world's population grows in cities, urban dwellers spend a large amount of time inside their home, making housing health ever more important. Critical for residents' health, the interactions between indoor residential environments and outdoor environmental conditions (*e.g.* air pollution, noise, heat) are mediated by the controversial and evolving relationship between housing and the street. Currently, there is a lack of ways to integrate and explore synergies among the plurality of perspectives that have addressed the interactions between housing, street and health (HSH). This paper proposes a systemic research framework to address conceptually, spatially and temporally HSH interactions. With a focus on European cities, determinants of housing health are identified through six perspectives, comprising environmental health, domestic architecture, building technologies, socio-economic inequalities, housing prices and urban planning. Their interrelationships are organised in a causal loop diagram, which can be used to highlight gaps in research and data. Subsequently, the paper explores the research and practical applications of the resulting systemic understanding, taking the context of Geneva, Switzerland, as an example. In sum, this study illustrates ways to integrate systemic, transdisciplinary and spatiotemporal approaches essential to holistically address the complexity of HSH relationships.

PRACTICE RELEVANCE

The interactions between housing, street and health (HSH) have been approached from different and often siloed perspectives, addressing issues ranging from diseases to architectural design and history, building technologies, socio-economic inequalities, housing prices and urban planning. This fragmentation hinders the coordination of interventions aimed at improving the health of residential environments, limiting the

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identification of synergies and trade-offs. This paper proposes a research framework enabling the integration of knowledge on the HSH interactions. The resulting holistic and systemic understanding is instrumental in fostering collaborations across disciplinary fields and among a variety of stakeholders, in raising awareness of the risks and opportunities associated with HSH interactions, and in supporting the design and implementation of health and wellbeing agendas at the building, neighbourhood or city level.

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1. INTRODUCTION

Cities are home to more than half of the world's population (UNDESA 2019). This population spends most of its time at home—a share likely to increase when considering the condensation of urban activities within housing units (*e.g.* home office), the ageing of society and the intensification of extreme weather events (González Serrano *et al.* 2023; Klepeis *et al.* 2001; Lawrence 2006; WHO 2015, 2018). Against this evidence, the quality of indoor residential environments is of paramount importance to public health, and so are the outdoor conditions that determine it (Fuller-Thomson *et al.* 2000; Haines *et al.* 2013; Hartig & Lawrence 2003; Lawrence 2012; Samet & Spengler 2003). As a circulation route, public space and built frontage, the street mediates the interaction between the physical boundaries of the dwelling and the broader urban environment (Marshall 2004a).[1] First associated with insalubriousness in dense medieval European areas and in the overcrowded dwellings of the industrial period (Benevolo 1975; Bobek & Lichtenberger 1966), the street was then linked in the 19th century to fresh air, light and status (Eleb & Debarre 1995), and to more salubrious social housing in early 20th-century developments (Lawrence 1983; Porotto 2018). Nevertheless, it has once again become a source of pollution and social isolation (Jacobs 1992; Joost *et al.* 2018), with direct and indirect effects on occupants' health (Sadat & Dehkordi 2022).

The study of housing–street–health (HSH) has so far been undertaken by separate disciplines, each mobilising distinct methodological approaches (quantitative versus qualitative, aggregate versus individual level). In particular, housing health research has relied predominantly on traditional public health approaches, whereby the independent effects of specific factors on health are isolated (*e.g.* traffic volume, air pollutant levels) (Diez Roux 2015; Galea *et al.* 2010). However, this fragmentation of knowledge hinders a shared understanding of the complex interactions shaping urban systems and health (Rydin *et al.* 2012; Tozan & Ompad 2015), including their conceptual, temporal and spatial interlinkages. Spatiotemporal analysis methods are emerging in epidemiological research to identify links between place of residence and health, and thus of priority areas for health interventions (Auchincloss *et al.* 2012; De Ridder *et al.* 2021; Lawrence 2021). Yet the interpretability of their results is constrained by the framework of analysis, which exposes them to the risk of a siloed and therefore incomplete view of the system under study.

As the study of HSH suffers from a disciplinary and methodological divide, this siloed approach also extends to the practice realm, where institutional fragmentation has led to a disjointed formulation and implementation of urban policies (Myers 2017; Rudolph *et al.* 2013).

There is a rising awareness across fields that to address complex societal challenges, compartmentalisation within and between research, politics and institutions cannot be maintained (Dardier *et al.* 2023; Lawrence 2006; Lawrence & Després 2004; O'Campo *et al.* 2011; Ramadier 2004); however, as promising as it is, the 'fusion' of different perspectives can only be achieved through platforms that enable transdisciplinary collaboration.

Therefore, to achieve a holistic understanding of HSH interactions and their evolution, there is a need for a framework enabling the exploration of synergies and integration of the plurality of fields addressing the residential context of health over time and space.

The goal of this paper is to introduce a systemic research framework for the study of HSH interactions. The next section illustrates the interdisciplinary and expert-based approach adopted to develop the framework. On this basis, Section 3 provides an overview of the state of the art

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of HSH relations predominantly in Europe, organised according to six disciplinary perspectives. Their intersections are explored using the causal loop diagram (CLD) displayed in Section 4, which maps the interrelations between the determinants of the HSH system dynamics identified in the state of the art. To exemplify the spatiotemporal investigation of these interrelations and the potential practical applications of the framework, Section 5 narrows the focus to the city of Geneva, Switzerland. The paper concludes by bringing attention to the limitations of the proposed framework and possible developments aimed at drawing on a systemic, spatiotemporal and transdisciplinary understanding of the multilayered HSH system complexity.

