Understanding obesity-related behaviors in youth from a systems dynamics perspective: The use of causal loop diagrams

Wilma E. Waterlander1 | Amika Singh2,3 | Teatske Altenburg2 | Coosje Dijkstra4 | Angie Luna Pinzon1 | Manou Anselma2 | Vincent Busch5 | Lieke van Houtum5 | Helga Emke2 | Meredith L. Overman6 | Mai J.M. Chinapaw2 | Karien Stronks1

Summary
This paper reports how we applied systems dynamics methods to gain insight into the complexity of obesity-related behaviors in youth, including diet, physical activity, sedentary behavior, and sleep, by integrating a literature review into causal loop diagrams (CLDs). Results showed that the CLDs consisted of multiple subsystems and three types of dynamics appeared, including (1) feedback loops, (2) connections between feedback loops and subsystems, and (3) mechanisms. We observed clear similarities in the dynamics for the four behaviors in that they relate to “traditional” subsystems, such as home and school environments, as well as to newly added subsystems, including macroeconomics, social welfare, and urban systems. The CLDs provided insights that can support the development of intervention strategies, including (1) the confirmation that a range of mechanisms cover and connect multiple levels and settings, meaning that there is no silver bullet to address obesity; (2) understanding of how interventions in one particular setting, such as school, might be influenced by the interactions with other settings, such as urban systems; and (3) a comprehensive view of (un)intended consequences. This way of framing the problem will assist moving towards public health interventions that respond to and operate in the complexity of the real world.

KEYWORDS
adolescents, causal loop diagrams, obesity, systems dynamics
1 | INTRODUCTION

Despite continuous and growing efforts to reduce the burden of childhood overweight and obesity, we see disappointing results, where not a single country has successfully halted the obesity epidemic in the general population to date. One explanation for this lack of progress is that most existing approaches, although multicomponent, focus on causes of obesity directly related to unhealthy behaviors, such as (lack of) health knowledge, attitudes towards health behavior, or unhealthy school environments. Most programs do not take into account the complexity of the problem, including underlying mechanisms (causes of the causes) that drive these unhealthy behaviors such as stress, peer pressure, or the political environment nor do they take into account dynamic properties, including feedback and adaptation in response to changes (i.e., interventions) in the system.

A recent overview of reviews covering 13 systematic reviews of interventions aimed at preventing overweight and obesity in adolescents concludes that the evidence base for the effectiveness of current interventions is weak, in particular because the vast majority of included interventions target the individual and are set in schools with a lack of structural and environmental interventions applied in the wider society. For example, a cluster randomized controlled trial evaluating a school-based obesity prevention intervention showed no significant intervention effects, despite a theoretically informed and extensively piloted intervention that achieved high levels of engagement, follow-up, and fidelity of delivery. The authors conclude that school-based interventions alone might not be sufficiently powerful to affect all relevant environments of an adolescent’s life and that therefore future programs should address the full complexity of the problem by using whole-of-systems approaches.

The lack of a detectable and/or sustainable impact of many public health interventions aligns with the conceptualization of overweight and obesity as a complex problem: the drivers are multiple, diverse, and dynamic, ranging from biological factors and personal behaviors to aspects of the physical, economic, sociocultural, and political environments that shape those drivers. Systems thinking is acknowledged to be particularly useful in understanding the complexity of public health problems. Although there is a growing body of literature on applying systems thinking in public health research, there is still relatively little guidance on how to create an understanding of systems dynamics and design and evaluate public health interventions in complex systems. It is therefore important to expand the evidence base on how systems methodologies can be applied and on what the practical value of systems thinking can be in public health research. Within systems approaches, systems dynamics has shown itself particularly useful in understanding the complexity of public health problems. One specific tool within systems dynamics is the use of causal loop diagrams (CLDs) to explore the multiple, interacting feedback loops operating in a system of interest. CLDs provide a visual image of an issue and are appropriate for use in explorative studies, because they are easier to build and understand and have fewer data and resource requirements than quantitative simulation models.

The aim of this study is to apply systems dynamics methods to gain insights into the complexity of obesity-related behaviors. We report on how we applied systems dynamics methods and on the extent to which this led to new understandings of the problem and its underlying dynamics.

2 | METHODS

2.1 | LIKE project

The results presented in this paper are part of a larger program entitled Lifestyle Innovations Based on Youth Knowledge and Experience (LIKE). LIKE combines systems dynamics and participatory action research to develop, implement, and evaluate a dynamic action program focused on promoting healthy lifestyle habits in young adolescents in the transition from tween to teen (aged 10 to 14). LIKE is embedded in the Amsterdam Healthy Weight Programme (AHWP) and is situated in three lower socioeconomic neighborhoods in Amsterdam (Netherlands).

The first part of the LIKE program seeks an understanding of preexisting systems that shape unhealthy lifestyle behaviors by conducting an in-depth needs assessment. Here, we aim to gain insight into the system from two different perspectives: the stakeholders’ perspective that provides an inside view of the system and the researchers’ perspective that provides a more outside view of the system, by building on existing evidence and interpreting the inside perspective. The different methods employed to gain insight into these perspectives are explained elsewhere. The current paper presents the results already achieved in terms of understanding the system from the outside perspective through the use of CLDs developed by academic experts within the LIKE program.

2.2 | Literature review from a complexity perspective

The general aim of this study was to gain insight into the complexity of obesity-related behaviors. Petticrew et al. describe methodological implications of such a complexity perspective for the conduct of systematic reviews, which we applied in our study design. For this purpose, we combined conventional approaches to systematic database searching to retrieve all relevant determinants with guidance around developing systems-based reviews to gain insight into system dynamic properties. In particular, our systems approach meant formulating an explanatory research question around deepening an understanding of relevant system dynamics (i.e., the mechanistic relationship between determinants through interaction and feedback), adopting a pluralist approach to study selection by study design and evidence type, and creating data extraction and presentation processes (i.e., CLDs) that allowed us to elucidate system properties. The exact procedures are detailed below.
2.3 | Procedures

We set up a six-step approach for developing the CLDs. The central aim was to identify factors that could explain the increase in childhood obesity rates in the Netherlands in the past two decades. We further operationalized the research aim by focusing on four types of behaviors that are particularly relevant to childhood obesity and are the focus of the AHWP including dietary behavior, physical activity (PA), sedentary behavior, and sleep, although the evidence on the direct link between the latter two behaviors and obesity is less consistent.²¹,²² Hence, the primary question for a CLD was: “What factors explain the dynamics in dietary behaviors, physical activity, sedentary behavior, and sleep, in the Netherlands in the past two decades?” We followed the six steps described below for each of the four behavior types; however, it should be noted that—by nature of principles of complexity—this was not always a linear process but rather iterative, in particular in Step 3 (see details below).

