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A dynamic multilevel ecological approach to drinking event modelling and intervention

Hugo Gonzalez Villasanti[1] | **Danielle Madden**[2] | **Kevin Passino**[3] | **John Clapp**[2]

[1]Crane Center for Early Childhood Research and Policy, College of Education and Human Ecology, The Ohio State University, Columbus, OH, USA

[2]USC Suzanne Dworak-Peck School of Social Work, University of Southern California, Los Angeles, CA, USA

[3]Department of Electrical and Computer Engineering, College of Engineering, The Ohio State University, Columbus, OH, USA

Correspondence
Danielle Madden, USC Suzanne Dworak-Peck School of Social Work, University of Southern California, Los Angeles, CA, USA.
Email: dmadden@usc.edu

Abstract

The complex and dynamic interplay between an individual's psychophysiological processes and multilevel interactions with his/her group and environment during alcohol drinking events is analysed in this work. Our aim is to provide a system dynamics model to accurately represent a drinking event and provide guidelines for feedback-based behavioural interventions. We employ a pharmacodynamics model of alcohol metabolism, with a self-regulation approach of decision-making to characterize the individual's drinking behaviour. The nonlinearities introduced by the acute effects of alcohol in cognition, along with social perception and influence, complete the individual's model, which serves as a basis for the group and environment's behaviour models. A sensitivity analysis revealed that influenceability and overestimation via descriptive social norms are key drivers of higher blood alcohol content levels. Furthermore, simulations showed that intervening early in the event, before cognition processes are inhibited, and targeting groups of individuals result in efficient implementations.

KEYWORDS

drinking behaviour, drinking events, drinking motives, feedback-based interventions, psychophysiological model

1 | INTRODUCTION

High-risk alcohol consumption in college settings is a common occurrence with 70% of students reporting drinking within the past month (Johnston, O'Malley, Bachman, & Schulenberg, 2015). Heavy alcohol use among this population is a major public health concern: over 1,800 fatalities are attributed to drinking each year (Hingson, Zha, & Weitzman, 2009). These deaths and many additional alcohol-related problems (i.e., injuries, assaults, vandalism) are a result of drinking behaviour at the event level. Broadly, between 10% and 25% of all unintentional and intentional injuries in the world are attributable to alcohol use (Rehm et al., 2009). There is a great need to develop and test interventions that can be implemented while an individual is consuming alcohol. However, although there is a push to develop more event-level interventions, it is unclear what may work at this level of abstraction. Our goal is to use a systems dynamic framework to suggest targeted strategies and leverage points during an event when an intervention may be best employed.

Efforts to prevent college drinking have typically relied on offline strategies (e.g., educational courses or advertising campaigns) that aim to change 'typical' behaviours (i.e., decrease the number of drinking occasions over the next month), but mixed results have been found and high-risk drinking continues (Wechsler et al., 2002). System dynamics has been utilized as a method to model drinking behaviour at the community and population levels (Holder, 2006; Gorman, Speer, Gruenewald, & Labouvie, 2001; Gruenewald, 2007), but little work has been dedicated to drinking events. There have been a few notable attempts to model the potential effectiveness of interventions to reduce alcohol use, but these have also focused on the population level. For instance, dynamical models of college student drinking behaviour have explored the applicability of reducing the availability of alcohol on a college campus or the potential benefits of policies that penalize heavy student drinkers (Ackleh, Fitzpatrick, Scribner, Simonsen, & Thibodeaux, 2009; Scribner et al., 2009). Additionally, agent-based modelling has been employed to explore the spreading 'social' influence of heavy drinking on a population (Gorman, Mezic, Mezic, & Gruenewald, 2006) or spatial dynamics has been utilized to model the impact of alcohol outlet density on neighbourhood violence or crime (Gorman et al., 2001; Gruenewald, 2007), but both have failed to attend to the problems that occur at the event level.