2. FRAMEWORK DEVELOPMENT: INTERDISCIPLINARY, EXPERT-BASED EXCHANGES

The research framework design was based on a series of activities coordinated by the Habitat Research Center (HRC) at the École Polytechnique de Lausanne (EPFL) and consisted in the following steps: (1) definition of the problem; (2) identification of the perspectives to address it; (3) scoping of the literature; (4) framework design; and (5) framework application.

The problem was framed based on the expertise of the members who make up the board of the HRC Healthy Habitats research field, and the growing acknowledgement of the complex links between health, transportation and the built environment (Dardier *et al.* 2023; Giles-Corti *et al.* 2022; UN General Assembly 2015).

The activities of the HRC aimed at gathering urban health researchers affiliated or collaborating with EPFL, providing a platform for a broader range of scholars to come together. Eventually, a team of 10 researchers with expertise in the fields of public health, transport, epidemiology, architecture, building engineering, demography, geography, urbanism and systems thinking was formed. Bilateral discussions, team sessions and a first exploratory literature review led to the definition of six perspectives that could be mobilised to address the HSH interrelations.

Subsequently, the team performed a narrative literature review for each perspective. Narrative reviews are unstructured exploratory reviews that synthetise 'evidence familiar to an author on a given topic or theme' (Sovacool *et al.* 2018: 23); their usefulness lies in gathering insights drawn from a range of perspectives, aligned with the researchers' priorities and the purpose of their study. In the present case, the literature selection process aimed to provide a synthesis of evidence based on relevant, high-quality papers from broadly used databases such as Google Scholar, Web of Science and Scopus. Key references were extracted from a range of fields, namely spatial, demographic and social epidemiology, environmental health, indoor environmental quality, urban housing theory and history, environmental economics, urban geography, and complexity science. Selection of articles, time frames and keywords varied according to disciplinary tradition. For instance, while the environmental health perspective focused on recent journal articles (2006–22), the architecture literature additionally and predominantly screened published books covering one of the main periods of urban expansion, from the mid-19th century to the early 20th century, and more specifically the subperiods of massive housing production in Europe.

Expertise in systems thinking and systems dynamics was used to design a CLD, which visually displays the interrelationships between system variables (Sterman 2000). The latter were extracted from the six syntheses of the literature (for CLDs in health system research, see *e.g.* Cassidy *et al.* 2022). Using the CLD and based on the authors' expertise related to the proposed distinctive areas, gaps were identified, leading, iteratively, to additional rounds of literature review.

Finally, to provide research and practice recommendations relevant to the six perspectives and their integration at the building, neighbourhood and city levels, the authors drew on their collective academic and practical experience in the built environment. As housing is highly dependent on cultural, political, economic and social contexts (Lawrence 1995; Pagani 2022; Pagani & Binder 2021), the city of Geneva in Switzerland was chosen as an example.

3. SIX PERSPECTIVES TO TACKLE THE HSH SYSTEM

Several disciplines have mobilised their worldviews, epistemologies and methods to investigate the multiscalar relations between residential environment conditions and health (De Leeuw 2017; Lawrence 2004). Consequently, the literature on HSH relationships needs to be sought through fragmented but complementary perspectives, addressing questions related to diseases, architectural design and history, building technologies, socio-economic inequalities, housing prices, and urban planning.

3.1 ENVIRONMENTAL HEALTH PERSPECTIVE

In urban environments, car traffic is a major source of air pollution and noise, which are leading causes of non-communicable diseases (NCDs) and thus of premature adult death (WHO 2016). The majority of human exposures to urban air pollution occurs while being indoors, with a wide range of health consequences for inhabitants (Nazaroff 2018; Rodopoulou *et al.* 2022). The infiltration of outdoor pollution into dwellings can cause allergies, a weakening of the immune system, cancer and several respiratory diseases (Turcu *et al.* 2021; WHO 2018). For instance, during the COVID-19 pandemic, virus incidence, severity and mortality were shown to increase for residents near roadways and waste facilities, *i.e.* locations where ambient levels of fine particulate matter (PM) and nitrogen oxides (NO_x) are higher (Frumkin 2021). Regarding the soundscape, long-term exposure to road traffic noise has been associated with sleep disturbance, annoyance, hypertension, ischaemic heart diseases, cognitive impairment and heightened blood pressure of children, and tinnitus (Babisch *et al.* 2009, 2014; Dzhambov & Dimitrova 2018; Fyhri & Aasvang 2010; Gilani & Mir 2022; Héritier *et al.* 2018, 2019; Jakovljević *et al.* 2006; Joost *et al.* 2018; Münzel *et al.* 2020; Van Kempen *et al.* 2018; Vienneau *et al.* 2022). Ambient noise can also discourage window opening, thereby aggravating bedroom air quality and its effects on health (Fan *et al.* 2022; Strøm-Tejsen *et al.* 2015). Overall, the negative impacts of noise have been estimated to lead to a loss of about 1 million healthy life-years (*i.e.* disability-adjusted life-years—DALYs) every year in Western Europe alone (Fritschi *et al.* 2011).

Beyond air pollution and noise, the impermeable surfaces of streets, as well as vehicle trips, air pollution and heat emissions from buildings, are responsible for an increase in the difference in average temperatures between city centres and the countryside—*i.e.* urban heat islands (UHI)—which represents a major threat to population health (Choi *et al.* 2022; Kovats & Hajat 2008). Several European studies have demonstrated how UHI and building overheating can worsen the effects of heatwaves and increase mortality and morbidity (Kovats & Hajat 2008; Lerch & Oris 2018; Rydin *et al.* 2012; Santamouris 2020; Saucy *et al.* 2021).