Step 1: Establishing CLD working groups

We established four working groups to lead the CLD development, one group for each behavior. Each group consisted of at least three academic researchers with expertise on that specific behavior. Representatives from each working group met regularly to monitor progress and to coordinate the methods across groups. Where needed, working groups reached out for additional support from academic colleagues during various phases of the CLD building process, including the literature selection as specified in the next step.

Step 2: Extracting determinants from the literature

Prior to the first meeting, two to three members of each working group conducted a pragmatic literature search using conventional methods of database searching (in PubMed) with a focus on systematic reviews supplemented with empirical studies (both qualitative and quantitative) on determinants of the specified behaviors. In addition, academic colleagues were asked to share systematic reviews they considered most relevant. The aim of this literature search was not to identify all possible determinants but rather to confirm the most important ones (see also Step 3). From this literature selection, one or two members of the group extracted all named determinants and grouped these into six broad categories to facilitate checking for completeness: behavioral, psychological, sociocultural, socioeconomic, policy, and physical environment. At the first meeting, each group reviewed the identified determinants and critically discussed the relevance for our target group (early adolescents) and our setting (urban setting in Amsterdam). For example, determinants relating to food deserts or lack of public transport were excluded, because those were not relevant to our setting as Amsterdam has a very dense availability of supermarkets with no profound inequalities in access between neighborhoods²³ as well as a high-quality public transport system (trams, metro, and busses). This resulted in a longlist of determinants for each behavior (see Appendix A).

Step 3: From variables to connections

Once we had all longlists of variables, we had a joint meeting with all working groups to start drawing connections between the variables (see Step 4 for details about drawing these connections). The initial maps that resulted from this exercise were reviewed by authors WW, AS, TA, CD, ALP, and KS and an external expert with long-standing expertise in systems dynamics methods. During this review process, it became apparent that groups struggled to draw connections between variables based on system dynamic principles, including considering nonlinear relationships, accumulation, feedback loops, effects of time delay, and unintended consequences.²⁴ This struggle particularly related to the fact that most studies in our literature selection (Step 2) examined the association between a (sub-) behavior and a single factor, with the association being unidirectional (from determinant to behavior). Therefore, when drawing connections, this resulted in all factors pointing at these sub-behaviors, with minimal interconnections between factors (in systems dynamics terms known as a “dead buffalo”). To solve this result, we specified five requirements to aid in creating an understanding in relevant system dynamic properties rather than creating a mind map with many connections.

The first, and arguably the most important, requirement related to excluding the main sub-behaviors from the CLDs, because undoubtedly, all factors would relate to that behavior, and instead, we tailored each CLD to the most relevant sub-behavior for our target group and setting. This tailoring was not only needed to avoid all determinants pointing to these sub-behaviors but also because the initial four behaviors were too broad and could be associated with too many determinants. For example, dietary behavior is relatively complex in itself, and the working group identified five sub-behaviors, including consuming a healthy breakfast, healthy lunch, healthy dinner, unhealthy snacks, and sugar-sweetened beverages (SSBs). From these sub-behaviors, we selected the one that we considered of greatest relevance to obesity prevention in our target group, being “frequent unhealthy snacking (including fast food, snacks, and SSBs)” and focused the CLD on that specific sub-behavior. A similar approach was taken for the other behaviors. They were framed as

1. dietary behavior: unhealthy snacking (as specified above);
2. PA: active transportation and outdoor active play (specified from four identified sub-behaviors based on the contribution to energy expenditure, including active transport, PA at/around school, organized PA, and unorganized PA);
3. sedentary behavior: leisure time screen use (we considered this behavior more relevant for overweight prevention than, e.g., sitting while reading or using a screen for academic activities. We further specified four time frames: [1] during recess; [2] after school; [3] during the night; and [4] during weekend days); and
4. sleep: sleep duration, sleep quality, and sleep routine (we defined healthy sleep behavior as the combination of adequate sleep duration, good sleep quality, and regular sleep timing). This meant that we included “sleeping sufficiently” (sleep duration), “sleep onset
a. Dynamic properties: An important concept in systems dynamics is initial properties included in every CLD: following four requirements to identify factors from the longlists to be initially included in every CLD:

b. Causal relationship: Causal thinking is a key construct in developing CLDs, which includes direct causation but also influence or affect (a influences b); however, it doesn't include association.

c. Importance or relevance: When building a CLD, it helps to focus on the most important determinants, rather than all possible determinants. While including all variables might be more precise, it doesn't aid in gaining insights into underlying dynamics because there is a risk of including many determinants that mean more or less the same (e.g., accessibility or visibility of unhealthy food) and therefore ending up with many (irrelevant) connections between those variables. Therefore, we initially set a rough guide of including the approximately 20 most relevant factors. This selection was done during a meeting within each working group, where there is little much discussion between group members about the inclusion or exclusion of determinants, partly because sometimes different determinants could be grouped together (e.g., recess exercise and extracurricular PA during weekend were joined into alternatives for sedentary behavior) and also because it was still possible to re-add determinants in the final step (see (d) below) and/or in the following stages of the CLD building process (e.g., Step 4).

d. Check for completeness: Once all factors were selected, we verified whether additional factors were needed to complete the CLD in a joint meeting with (representatives from) each CLD working group. This resulted in a shortlist of factors for each behavior.