In an effort to expand the existing models of events where individuals engage in alcohol consumption activities, we collaborated to dynamically model drinking behaviour. A detailed explanation of our partnership between social work scientists and engineering is available in Clapp et al. (2018). Initially, drawing from basic social psychology theory (Lewin, 1951), we explored a dynamical model of a group embedded in a drinking event (Giraldo, Passino, & Clapp, 2017), where the drinking behaviour of the individual is a result of the multilevel interaction between the individuals in the group, the environment and the strength of each individual's personal motivations and characteristics. The mathematical formulation of the model examined parameters related to an individual's intoxication by employing computer simulations and Lyapunov stability theory. This model was then refined by providing a characterization of the individual's decision-making process and a representation of alcohol metabolism dynamics by using field data to establish the parameters in the model (Giraldo, Passino, & Clapp, 2017; Giraldo, Passino, Clapp, & Ruderman, 2017). This iterative modelling process was then expanded to include an analysis of behavioural interventions during drinking events that use feedback of individual's drinking behaviour (Gonzalez Villasanti, Passino, Clapp, & Madden, 2019). Using stability and controllability results for a networked dynamical systems model, we characterized the viability of interventions at the environment or individual level, as a function of the system's initial conditions and social and physical characteristics.

The focus of these works was to take advantage of the control-theoretic tools to identify leverage points in the system to reduce high-risk drinking behaviours. The compromise of obtaining rigorous mathematical results was the use of tractable models, which did not entirely capture the complex nonlinearities imposed by the alcohol pharmacodynamics and its acute effects on cognition and decision-making. We feel that the next necessary steps in our model building process are to employ empirical and theoretical evidence for those nonlinearities using the system dynamics framework and to accurately represent the drinking event dynamics and provide guidelines for behavioural interventions at the individual, group and environment levels. In the following section, we present the socio-ecological model of a drinking event by characterizing a system dynamics model of the individual's physiological and cognitive processes, which will form the basis for the group and environment models. A sensitivity analysis is performed in the next section, where we select key variables that drive the event-level drinking behaviour. Guidelines for a behavioural intervention design using feedback from current drinking behaviour are analysed in the next section. We finalize the paper with a discussion and identification of possible future research.

2 | A MODEL OF A DRINKING EVENT

A more detailed definition of a drinking event is provided in Clapp et al. (2018), but in the most general sense, a drinking event can be defined as beginning when the first sip of alcohol is consumed and ending when any trace of alcohol has left the body. Our model focuses on the aspects of a drinking event for only one hypothetical drinker. Similar to a social ecological framework, drinking events can be conceptualized as systems where an individual drinker (micro) is embedded in a social group of drinkers (mezzo) situated in a larger drinking environment such as a bar (macro). We employ the term *subsystem* in this manuscript and in the models when referring to the systems representing the drinking behaviour at the individual, mezzo, and macro levels. The model figures were generated using STELLA v1.0 and follow the standard stocks and flow diagrams, with integrators (stocks) as rectangles, other variables and parameters as circles and subsystems represented as rectangles with curved corners. More information about these subsystems and the generation of this model can be found in Clapp et al. (2018). Generally, interventions could feasibly be implemented at each level of abstraction, and for clarity, a visual depiction of the subsystems and their connections is presented in Figure 1. The individual is affected by both his/her group and the environment's