The design attributes of dwellings, particularly the orientation of rooms and floors, play an important role in shaping the interactions between environmental conditions (*e.g.* air pollution, noise and heat) and inhabitants' health. The lack of cross-ventilation or of shading systems as well as top floor location have been shown to determine the overheating propensity of the building and the mortality risk during a heatwave (Kovats & Hajat 2008; Mavrogianni *et al.* 2022; Petrou *et al.* 2019; Vardoulakis *et al.* 2015). Bedrooms facing roads with higher traffic and, this time, lower floor location (first to third) have been associated with higher blood pressure, lifetime-ever asthma and past-year rhinitis in children (Babisch *et al.* 2009; Chang *et al.* 2017; Liu *et al.* 2020). While bedrooms located on the 'quiet side' can reduce sleep disturbances (Bartels *et al.* 2021; Bodin *et al.* 2015; Van Renterghem & Botteldooren 2012), bedrooms on the street side have been linked to increased sleep onset latencies and associated with obesity markers in adults (Oftedal *et al.* 2015; Pirrera *et al.* 2014). More generally, windows facing a yard, water or green space were demonstrated to reduce the risk of noise annoyance and concentration problems (Bodin *et al.* 2015).

The way housing is designed and used has evolved over history, across societies and environments (Pagani & Binder 2021). Architectural lenses are therefore pivotal to achieving an enhanced understanding of housing layout decisions in relation to the street and health.

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3.2 ARCHITECTURAL PERSPECTIVE

Housing is a preliminary and collective component of cities (Brinckmann 1908: 170). Investigating housing layout means achieving a better understanding of society at large—including the evolution of customs, mindsets and beliefs (Eleb 2021). The varying hierarchisation of rooms in the dwelling is the material expression of the changing status attributed to indoor spaces (whether public/private, representative/service), outdoor spaces (*i.e.* street, courtyard), and their relationship with each other. Such shifts can be retraced by examining turning points in the history of modern housing in Europe, from its invention until today. In the bourgeois housing at the turn of the 19th and 20th centuries, for instance, reception areas most often faced the street, while service areas such as kitchens were pushed to the back—facing the courtyard, the less visible side (*e.g.* Barbey *et al.* 1982: 292; Eleb & Debarre 1995: 49). However, growing tensions between the societal codes of the time and rational hygienic rules could bring about different design outcomes (Eleb & Debarre 1995: 140). More specifically, the increased attention paid to sunshine, daylight, hygiene and ventilation was shown to affect the hierarchy of outdoor areas, rooms and floors. Regarding the former, a good orientation of buildings and main living areas was observed to sometimes prevail over the needs of status representation (Conseil d'Etat 1899; Duc *et al.* 2008; Wall Gago 2015: 140); consequently, the hierarchy that distinguished the less desirable courtyard from the street as a privileged view was lost or redefined, implying adjustments in the distribution of indoor spaces, the quality of the facade or outdoor areas themselves (Eleb & Debarre 1995: 310; Richard-Bazire 2018). The raising attention paid to health and family life in the 19th–20th centuries also impacted the status of indoor rooms, *e.g.* through the increased importance of bedrooms and dining rooms, which required an improvement of the outdoor spaces they overlooked (Eleb & Debarre 1995: 311). Finally, the need to upgrade living conditions was shown to result in the once-preferred lower floors losing importance against the upper ones—today even more valued for their views and privacy from the 'bustling street' (Wall Gago 2015: 260).

The complex evolution of the status of urban streets, their design and their influence on housing has been documented across countries and historical periods, *e.g.* Europe (Castex *et al.* 2004; Lillebye 1996), Lisbon (França 1965), Paris (Des Cars & Pinon 1991) and Vienna (Porotto 2019). From an opportunity for self-representation, street facing is now a threat to social interactions; residents living on busy streets are reported to be more socially withdrawn and less likely to know their neighbours (Appleyard & Lintell 1972; Hartig & Lawrence 2003). Due to several constraints (*e.g.* technical complexity, building regulations, heritage protection; Grand Conseil de la République et canton de Genève 2021; Wall Gago 2015: 292), worsened by the architects' and building professionals' lack of specialised knowledge about health and wellbeing (Lawrence 2021; Pineo 2020; Rice 2019), renovation strategies have seldom revaluated the positioning of rooms towards the street, *e.g.* by making bedrooms face the quieter courtyards. In parallel, however, increasing attention has been paid to building technology solutions that enable control over housing indoor conditions and comfort.

3.3 BUILDING TECHNOLOGY PERSPECTIVE

Beyond architectural design, building technology plays a relevant role in moderating the relationship between housing and the street. Passive and active solutions to limit the infiltration of outdoor pollution are, to date, the building envelope (permeability, exposure), mechanical ventilation systems, outdoor air filters and their maintenance, hybrid natural–mechanical ventilation systems, and human behaviour (Belias & Licina 2022; Ferguson *et al.* 2021; Foster *et al.* 2020; Martins & Carrilho da Graça 2018; Vardoulakis *et al.* 2020). However, these solutions also come with a downside. Due to a lack of consideration of regional and local, seasonal, and diurnal variations, outdoor air is often over-filtered, resulting in higher-than-needed energy consumption (Belias & Licina 2022; Shrubsole *et al.* 2019). In the same vein, energy conservation measures often imply more airtight building envelopes, which reduce the exchange between indoor and outdoor air, bringing about an increase in indoor pollutants and aggravating the effects of climate change and UHI on building overheating (Coombs *et al.* 2016; González Serrano & Licina 2022; Taylor *et al.* 2019; Vardoulakis *et al.* 2015). While reducing thermal discomfort and health