Step 4: Drawing the connection circle

The shortlisted factors were included in a connection circle, using STICK-E software (STICK-E Version 2, © Deakin University). The connection circle was used to examine all possible connections between factors and their polarity. A positive polarity indicated positive causation (as a cause increases, the effect increases; as a cause decreases, the effect decreases). A negative polarity indicated inverse causation (as a cause increases, the effect decreases; as a cause decreases, the effect increases). At this stage, we also checked variable names because the exact formulation had to align with the properties of systems dynamics maps. For example, variables should be formulated neutral (e.g., knowledge) rather than in a specific direction (increased knowledge) because a “decrease in increased knowledge” is confusing. Also, variables should represent a factor that is quantifiable and can change over time, for example, “happiness” rather than “state of mind.” We also specifically avoided drawing too many connections, which would have made the CLD unreadable, by removing duplicate connections running via direct and indirect pathways. For example, increased marketing of unhealthy food leads to increased availability of unhealthy food (i.e., more marketing = more sales = more availability), which leads to increased accessibility of unhealthy food. However, increased marketing might also show a direct link to accessibility (e.g., being able to order fast food by clicking on an advertisement in a social media feed). The latter connection was removed, because it is more likely that this association would be mediated via availability rather than existing via direct causation.

Step 5: Developing the CLDs

Once all connections were identified, we moved the connection circle to the diagram view in STICK-E, revealing the CLD (see Figure 1A–D). We again reviewed all connections to make sure they were correct. We also checked whether additional factors needed to be included in the CLDs, in particular because certain causations operate through mediating factors that could not be identified from the literature. For example, the factor “use of social media by youth” has an impact on “screen use in peers,” but there is likely an addictive effect of social media involved, a factor that was not identified via the literature search. The missing factor was then added to the CLD after discussion within the working group, including a check on the set requirements (i.e., dynamic properties, causal relationship, importance, or relevance) and where needed also checked again in the literature. Once the CLDs were completed, they were sent to academic experts linked to the LIKE project who were not directly involved in the CLD building process to critically review and comment on the completeness, missing links between factors and sub-behaviors, missing links between determinants, correctness of links between factors and sub-behaviors, and fit to the target group and setting, that is, 10–14-year-olds from a disadvantaged neighborhood in Amsterdam.

Step 6: Interpreting the CLDs

At this stage, the CLDs read like a map of factors with connecting arrows rather than a systems dynamics map. The next step therefore involved interpreting the CLD, including an unraveling of the underlying systems dynamics. For that purpose, we exported the CLDs to Vensim (PLE 8.0.9) and used the feedback loops function to identify reinforcing and balancing feedback loops. The resulting loops were used to understand mechanisms, subsystems, and connections between subsystems.

3 | RESULTS

The longlists of factors identified from the literature, the selected factors for each CLD, and the factors that were added during the CLD
building process are displayed in Appendix A. The longlists and the final CLDs consisted of 55 and 28 factors for dietary behavior, 58 and 19 for screen use, 47 and 20 for PA, and 30 and 13 for sleep, respectively.

Figure 1A–D shows the final CLDs that were developed in the process, and Table 1 describes the observed dynamics within those CLDs. The numbered squares in the CLD indicate the subsystems involved (see Table 1 for labels). A first observation is that the resulting CLDs for each behavior consisted of multiple subsystems, whereby clear similarities emerged in subsystem types between the four CLDs. For all behaviors, we found subsystems relating to determinants that are typically included in empirical research, such as home environment, school environment, and social factors. However, we also found determinants relating to subsystems generally not included in empirical research, including macroeconomics, social welfare, technology, and urban systems. A second observation is that three types of dynamics appeared within and between these subsystems, including (1) feedback loops (i.e., a chain of connected variables that continue to re-affect themselves, which can be reinforcing or balancing) and (2) connections between feedback loops and between subsystems (i.e., through variables that are included in multiple feedback loops). These could subsequently be used to describe (3) mechanisms in the system (i.e., using subsystems and feedback loops to organize ideas in the system).

First of all, with regard to feedback loops, we found 11 loops in the unhealthy snacking CLD, eight in the PA, nine in the sleep, and seven in the screen use CLD. Important to note is that we mostly found reinforcing feedback loops that would strengthen the unhealthy behavior dynamics, as opposed to balancing loops that would counteract those dynamics, except for the PA CLD where it was the other way around. This latter effect is most likely because the sub-behaviors in this CLD (i.e., active transportation and outdoor active play) were framed the other way around (positive for health) as opposed to the sub-behaviors in the other CLDs (framed as negative for health). Looking at the feedback loops in more detail, in the unhealthy snacking CLD, we found reinforcing feedback loops relating to revenue and marketing of unhealthy food, household food budgets, and social norms towards unhealthy food. The balancing feedback loops in this CLD related to a decrease in peer pressure to eat unhealthy snacks, which resulted from school food policies that limit availability and exposure to unhealthy food. In the sleep CLD, we observed many interrelating feedback loops in particular with regard to the various determinants of sleep quality including presleep worries, presleep alertness, and wake up after sleep onset. Because these variables interrelate with each other and all can be individually linked to factors such as stress and screen use, we observed many feedback loops that also interrelated with each other; for example, screen use leads to more presleep alertness that leads to more waking up after sleep, which leads to more screen use. In the PA and screen use CLDs, we observed in particular many feedback relating to social norms, where, for example, social norm towards walking/cycling affects perceived safety that affects walking/cycling, which in turn affects social norm
(fewer cyclists on the street). With regard to screen use, we found that all feedback loops operated through either social norm or the 24/7 availability of technology and related revenues and peer pressure.

Second, with regard to connections, we found multiple connections between subsystems. An example of this multiplicity was found in the influence of macroeconomic factors such as poverty or the price of unhealthy food upon factors relating to the home setting. Also, we found dynamic connections between the four behavior types. Notably, screen use was included in all CLDs, as it linked to sleep, unhealthy snacking, and PA. For example, in the PA CLD, the various options for sedentary behavior (including screen use) lead to less outdoor play.