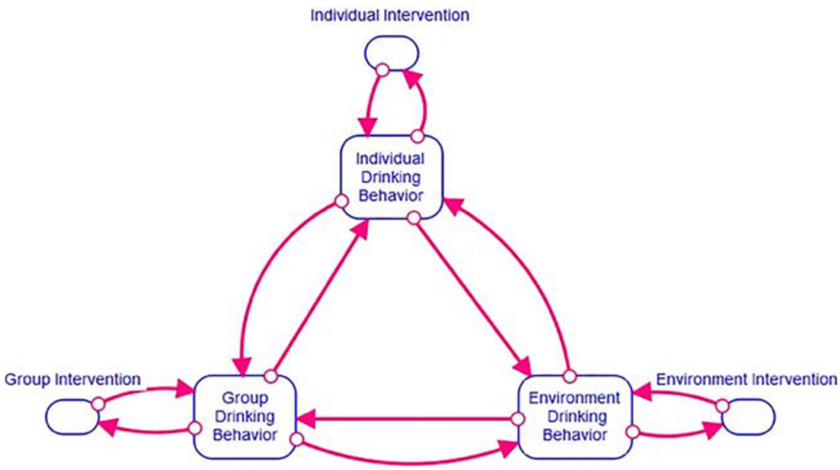

FIGURE 1 Socio-ecological model of a drinking event [Colour figure can be viewed at wileyonlinelibrary.com]

drinking behaviour. The group agent is affected by the environment and by the individual agent, who is a member of it, whereas the environment is affected by the group agent. The influence of the single individual agent on the environment is generally small, although for completeness, it is also considered in Figure 1. We consider interventions that affect each of the three above-mentioned levels, and these will be detailed in the following sections.

2.1 | Individual drinking behaviour subsystem

The individual's dynamic drinking behaviour results from the interaction between the internal alcohol pharmacokinetics in the human body and the individual's drinking rate, which is affected by personal motivation and external influences. For instance, an individual drinker might be motivated to get slightly buzzed, but drink quickly due to peer influence (e.g., friends buying shots) and environmental factors (e.g., drink specials) and ‘overshoot’ their initial desired motive. The processes of absorption, distribution, metabolism and elimination of alcohol in the human body have been modelled using compartment models (Shargel, Wu-Pong, & Yu, 2007). In Umulis, Gürmen, Singh, and Fogler (2005), a five-compartment model is considered by including the stomach, gastrointestinal, liver, central and muscle compartments. Lower dimensional models were considered in Levitt and Levitt (1998), where alcohol flows between the liver and body water compartments, and in Norberg, Gabrielsson, Jones, and Hahn (2000), where the central (which includes the blood) and peripheral compartments were considered. We assume that the alcohol elimination is a zero-order process with elimination rate $Z_i \geq 0$, the maximum metabolic rate. This assumption is reasonable for higher alcohol concentrations (Norberg et al., 2000). Modelling the central and peripheral compartments, with $x_c^i(t)$ and $x_p^i(t)$ as their respective alcohol concentrations at time t, with oral alcohol intake $u^i(t)$ into the peripheral compartment, the differential equations representing the pharmacodynamics of alcohol are

$$\begin{aligned} V_{i,p}\dot{x}_p^i(t) &= -a_i x_p^i(t) + a_i x_c^i(t) - Z_i + u^i(t) \\ V_{i,c}\dot{x}_c^i(t) &= a_i x_p^i(t) - a_i x_c^i(t), \end{aligned} \tag{1}$$

where $a_i > 0$ is the intercompartmental flow rate and $V_{i,p} > 0$ and $V_{i,c} > 0$ are the peripheral and central compartments volumes, respectively. We employ the values reported in Norberg et al. (2000), which are $Z_i = 100$ g/min, $a_i = 10$ dl/min. We selected the volumes $V_{i,p}$ and $V_{i,c}$, such that the blood alcohol content's (BAC) time trajectory matches the experimental data for beer consumption over a time range of 20 min (see Mitchell, Teigen, & Ramchandani, 2014). Hence, we chose $V_{i,p} = 480$ dL and $V_{i,c} = 81$ dL. Figure 2 depicts a stock and flow diagram of the above differential equations, where the drinking rate $u^i(t)$ is the output of the subsystem ‘individual's decision-making’ to be described below. This block has as inputs the individuals' BAC, BAC rate and the external input from the group and environment agents, as well as the intervention input. In this work, we consider the term *drinking behaviour* to be described by the agent's BAC $x_c^i(t)$, the BAC rate $v_c^i(t) = \dot{x}_c(t)$ and the drinking rate $u^i(t)$. In this scenario, the individual must aggregate the available information concerning his/her own drinking behaviour and that of the external environment and choose his/her drinking rate at a given time in the event.