risks, air-conditioning systems have been associated with a range of problems, such as reduced social interaction, increased energy consumption—and consequently CO_2 emissions and costs, especially for low-income households—and even greater UHI effects (Davies *et al.* 2008; Ford *et al.* 2022; Santamouris 2020; Vardoulakis *et al.* 2015). In Sweden, mechanical ventilation has also been found to aggravate noise disturbance, especially in older multifamily buildings and rented apartments, which are often poorly insulated and occupied by poorer inhabitants (Wang & Norbäck 2021). Furthermore, access to technologies such as insulation, building materials or mechanical ventilation is often limited for low-income groups in developed countries, and large numbers of people in the developing ones (WHO 2018), thereby reinforcing health inequalities.

3.4 SOCIO-ECONOMIC PERSPECTIVE

Health inequalities are a major challenge in public health (European Public Health Alliance 2019). In the field of environmental health, the term 'triple jeopardy' is used to state that communities with low socio-economic status (SES) face higher exposure to environmental hazards (*e.g.* air pollution), greater susceptibility to poor health, which altogether result in health disparities (Ferguson *et al.* 2021; Hajat *et al.* 2015; Jennings *et al.* 2016). The translation of socio-economic and environmental inequality into health inequality occurs via several mechanisms, among which poor housing conditions (Fuller-Thomson *et al.* 2000; Lawrence 2012; Smit *et al.* 2011; WHO 2018). Low-income dwellers commonly reside in poor-quality neighbourhoods (*e.g.* closeness to major roads or train tracks, limited green spaces; Ferguson *et al.* 2021; Sun *et al.* 2021; Wang & Norbäck 2021) and poor-quality housing (*e.g.* smaller size, insufficient sunlight, poor sound insulation). Such dwellings have been argued to be disproportionality affected by indoor air pollution (Vardoulakis *et al.* 2020), heat (Friel *et al.* 2011), and noise (UNEP *et al.* 2022; Schmit & Lorant 2009). Furthermore, due to significantly greater unemployment rates than in the general population, low SES residents tend to spend more time at home, thereby increasing their exposure to pollution (Ferguson *et al.* 2021). In return, residents with NCDs are more likely to miss work, become unemployed or retire early (Alwan *et al.* 2011). Consequently, low SES dwellers spend a large share of income on rent, trying to minimise it to cover other basic needs (Haines *et al.* 2013).

A growing body of literature has discussed the linkages between poverty, racism, neighbourhood quality and health across different countries, leading to the frequent observation that 'your Zip code determines your health more than your genetic code' (Diez Roux 2001; Frumkin 2021; Ladoy *et al.* 2021; Roux & Mair 2010; Rudolph *et al.* 2013). By using geographical information systems (GIS), empirical studies have added the spatial component to the investigation of the aforementioned linkages, thereby revealing the spatial footprint of health inequalities (Cromley 2003; De Ridder *et al.* 2021; Kihal-Talantikite *et al.* 2019; Ladoy *et al.* 2021). However, exposure to environmental hazards does not solely affect communities with low SES; areas with higher SES have also been associated with high levels of outdoor air pollution and noise (Ferguson *et al.* 2021; Hajat *et al.* 2013; Havard *et al.* 2011; Padilla *et al.* 2014). This result can be explained by the added value that wealthier households attribute to proximity to urban services (transports, amenities). While the cohabitation between low and high SES in urban centres might benefit lower social classes (*i.e.* via increased accessibility to and quality of environmental and health structures; Macintyre *et al.* 2002; Stafford & Marmot 2003), neighbourhood inequalities have been argued to potentially erode local social cohesion and thus social capital, increase the psychosocial stress induced by social comparison, and reduce the affordability of essential services such as housing (Lerch *et al.* 2017; Macintyre *et al.* 2002; Mackenbach *et al.* 2017; Pearce & Smith 2003; Subramanian & Kawachi 2004; Wilkinson 1996). The apparently controversial relationship between housing and health justice mirrors and is mirrored by housing price patterns.

3.5 HOUSING PRICES PERSPECTIVE

The way environmental amenities affect market prices for homes is typically estimated using the hedonic approach (Baranzini *et al.* 2008a). Accordingly, housing prices have been found to decline significantly because of their adjacency to arterial or high-traffic roads, whether due to noise and air pollution or visual impact (Baranzini & Ramirez 2005; Bateman *et al.* 2001; Filippova & Rehm

2009; Lake *et al.* 1998; Łowicki & Piotrowska 2015; Theebe 2004). While the willingness to pay for a reduction in air and noise pollution has been shown to be consistent across housing markets, results can differ between single-family houses and multi-unit properties (Larsen & Blair 2014; Smith & Huang 1995); for instance, a recent study in Copenhagen found prices of single-family houses to be more affected by noise than apartments (von Graevenitz 2018). Such results were explained by the higher value placed on positive traffic externalities (*e.g.* public transportation, shopping), but also by households' unawareness of the health risks associated with traffic noise (Larsen & Blair 2014; von Graevenitz 2018). The layout of the street can also affect residential property value, and beyond; in England, a well-designed street layout was demonstrated to reduce the risk of burglary and robbery, with calculated social cost savings of more than £8000 and £9000 per household, respectively (Space Syntax 2008).