Third, from the feedback loops, subsystems, and connections that came to light in the CLDs, we were able to identify several mechanisms—where “mechanism” is defined as a segment of a larger process in the system. We found three to five such mechanisms in each CLD. Mechanisms generally included a combination of different feedback loops, and they provided a qualitative description of what we observed in the CLD. In the sleep CLD, for instance, we identified a mechanism relating to adolescents' brain development and sleep; it showed that adolescents are still in the developmental phase, which involves learning to plan and foresee medium- or long-term consequences of choices. They therefore have difficulties in efficiently planning their homework and getting their homework done during the day. The pressure to perform at school leads to more evening homework activities, presleep worries, mental alertness, and hence, later bedtimes. This creates more tiredness during the day, hampering school performance and strengthening the vicious circle. In the screen use CLD, we found that the 24/7 availability of technologies resulted in an increased use of social media, online and other digital games, and passive media such as Netflix. The use of such media also has an addictive effect that further fuels screen use. Additionally, social pressure among adolescents fosters anxiety of being left out (fear of missing out [FOMO]), and FOMO further intensifies screen use. Clear connections also emerged between screen use and sleep, further revealing how the different mechanisms interrelate.

4 | DISCUSSION

4.1 | Principal findings

By highlighting the system dynamics underlying the obesity-related behaviors in question, the CLDs presented in this paper bring new insights to existing conceptual models on determinants of dietary behavior, PA, sedentary behavior, and sleep in adolescents. Most of the current literature focuses on single determinants directly related to the behaviors studied, possibly implying that associations or relationships between determinants and behaviors are linear and form an important explanation for the presence or absence of that behavior. By integrating the existing literature and expert views into CLDs, we were able to generate a holistic and dynamic perspective on the lifestyle behaviors in question. We did so by drawing connections
between factors and subsystems and by qualitatively interpreting the mechanisms that arose from the observed dynamics in the CLDs. The CLDs confirm that there are many interrelating factors explaining obesity-related health behaviors and that there are powerful dynamics underlying these determinants that are generally not emerging from observational or intervention studies. Although those dynamics vary slightly between the four studied behaviors, we observed clear similarities in that they relate both to “traditional” subsystems, such as the home and school environment, and to newly added subsystems, including macroeconomic and microeconomic systems, social welfare, technology, and urban systems.

4.2 Reflections on the most important findings

The Foresight Obesity Systems Map was the first conceptual model to show obesity as a consequence of complex adaptive systems; however, this map still has a structure centered on the individual rather than focusing on underlying systems dynamics. An important observation from the CLDs is the appearance of numerous reinforcing feedback loops that could strengthen the unhealthy behaviors and only a few balancing loops that could support the healthier alternative. Moreover, the reinforcing feedback loops were generally linked to higher level subsystems (such as macroeconomic or urban systems), in contrast to the balancing feedback loops, which were observed in home settings or school systems. An explanation for this finding could be that the main question in our study was framed in terms of factors that could explain the recent increase in childhood obesity rates—a question that logically leads to causal relationships that strengthen the outcome as opposed to balancing it. Indeed, in the PA CLD, where the sub-behaviors were framed the other way around, we found more balancing as opposed to reinforcing feedback loops. In future studies, it will therefore be important to deliberately specify the question in all relevant directions by focusing on factors that form a risk factor as well as factors that protect from obesity-related behaviors.

We observed that the balancing feedback loops found in our CLDs generally related to some kind of intervention (e.g., school food rules and rules around screen use) but also that these balancing loops were linked to counteracting subsystems such as social pressure to use screens or food prices of unhealthy food. This finding illustrates that using CLDs and searching for balancing feedback loops could be a promising approach to develop intervention strategies because it aids looking beyond specific settings and behaviors, thus providing a more holistic view of potential consequences, intended or unintended. For example, from the CLDs, it became clear that although interventions in home or school settings might be effective in changing behaviors in one particular setting, the interactions with macroeconomic and urban systems make those effects hard to maintain in the “real” world. This was also observed in a recent study by Ram and colleagues who conducted a natural experiment examining the effect on...
mental health outcomes when people relocated to a new, more favorable neighborhood. Although participants, in comparison with controls, now lived closer to parks and in more walkable areas, had better access to public transport, and showed marked improvements in their neighborhood perceptions, there was no overall effect on mental health and well-being outcomes. The authors conclude that changes in the built environment alone are unlikely to produce detectable improvements in mental health and well-being. The CLDs that we developed within the current study support this view that a focus on a single mechanism has insufficient power to achieve substantial and sustainable change in the system. A range of mechanisms cover and connect multiple levels and settings. For example, unhealthy sleep hygiene at home may be a result of societal pressure to perform at school, leading to tiredness at school. Therefore, addressing a part of that chain, such as exclusively focusing on the home setting, is unlikely to effectively tackle unhealthy sleeping behavior in adolescents. There is no silver bullet to address obesity, and multiple actions will likely be needed to effect sustainable changes where it is crucial to move beyond promoting the narrow public health benefits of prevention interventions and show that a more paradigmatic shift would have a multiplicity of sustained benefits across sectors including the economy and environment. A key observation reflecting this observation in our study is the central position of screen use in the CLDs. It revealed the ways in which screen use connects dietary behavior, PA, and sleep—with more screen use leading to more unhealthy snacking, less PA, and lower sleep quality, whereas the latter again led to more snacking and less PA. This finding underlines the importance of addressing multiple behaviors simultaneously when promoting obesity-related behaviors in adolescents.

However, developing intervention strategies that target different levels of the system is not easy. An important dynamic for such strategies relates to group-level processes, including social norms. Social norms, such as norms about PA, dietary behavior, or screen use, shape individual behavior. Adolescents’ individual behavior, in turn, also affects what is perceived as normal by other adolescents, thus impacting such behaviors of their peers. Our CLDs on screen use and PA in particular suggest that feedback via social norm can be very powerful as it explained the majority of the identified feedback loops. It thereby underlines the importance of actions focusing on group-level determinants, such as social norms with respect to “normative physical activity,” in order to effectively promote healthy energy-related behaviors. Of course, social norm is a complex construct itself, heavily influenced by, for example, social media, marketing, and policy that emerged out of a paradigm that values free market principles (e.g., weak industry self-regulation rather than strict policies), which again all should (and can) be considered when using systems models to understand health-related behaviors. Crielaard et al. show how systems dynamics modeling can be used to further unpack the influence of social norm on obesity by simulating the system’s emergent behavior.
| CLD               | Subsystems                              | Feedback loops                                                                 | Mechanisms                                                                                                                                                                                                 |
|------------------|-----------------------------------------|-------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Diet             | 1. Food prices                          | R1/R2: Price of unhealthy food – household budget spent on unhealthy food – revenue – price of food processing – price of unhealthy food | Higher availability of unhealthy snacks decreases the price of unhealthy snacks, which increases accessibility of unhealthy snacks. This leads to more revenue, which leads to more marketing, and then to a higher availability. A lower price of unhealthy snacks increases the amount of the household budget spent on unhealthy snacks and drinks. |
|                  |                                         | R3/R4: Price of unhealthy food – accessibility of unhealthy food – household budget spent on unhealthy food – revenue – price of food processing – price of unhealthy food |                                                                                                                                                                                                            |
|                  | 2. Peer pressure                        | R5: Exposure to unhealthy food marketing (on social media) – peer pressure to eat unhealthy – accessibility of unhealthy food – revenue – exposure to unhealthy food marketing (on social media) | Accessibility to unhealthy snacks and exposure to unhealthy snack marketing lead to peer pressure to eat unhealthy snacks, which lead to a positive attitude and normalization of unhealthy snacks. School food rules can balance the accessibility of unhealthy snacks and in turn also limit peer pressure. |
|                  |                                         | R7: Boredom/hanging together – screen time – unhealthy sleep behavior – boredom/ hanging together | Boredom and hanging out together increases sedentary behavior and increases screen time. Increased screen time leads to an increase in unhealthy sleep behavior, which will lead to more boredom/hanging together because the adolescents are tired. Hanging together also leads to an increase in eating unhealthy snacks as a social activity (LINK to screen use/sleep). |
|                  |                                         | R1: School food rules – eating as a social activity – peer pressure to eat unhealthy – school food rules | School food rules can balance the accessibility of unhealthy snacks and in turn also limit peer pressure.                                                                                                                                                  |
|                  |                                         | R2: School food rules – accessibility of unhealthy food – peer pressure to eat unhealthy – school food rules | School food rules can balance the accessibility of unhealthy snacks and in turn also limit peer pressure.                                                                                                                                                  |
|                  | 3. Traditional eating patterns          | R6: Normalization of the consumption of unhealthy food – fading of traditional eating patterns – frequency of eating moments | Normalization of unhealthy snacking leads to the fading of traditional eating patterns and to an increase of eating moments during a day; this again will lead to a normalization of unhealthy eating and so forth. |
|                  | 4. Poverty                              | R8: Length work hours – available time – stress – household food budget spent on unhealthy food – health – poverty – length work hours | Length and inflexibility of work hours leads to stress and less available time, which leads to increased household budget spent on unhealthy snacks, which leads to less health and more poverty (i.e., less income) and again leads to more length and inflexibility of work hours and so forth. |
| Physical activity| 1. Physical capabilities                | R1: Motor skills – confidence to participate in outdoor active play – enjoyment in participating in outdoor active play – motor skills | More outdoor active play leads to better motor skills and fitness, which makes youth more confident and increases the enjoyment in outdoor active play. This in turn increases chances of children to participate in outdoor active play, partly through better developed imagination (youth learn to know more games they can play). |
|                  | 2. Social norm                          | R2: Attractive environment for PA – imagination for outdoor active play – enjoyment in participating in outdoor active play – outdoor active play/active transport peers – social norm – safety outdoor active play/active transport environment (child perceived) – attractive environment for PA | Having more PA equipment and materials available—which can be stimulated by local government policies and parents—leads to an attractive PA environment and through that more active transport/outdoor active play. Parents will stimulate youths’ outdoor active play/active transport, when they perceive the environment as safe and attractive and if it is regarded as “normal” (social norm). |
|                  |                                         | R3: Attractive environment for PA – outdoor active play/active transport peers – social norm – safety outdoor active play/active transport environment (child perceived) – attractive environment for PA | If there are more options to spend time sedentary, the social norm related to outdoor active play/active transport changes, resulting in less children playing and being outside. For parents, it has also become easier to let |

(Continues)
### TABLE 1 (Continued)