Investments made to provide healthy habitats must therefore account for their potential effects on housing prices, and thus affordability. This is particularly relevant in environmentally sustainable, 'climate friendly' or 'green' projects, which, despite the potential co-benefits for health, have been found to threaten existing residents with displacement, thereby negatively affecting their mental health and wellbeing (Dooling 2009; Jennings *et al.* 2016; Rice *et al.* 2020). Urban planning and policymaking have been called to address these concerns as a means of promoting public health.

3.6 LEGISLATIVE AND URBAN PLANNING PERSPECTIVE

By shaping the HSH interrelations, urban planning, design and management can contribute to a reduction of social and economic and therefore health inequities (Geddes *et al.* 2011; Pineo 2020; Smit *et al.* 2011). Adequate spatial layout and configuration (*e.g.* street visibility and aesthetics, the right balance of residential density, mixity of land use and of housing types) as well as accessibility and affordability of public transports, soft mobility infrastructure, local green spaces, or health services have been demonstrated to have direct and indirect effects on physical and mental health (*e.g.* by reducing environmental threats, encouraging physical activities, creating communities) (Choi *et al.* 2022; Ferguson *et al.* 2021; Foster *et al.* 2020; Friel *et al.* 2011; Giles-Corti *et al.* 2016; Ladoy *et al.* 2021; Martins & Carrilho da Graça 2018; Murage *et al.* 2020; Pineo *et al.* 2020; Sadat & Dehkordi 2022).

The implementation of urban interventions addressing the HSH system is tightly related to the regulations that enact them and the actors who formulate them. In high-income countries such as the ones in this study, building regulations, policies and agendas have been designed to guide large-scale refurbishment programmes, provide acceptable indoor environmental quality and support the lowest SES households; on the contrary, urban areas in low- and medium-income countries struggle to enact the 'most basic' regulations for building form and quality (Rydin *et al.* 2012: 2092). In all these settings, stakeholder empowerment is key; policy processes designed to ensure the participation of citizens' groups can ease the legitimacy of norms and potentially transform demands into standards (de Oliveira *et al.* 2015; Friel *et al.* 2011).

As well as in public participation, multi-stakeholder approaches are also relevant within governments, especially to overcome sectoral barriers (de Oliveira *et al.* 2015). Notably, housing and public health communities have been criticised for rarely working together, therefore missing the opportunity to address their agendas simultaneously (Haines *et al.* 2013). Acknowledging the need to move beyond the siloed thinking of urban governance, the Health in All Policies approach has promoted the integration of transport, housing, infrastructure, land-use legislation and planning (Rudolph *et al.* 2013); such an approach can optimise the use of existing resources and help to avoid unintended consequences (Giles-Corti *et al.* 2016). However, ways to integrate knowledge and explore synergies across the plurality of perspectives specifically addressing the HSH system are still lacking.

4. A SYSTEMIC RESEARCH FRAMEWORK

A growing body of research advocates the benefits of using a systems approach to urban health and wellbeing (Bai *et al.* 2016; Diez Roux 2015; Gatzweiler *et al.* 2017a, 2017b). Such an approach requires looking at the causes and outcomes of health in cities in a transdisciplinary and integrated fashion (Lawrence 2004, 2006; Lawrence & Gatzweiler 2017). Systemic representations make it possible to understand interdependencies across sectors (synergies, trade-offs), integrate various sources of data, and explore the systemic effects of interventions across disciplines (interdisciplinary) and beyond academic boundaries (transdisciplinary) (Bai *et al.* 2016; Gatzweiler *et al.* 2017b).

The CLD shown in Figure 1 organises the elements that shape the HSH interactions as they emerged from the state of the art. Polarity symbols (±) characterise links (*i.e.* arrows) between elements (*i.e.* variables); a positive link indicates a change in the same direction, while a negative link indicates a change in the opposite direction. When cause-and-effect chains amplify what is