| CLD   | Subsystems                                                                 | Feedback loops                                                                                                                                                                                                                                                                                                                                 | Mechanisms                                                                                                                                                                                                 |
|-------|----------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|       |                                                                            | B3: Options for sedentary activities – outdoor active play/active transport peers – social norm – safety outdoor active play/active transport environment (parent perceived) – parenting practices stimulating outdoor active play/active transport – options for sedentary activities                       | children participate in sedentary activities (LINK to screen use).                                                                                                                                                                                                 |
|       |                                                                            | B1/B2: Safety outdoor active play/active transport environment (parent perceived) – parenting practices stimulating outdoor active play/active transport – social norm – safety outdoor active play/active transport environment (parent perceived) | A perceived (more) unsafe environment leads to more parents choosing for their kids to use public transport rather than cycling/walking. This changes the social norm regarding cycling/walking and again influences perceived safety of the environment. This is also influenced by the availability of money for public transport in youth. |
|       |                                                                            | B4: Available money for public transport – use of public transport – social norm outdoor active play/active transport – safety outdoor active play/active transport environment (parent perceived) – parenting practices stimulating outdoor active play/active transport – available money for public transport |                                                                                                                                                                                                               |
|       |                                                                            | B5: Traffic density – neighborhood deprivation – amount of green/blue space – traffic density                                                                                                                                                                                                                                               | More urbanization leads to increased traffic density, which results in children and parents experiencing the environment as less safe. An attractive PA environment (e.g., amount of blue/green space, safe environment, and attractive opportunities to play outside) can positively influence outdoor active play and inhibit youths' use of alternative sedentary options. |
| Sleep | 1. Screen use                                                              | R1: Screen use – evening snacking and caffeine use – presleep alertness – screen use                                                                                                                                                                                                                                                                                                    | Screen use in the evening creates more presleep arousal and mental alertness due to interaction with others via (social) media. This in turn leads to more worrying, for example, via fear of missing out and wanting to fit in, which leads to later bed times and staying up late when finally lying in bed. In bed, the screen (mobile, tablet) often tags along, where it keeps providing cues to check and keep using the screen until late hours. |
|       |                                                                            | R2: Screen use – evening snacking and caffeine use – presleep alertness – wake up after sleep onset – screen use                                                                                                                                                                                                                                                                  | Caffeine use creates more presleep arousal and mental alertness, which causes youth to go to bed later as well as impairs their quality of sleep. In turn, this leads to more daytime sleepiness, again more caffeine use, and daytime napping. This mechanism is strengthened by the dominant peer norms that it is cool to drink caffeinated energy drinks and go to bed very late. |
|       |                                                                            | R3: Screen use – FOMO – presleep worrying – presleep alertness – screen use                                                                                                                                                                                                                                                                                                     |                                                                                                                                                                                                               |
|       |                                                                            | B2: At-home rules on sleep and evening screen use – healthy bedtime routine – presleep alertness – screen use – at-home rules on sleep and evening screen use                                                                                                                                                                                                                             | Clear rules at home can help reduce evening screen use, which leads to a healthier bedtime routine and less presleep alertness, and these positive effects can help reinforce clear rules at home. |
|       |                                                                            | R4: Pressure to perform in school – presleep worries – presleep alertness – wake up after sleep onset – daytime sleepiness – poor school performances – pressure to perform in school                                                                                                                                                                                                                   | During adolescence, youth (because of their brain development) generally have difficulties to efficiently plan their homework and get it done during the day/not too late. However, the pressure to perform at school leads to more evening homework activities, presleep worries, |
|       |                                                                            | R5: Pressure to perform in school – evening homework – healthy consistent bedtime                                                                                                                                                                                                                                                                                                    |                                                                                                                                                                                                               |
| CLD | Subsystems | Feedback loops | Mechanisms |
|-----|------------|----------------|------------|
| R6: Pressure to perform in school – evening homework – evening snacking and caffeine use – presleep alertness – wake up after sleep onset – daytime sleepiness – poor school performances – pressure to perform in school | mental alertness, and, as a consequence, later bedtimes and staying up late. This creates more tiredness during the day, which hampers their school performances, adding to the problem and strengthening this vicious circle. |
| R7: Pressure to perform in school – daytime PA – natural daylight exposure – circadian rhythm – healthy bedtime routine – presleep alertness – wake up after sleep onset – daytime sleepiness – poor school performances – pressure to perform in school | |
| B1: Daytime PA – natural daylight exposure – circadian rhythm – healthy bedtime routine – presleep alertness – wake up after sleep onset – daytime sleepiness – daytime PA | |

4. Sleep environment | No feedback loops identified | Poverty-related issues cause adolescents to worry more, yet also affect their sleep because of co-sleeping and due to their home environment more often being crowded, noisy, and unsafe compared with peers with a higher socioeconomic position. |

5. Reinforcing sleep factors | Presleep worrying – presleep alertness – wake up after sleep – screen use | Different factors relating to sleep quality reinforce each other in a vicious circle, which in turn is often reinforced by screen use. For example, screen use leads to more presleep worrying and presleep alertness and also to more waking up after falling asleep, which again triggers screen use (checking phone after waking up). |

| Screen use | 1. Revenue | R1: 24/7 availability of technologies – dependency on technologies – screen use for school/work – revenue – further development of technologies – 24/7 availability of technologies | The 24/7 availability of technologies—for example, smartphones, apps, and Wi-Fi—has resulted in an increase in dependency of technologies of both adolescents and adults, for communication but also practical reasons (e.g., alarm clock). The frequent use of these technologies generates income (revenue) for the developers of the technologies (of smartphones, apps, etc.), which subsequently provides the opportunity for technology developers to develop more/improved technologies that further increase the dependency of technologies. |
| Screen use | 2. Social norm | R3: Screen use as social norm – screen use peers – alternative options – screen use as social norm | The 24/7 availability of technologies has resulted in an increased use of social media, (online) games, and passive media (e.g., Netflix) by youth. The use of these media/games has an addictive/attractive effect on itself, thereby further increasing the screen use of youth. Additionally, the addictive/attractive effect results in youth being anxious to miss out on something (i.e., fear of missing out). They want to know the latest news/posts on social media of friends or significant others, and they want to finish all levels of a certain game and have seen the series/movies that their friends (or (Continues)
TABLE 1 (Continued)

| CLD                  | Subsystems                                                                 | Feedback loops                                                                 | Mechanisms                                                                 |
|----------------------|-----------------------------------------------------------------------------|--------------------------------------------------------------------------------|----------------------------------------------------------------------------|
|                      |                                                                             | technologies – 24/7 availability of technologies                               | significant others) talk about. This fear of missing out further increases screen use. |
|                      |                                                                             | – screen use as social norm                                                    |                                                                            |
| 3. Rules for screen use | B1: Setting and adhering to rules around screen time – screen use by peers – getting notifications (response) – fear of missing out – screen use as social norm – setting and adhering to rules around screen time | Setting rules around screen use can limit screen use by adolescents and their peers and in turn notifications, fear of missing out, and screen use as social norm, which can further strengthen the effects of rules around screen use. However, setting of rules is also influenced by the social norm and use of screens by adults. |
(for instance, participation in outdoor active play leads to increased motor fitness or change of social norm). When it comes to the development of interventions, it is important to specify the time frame that applies to specific mechanisms, because that will also guide the type of intervention that is required and the ways that effectiveness should be determined.

5 | CONCLUSION

Our findings demonstrate that there are many interrelating factors explaining obesity-related behaviors and that there are powerful dynamics underlying these determinants, which are generally not included in observational or intervention studies. We observed clear similarities in the highlighted dynamics in the four studied behaviors: the causal loops include traditional themes, such as home and school environment, as well as less explored themes relating to macroeconomic systems, social welfare, technology, and urban systems. The use of CLDs can support developing intervention strategies, because they create a more dynamic, holistic view of intended and unintended potential consequences, and of the ways in which interventions in one particular setting, such as home or school, might be influenced by the interactions with other settings, such as macroeconomic and urban systems.

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CONFLICT OF INTEREST

None declared.

ORCID

Wilma E. Waterlander https://orcid.org/0000-0003-0956-178X
Helga Emke https://orcid.org/0000-0001-8675-2577

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**APPENDIX A: LONGLIST AND SHORTLIST OF FACTORS RELATED TO OBESITY-RELATED BEHAVIOR EXTRACTED FROM THE LITERATURE THAT WERE INCLUDED IN THE CAUSAL LOOP DIAGRAMS**

| Dietary behavior | Physical activity | Sedentary behavior | Sleep |
|------------------|-------------------|--------------------|-------|
| - Unhealthy snacking and consumption of sugar-sweetened beverages | - Access/availability of family transport | - Sedentary behavior at baseline | - Accessibility to media device(s) in the bedroom: (1) TV, (2) game console, (3) computer, (4) tablet, and (5) mobile phone |
| - Dieting | - Access/provision of school facilities/resources | - Eating in front of TV | - Late-night (multimodal) media use via (1) TV, (2) computer, (3) tablet, and (4) mobile phone |
| - Skipping meals | - Availability of PA equipment (PA materials) | - Food intake | - Late-night (multimodal) media use via (1) game console, (2) computer, (3) tablet, and (4) mobile phone |
| - Nutrition education obtained from parents | - Active means of transport to school | - Between meal snacking | - Depressive symptoms |
| - Healthy (parental) role model behavior | - Access/distance to destinations | - Sometimes eating breakfast | - Sometimes eating breakfast |
| - House food rules | - Traffic-related hazards (safety OAP/AT environment [parent perceived]) | - Child independent mobility | - Deparvation |
| - Pressure to finish eating/plate | - Traffic density | - After school MVPA (alternative options for screen use)* | - After school MVPA (alternative options for screen use)* |
| - Involving child in nutrition-related practices | - Availability/access/proximity of public transport system (public transport network) | - SES/parental education | - SES/parental education |
| - Healthy food routines parents | - Use of public transport | - Otracism (social support) | - Octracism (social support) |
| - Healthy body image | - Priority spending money on public transport | - Playground density (number of children at playground) | - Playground density (number of children at playground) |
| - Disordered eating behavior | - Availability/access/proximity of recreational facilities (attractive environment for PA) | - TV set in bedroom | - TV set in bedroom |
| - Peer pressure to eat unhealthy | - Environment aesthetics (attractive environment for PA) | - Existence of safe places to cross roads (school neighborhood) | - Existence of safe places to cross roads (school neighborhood) |
| - Social support healthy eating towards child and parents | - Amount of green/blue space | - Time (year of measurement) | - Time (year of measurement) |
| - Parental support healthy eating | - Urbanization | - Time (SB at school vs. out of school) | - Time (SB at school vs. out of school) |
| - Nutrition knowledge child and parents (nutritional knowledge of main caregiver) | - Pediatrician and cyclist safety structure (safety OAP/AT environment [parent perceived]) | - Neighborhood SES | - Neighborhood SES |
| - Availability of unhealthy and healthy foods and drinks (availability of unhealthy food) | - Walkability | - Weekday days | - Weekday days |
| - Accessibility of unhealthy and healthy food and drinks (accessibility of unhealthy food) | - PA-related policies by local government | - Activity setting (type/location) | - Activity setting (type/location) |
| - Visibility healthy foods and drinks | - PA school policy | - Campus area per student | - Campus area per student |
| - Income parents | - PA-related school policies (time allowed for free play, field trips) | - School’s facilities (lack of/poor quality) (alternative options for screen use)* | - School’s facilities (lack of/poor quality) (alternative options for screen use)* |
| - Highest attained education parents | - Organized activities | - Changing facilities | - Changing facilities |
| - Level of education child | - Recess (proportion class time vs. recess) | - Bike storage facilities | - Bike storage facilities |
| - Risk perception child | - School type (high school vs. vocational) | - Safe play (= boring) | - Safe play (= boring) |
| - Attitudes towards healthy/unhealthy eating child and parents (positive attitude towards unhealthy food) | - Encouragement from significant others (parenting practices stimulating OAP/AT) | - Spacious environment | - Spacious environment |
| - Self-efficacy towards healthy eating child and parents | - Having a companion for PA (OAP/ACT peers) | - School’s building design (e.g., more stairs) | - School’s building design (e.g., more stairs) |
| - Sleep deprivation child (unhealthy sleep behavior) | - Parental modeling | - Outdated/poor equipment | - Outdated/poor equipment |
| - Mental health child | - Parental watching | - Rainfall | - Rainfall |
| - (Un)healthy food drink preferences child | - Awareness of PA | - After school program collects feedback on activities children want | - After school program collects feedback on activities children want |
| - Price of healthy and unhealthy food and drinks (price of unhealthy food) | - Parental concern about environment (safety OAP/AT environment [parent perceived]) | - After school staff provided with 1–4 h of PA training | - After school staff provided with 1–4 h of PA training |
| - Marketing of healthy and unhealthy foods and drinks (marketing of unhealthy food) | - Safety OAP/AT environment (child perceived) | - Duration after school PA program session (alternative options for screen use)* | - Duration after school PA program session (alternative options for screen use)* |
| - Social media exposure related to body image | | - After school program conducted outside (alternative options for screen use)* | - After school program conducted outside (alternative options for screen use)* |
| - Social norm healthy eating | | - At least 25% of after school programs allocated to PA | - At least 25% of after school programs allocated to PA |