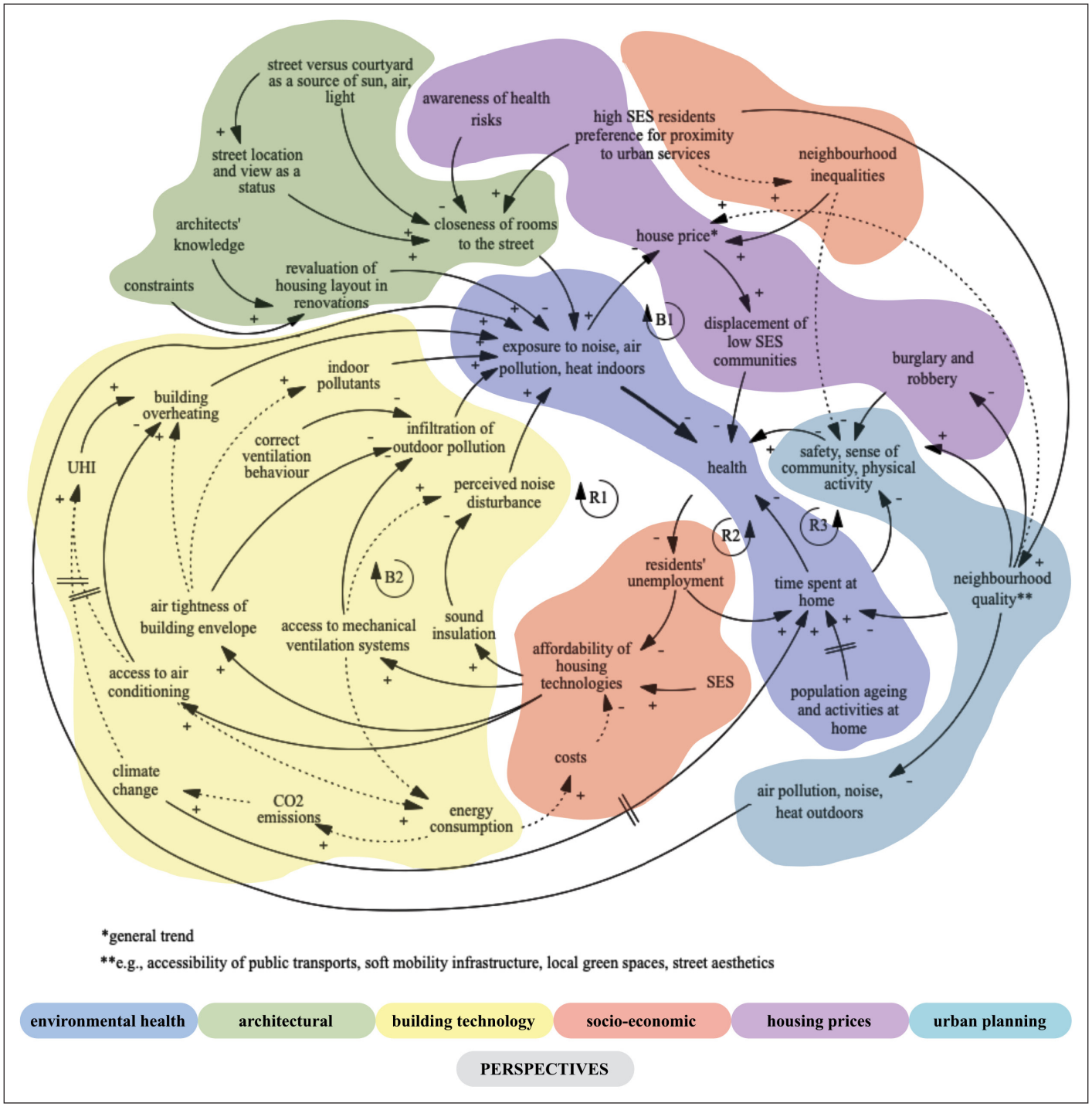

Figure 1: Causal loop diagram (CLD) of housing–street–health (HSH) interactions.

Note: R = reinforcing loops, B = balancing loops. A positive/negative (±) link indicates a change of the variables in the same/opposite direction. Hash marks = delays; dotted lines = unintended consequences; thick lines = stronger interrelations; SES = socio-economic status. Relationships are displayed for illustrative purposes and are not exhaustive.

Source: Authors.

happening in the system, positive or reinforcing loops (R) occur; conversely, negative or balancing loops (B) counteract and oppose change (Meadows 2008; Sterman 2000). Colours in the diagram differentiate the perspectives from which the variables and links are derived.

The CLD puts forward interrelated loops with multidimensional ramifications. For instance, as loop B1 illustrates, measures to reduce exposure to noise, air pollution and heat (via architectural design, building technologies or other urban interventions) can result in higher housing prices, causing low-income residents' displacement, and thus affecting their health. Poor health reduces people's ability to work, and consequently the affordability of and access to building technologies (*e.g.* good airtightness, mechanical ventilation, sound insulation, air-conditioning) that are critical to limit the exposure to environmental threats. As environmental exposure is the leading cause of NCDs, the benefits of declining housing prices on displacement and mental health are outweighed by the effects of loop R1, and consequently R2 and R3, which reinforce diseases via social, economic and technical barriers. Overall, Figure 1 depicts a system that *perpetuates* housing and health injustice; due to the interrelatedness of system variables, any intervention (*e.g.* on neighbourhood quality) can adversely affect low SES residents.

5. IMPLEMENTING THE RESEARCH FRAMEWORK IN THE CONTEXT OF GENEVA

5.1 RESEARCH PATHWAYS FOR A SPATIOTEMPORAL UNDERSTANDING OF HSH INTERACTIONS

Most studies on housing and health have examined relationships between isolated variables at one point in time (Lawrence 2012). However, the interactions between HSH are spatiotemporal dependent. To investigate the housing, street and health dynamics across time and space, a range of data must be collected and analysed.

Figure 2 displays several layers of geographical and temporal data that shape the HSH system through the interactions depicted by the CLD (Figure 1).

The *demographics and health* layer must collect population data in the territory. Recent studies in the city and state of Geneva have combined socio-economic data (or indexes), health data and the reference dataset of Swiss addresses to uncover geographical footprints of a range of diseases, thereby identifying areas of intervention (De Ridder *et al.* 2021; Guessous *et al.* 2014; Ladoy *et al.* 2021). The data came from cross-sectional population-based studies (*e.g.* Bus Santé), hospitals and open-access data (*opendata.swiss*) or were publicly available. In the same vein, other studies used the Swiss National Cohort (SNC) Database, which provides longitudinal individual-level data on the exhaustive population of Switzerland with small-scale geographical information, using death as the ultimate measure of health (Bopp *et al.* 2009; Saucy *et al.* 2021). The SNC provides longitudinal data on residents' SES, key to highlight patterns of health inequality; it has also been linked to samples of the Swiss population that participated in health surveys and medical cohorts.

As explored in Geneva (Fleury *et al.* 2021) and other contexts (*e.g.* Kihal-Talantikite *et al.* 2019; Padilla *et al.* 2014; Tomlinson *et al.* 2011), data on *environmental conditions* are of fundamental importance to the study of urban health; spatiotemporal data on air (NO_2, $PM_{2.5}$, PM_{10}), noise, land pollution and temperature can be retrieved from federal and cantonal offices, the national weather service (MeteoSwiss), as well as through the Information System of the Geneva Territory (SITG), a rich GIS database of the city of Geneva.

Interactions between outdoor pollution and residents' indoor exposure are determined by *housing technologies and architecture*. Since routine measurements of indoor air pollutants in Geneva are still lacking, there is an urgent need to produce data on the effectiveness of several building technologies in limiting perceived and actual pollution levels. Available information on room layout, orientation, outdoor features, renovation date and other housing features must also be included, and should be complemented by research on dwellings' architectural design and history, thus enabling the tracing of the conditions that led to a particular dwelling architecture (*e.g.* see the repertoire collected by Wall Gago 2015 on the residential buildings of the *Ceinture Fazyste*, 1860–1910, in Geneva).

The study of the interactions between housing quality, environmental exposure and affordability—and thus of housing and health justice—needs data on *housing prices* and their evolution over time. Previous studies in Geneva have combined several databases (*e.g.* SITG database, cantonal statistics on rents, Swiss censuses) to examine the impact on rent of noise and air pollution (Baranzini & Ramirez 2005), of views and land use (Baranzini & Schaerer 2011), or tenant level of education and nationality (Baranzini *et al.* 2008b).

Given that rent is not the sole determinant of housing choice, data on *residential satisfaction* must be included. The latter would support the identification of the attractiveness of certain areas and the trade-offs made in choosing a dwelling (*e.g.* proximity to amenities and noise) (Lawrence 2009; Pagani *et al.* 2021).

Finally, the *urban planning and regulations* layer needs to put together information on, for example, building permits (size, height), mobility (traffic speed limits, pedestrian zones), and distances, for example, to green areas, hospitals or the city-centre (Baranzini & Ramirez 2005), available in the SITG digital maps. This data are of primary importance to uncover systemic relations at the urban scale and evaluate the effects of current and future interventions.

Overall, investigating the interrelations within and between layers across space and time would help display the differentiated reciprocal effects between 'some health outcomes, [...] some population groups, and [...] some types of areas' (Macintyre *et al.* 2002: 128) in the city, thereby refining and enriching knowledge of the system linkages shaping the HSH interactions (Figure 1) in the context of Geneva.

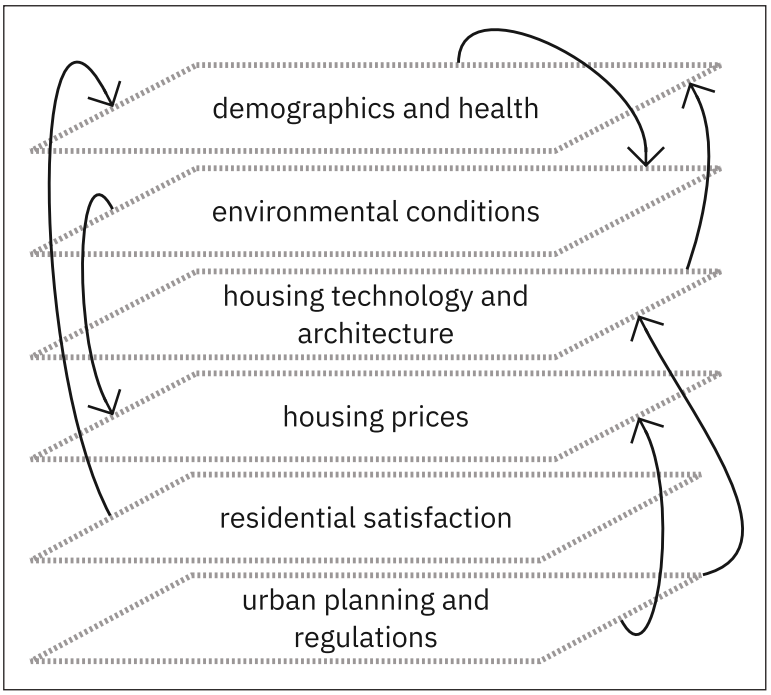

Figure 2: Spatiotemporal layers shaping the housing–street–health (HSH) interactions.

Note: Arrows are used to indicate possible interrelationships, which are detailed in the causal loop diagram (CLD).

Source: Authors.

5.2 PRACTICAL APPLICATIONS OF A SYSTEMIC UNDERSTANDING OF HSH INTERACTIONS

Systemic knowledge about HSH interactions can contribute in many ways to direct public policies and urban development strategies towards health promotion and disease prevention.

First, it would be pivotal to assess, update and implement *synergistically* and *holistically* the existing research agendas elaborated by the canton for 2030, such as the cantonal plan for health promotion and prevention (État de Genève 2017) and the climate action strategy (République et canton de Genève 2021). The former is aimed at promoting health and preventing diseases across lifestyles, paying particular attention to health inequalities. To address the various risk factors associated with the quality of the built environment (*e.g.* air pollution, lack of physical activity), it advocates for urban amenities that encourage physical activity (*e.g.* cycling facilities, pedestrian zones), the

provision of housing adapted to households' needs, green spaces and places of encounter free from environmental nuisance and that promote social cohesion, wellbeing and mental health (État de Genève 2017: 30). The climate action strategy has been designed in the framework of the ecological transition, with the goal to preserve quality of life, health and the environment. In a complementary way to the abovementioned agenda, it cites pedestrianisation as an effective way to address the challenges of a warming climate for a sedentary population, while achieving net zero targets (République et canton de Genève 2021: 90, 95). Within this framework, the proposed approach would help to go beyond the at-present-siloed considerations of outdoor health and indoor health, and design indicators and policies at the interface of, for example, indoor comfort and health, architectural and urban forms of the street, accessibility to and from a variety of locations (*i.e.* the 15-Minute City; Allam *et al.* 2022). Moreover, it would contribute to shedding light on a system that disproportionately impacts the health of the most vulnerable households, supporting ongoing reflections on the unintended consequences of actions aimed at promoting health via urban and housing improvements (*e.g.* green gentrification; Quinton *et al.* 2022).