(Continues)
| Dietary behavior | Physical activity | Sedentary behavior | Sleep |
|------------------|------------------|-------------------|-------|
| Impulsive behavior child | - Involvement of social contact | - Perceived school climate/support (teacher) | - Sports and other after school activities during the day (daytime sports and PA) |
| - Nutrition education at school | - Encouragement at school | - School social capital (e.g., connectedness) | - Sports and other after school activities during the evening (evening sports and PA) |
| - Cooking skills child and parents (cooking skills main caregivers) | - Teacher management (organization of activities) | - Hours of PE | - Pressure to perform in school (pressure to perform in school) |
| - Availability of parents around eating times/moments (available time) | - PA level at school (teacher PA level) | - Extracurricular PA weekend (alternative options for screen use)* | - Poor school performance |
| - Length and inflexibility of working hours | - Seeing people exercise (neighborhood) (OAP/AT peers) | - Duration morning breaks (>15 min) | - Stressful school environment and/or being bullied |
| - Fading of traditional eating patterns | - Affective judgement (enjoyment in participation in OAP) | - Duration lunch break | - Sleep disturbances (wake up after sleep onset and sleep onset latency [sleep quality]) |
| - Frequency of eating moments | - Imagination for OAP | - Provision of pedestrian training | - Mental health issues |
| - Household budget spent on unhealthy food | - Previous positive experience with OAP | - PA infrastructure (lack of, e.g., limited physical environment) (alternative options for screen use)* | - Medicine use |
| - (healthy) Food routines at home | - Interest | - Existence of lollypop person (crossing guard) | - Obesity |
| - Adequate kitchen equipment | - Perceived behavioral control | - Number of PA policies | - Obstructive sleep apnea |
| - Physical activity child | - Perceived physical appearance | - School offers intramural sport (alternative options for screen use)* | - Clinical sleep disturbances |
| - Sedentary behavior | - Perceived fitness (motor fitness) | - Recess exercise (alternative options for screen use)* | - Seasonal effects on duration of days |
| - Smoking | - Perceived competence (motor skills) | - Physical self-concept (confidence to participate in OAP) | - Biological morningness or eveningness preference |
| - Stress levels of child and parents (stress) | - Physical self-concept (confidence to participate in OAP) | - Self-efficacy (confidence to participate in OAP) | - Adolescent circadian rhythm |
| - Screen time | - Self-worth (confidence to participate in OAP) | - Self-worth (confidence to participate in OAP) | - Daytime napping |
| - Portion size (portion size of unhealthy food) | - Autonomous motivation/regulation | - Motivation (motivation to participate in OAP) | - Daytime sleepiness |
| - Unconscious overeating | - Physical self-concept (confidence to participate in OAP) | - Social norm OAP/AT | - FOMO |
| - Emotional eating | - Goal setting/planning | - School offers intramural sport | **Passive media use = watching movies, series, Netflix, YouTube, and so forth without the goal of social interaction.** |
| - Eating together at the table | - Intention | - school offers intramural sport | *Active media use = media use with an activity and/or social interaction component.* |
| - School food rules | - Knowledge of PA benefits | - Provision of pedestrian training | - Adolescent circadian rhythm |
| - Availability of healthy school canteen | - Parental occupation | - PA infrastructure (lack of, e.g., limited physical environment) | - Daytime napping |
| - Availability of healthy sport canteen | - Payment of fees | - Existence of lollypop person (crossing guard) | - Daytime sleepiness |
| - Attractive presentation of unhealthy food and drinks | - Income individual or household | - Number of PA policies | - FOMO |
| - Duration of lunch breaks | - Education level | - School offers intramural sport | **Passive media use = watching movies, series, Netflix, YouTube, and so forth without the goal of social interaction.** |
| - Opening hours of school canteen | - More options to spend free time sedentary | - Recess exercise (alternative options for screen use)* | *Active media use = media use with an activity and/or social interaction component.* |
| - Meal duration | - Involvement of social contact | - Physical self-concept (confidence to participate in OAP) | - Adolescent circadian rhythm |
| - Bringing own lunch to school | - Encouragement at school | - Goal setting/planning | - Daytime napping |
| - Availability of vending machines with unhealthy food at school | - Teacher management (organization of activities) | - Intention | - Daytime sleepiness |
| - Parents have a paid job | - PA level at school (teacher PA level) | - Knowledge of PA benefits | - FOMO |
| - Authoritative parenting style | - Seeing people exercise (neighborhood) (OAP/AT peers) | - Parental occupation | - Adolescent circadian rhythm |
| - Authoritarian parenting style | - Affective judgement (enjoyment in participation in OAP) | - Payment of fees | - Daytime napping |
| - Permissive parenting style | - Imagination for OAP | - Income individual or household | - FOMO |
| - Using food as a reward | - Previous positive experience with OAP | - Education level | - Adolescent circadian rhythm |
| - Boredom/hanging together | - Interest | - More options to spend free time sedentary | - Daytime napping |
| - Eating unhealthy as social activity | - Perceived behavioral control | - Involvement of social contact | - FOMO |
| - Normalization of the consumption of unhealthy food | - Perceived physical appearance | - Encouragement at school | - Adolescent circadian rhythm |
| - Exposure of unhealthy food (social) media | - Perceived fitness (motor fitness) | - Teacher management (organization of activities) | - Daytime napping |
| - Price of food processing | - Perceived competence (motor skills) | - PA level at school (teacher PA level) | - FOMO |
| - Revenue | - Physical self-concept (confidence to participate in OAP) | - Seeing people exercise (neighborhood) (OAP/AT peers) | - Adolescent circadian rhythm |
| - Poverty | - Self-efficacy (confidence to participate in OAP) | - Affective judgement (enjoyment in participation in OAP) | - Daytime napping |
| - Health | - Self-worth (confidence to participate in OAP) | - Imagination for OAP | - FOMO |

*Several factors from the longlist have been collapsed into the factor “alternative options for screen use.”*