Besides, the analysis of the HSH interactions across different spatiotemporal data layers would make it possible to map the several interconnected dimensions of 'health' of a given territory; the resulting findings would offer tangible contribution to the formulation of territorial diagnoses, which help to identify the strengths, weaknesses, opportunities and challenges faced by a given region, and support decision-making aimed at improving quality of life (*e.g.* De Ridder *et al.* 2019; Joost *et al.* 2017).

Finally, such an integrative understanding would help to create a common ground between researchers and stakeholders acting at different scales and within different fields of expertise. In doing so, it would raise the awareness of policymakers, urban planners, architects and residents about the risks and opportunities for health embedded in the relationships between a range of factors (*e.g.* housing layout and its orientation toward the street), beyond what is currently considered in, for instance, renovation strategies (*i.e.* energy efficiency, heritage protection, fire regulations, sound insulation).

6. MOVING FORWARD: DISCUSSION AND CONCLUSIONS

This paper addressed the need to go beyond the siloed knowledge and approaches to the study of housing, street and health (HSH) in cities. It demonstrated how a systems approach can support the integration of existing perspectives which have thus far partially investigated HSH interactions. By visually displaying the state of the art across several fields, the proposed system representation can support the construction of research agendas (*e.g.* via the detection of data gaps or interrelationships needing further inquiry) and frame a holistic interpretation of research findings.

It must be considered, however, that the proposed causal loop diagram (CLD) does not aim to provide an exhaustive picture of HSH relations, but rather outlines ways to approach inter- and transdisciplinary enquiries of the system. For example, to account for the central role of the environmental, social and cultural settings in shaping HSH interactions, the literature screened was narrowed down predominantly to the European urban context; the system represented may vary considerably when investigating other geographical and urban settings (*e.g.* slums, new developments across continents). Also, the narrative literature review supporting the design of the CLD relied on the expertise of each author in their disciplinary field and is thus subject to bias (Sovacool *et al.* 2018). As the system boundaries are drawn based on the field and number of researchers taking part in the process, several topics were inevitably overlooked, such as the effects of occupant behaviour (on ventilation behaviour, indoor pollutant sources; *e.g.* Yang *et al.* 2020), the effects of housing supply shortage on housing choice (Karlen *et al.* 2022), or homelessness and climate change (Ramin & Svoboda 2009). Beyond involving a larger panel of experts, meta-narrative (Kim *et al.* 2021; Wong *et al.* 2013), scoping or systematic reviews (Namatovu & Semwanga 2020; Singh *et al.* 2021) can help to obtain a broader and sharper picture of HSH relations. However, special attention should be paid to the nature of the identified linkages (*e.g.* correlation, causation) and how they are extracted (*e.g.* Cassidy *et al.* 2022; Eker & Zimmermann 2016; Kim & Andersen 2012). Moreover, the construction and validation of the CLD would benefit from the engagement

of non-research stakeholders in the elicitation of variables and interrelationships as well as in the generation of data for spatiotemporal analyses (*e.g.* community based or participatory system dynamics; Hovmand 2014; Macmillan *et al.* 2016).

Overall, this paper illustrated how the integration of systemic, transdisciplinary and spatiotemporal approaches would benefit research and practice in many ways.

From a research perspective, the proposed research framework can guide engagement in collaboration and partnerships across and beyond disciplines, providing opportunities to build and address existing research agendas simultaneously. More specifically, it would help formulate and answer research questions related to (1) the structure of the multidimensional and multi-scalar HSH interrelationships; (2) their evolution over time and space; and (3) the effects of potential urban and public health interventions.

From a practitioner's viewpoint, the proposed approach would make it possible to map the *health of our cities*, thereby (1) enabling the creation of common ground for dialogue among different stakeholders in policymaking processes at different scales (*i.e.* municipality, city, state); (2) raising public awareness about the risks and opportunities related to HSH interactions; and (3) supporting the implementation of existing research agendas via the design of interventions based on a holistic understanding of the several issues that need to be addressed.

NOTE

1 In this context, the 'street' is used as a category comprising a wide range of spaces, *e.g.* lanes, alleys, avenues, boulevards and piazza (Marshall 2004b).

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AUTHOR CONTRIBUTIONS

The paper was conceptualised by AP and DC. AP coordinated the collaboration between the co-authors, designed the causal loop diagram (CLD), drafted the paper, reviewed and edited the manuscript, and acquired the Swiss National Science Foundation (SNSF) funding. DC, VB, SJ, CWG, DL, ML, CR and IG identified key references in their research fields, provided input on research pathways and practical applications of the framework, and commented/edited the manuscript and the CLD. PV acquired the Habitat Research Center (HRC) funding. All authors have read and agreed to the published version of the manuscript.

COMPETING INTERESTS

The authors have no competing interests to declare.

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