Modelling the individual's decision-making with respect to drinking behaviours has been approached from various cognitive perspectives. The expectancy valence

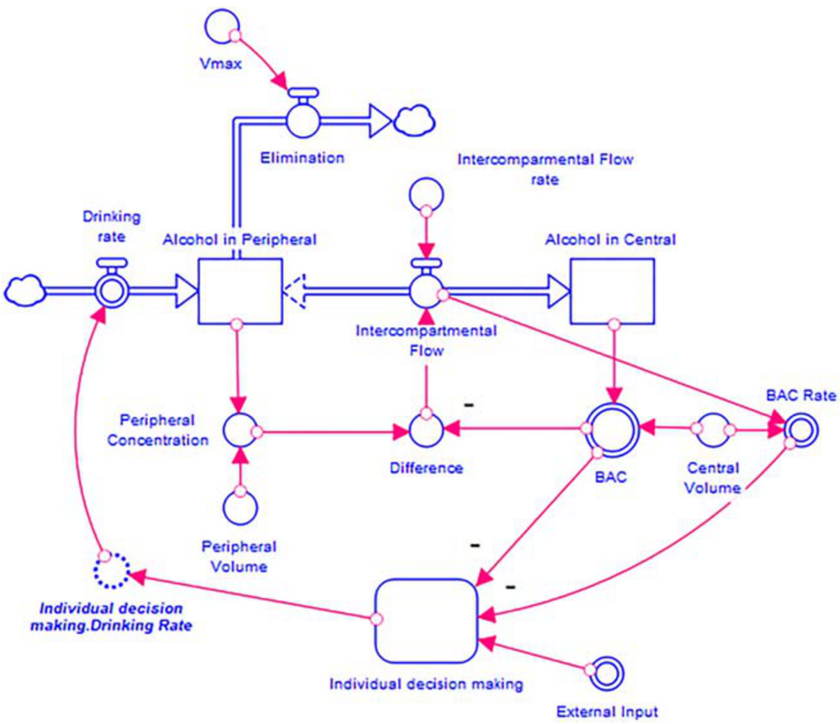

FIGURE 2 Diagram of the individual agent's metabolism model. BAC, blood alcohol content [Colour figure can be viewed at wileyonlinelibrary.com]

model, a stochastic cognitive model that assesses an individual's valuation of gains and losses, was employed to show that alcohol increased responsiveness to risky rewards, while reducing responsiveness of risky loses (Lane, Yechiam, & Busemeyer, 2006). Quantitative models from behavioural economics were employed in Murphy, Correia, and Barnett (2007) to reveal the effect of the allocation of time and money on college students' drinking behaviour. The behavioural effects from a neurochemical perspective were investigated in Spanagel (2009), whereas social psychologists have proposed the self-regulation model (Baumeister & Vohs, 2003; Hustad, Carey, Carey, & Maisto, 2009) when explaining risky drinking behaviours. This theory has close ties with feedback control theory (Carver & Scheier, 1998; Pezzulo & Cisek, 2016), as it involves the computation of an error signal by comparing the goal and the perceived status of the environment. The individual acts according to this error to alter his/her environment. Lower self-regulation abilities are correlated with heavier drinking in college students (Hustad et al., 2009). This concept has been also studied under the fields of *perceptual control theory* (Powers, 1973). Using this later cognitive model in a drinking event setting, the individual forms a mental representation of his/her own drinking behaviour as well as the perceived drinking behaviours of the group and the environment.

Individuals perceive their own drinking behaviour employing interoceptive, proprioceptive and behavioural cues and compare them with expectations and norms regarding intoxicated status (Kaestle, Droste, Peacock, Bruno, & Miller, 2018). As suggested above, the mental models associated with these cues are dynamically influenced by alcohol consumption and event dynamics. In a work by Martin and Earleywine (1990), it is reported that individuals overestimate their BAC when their BAC is growing while drinking, that is, $v_c^i(t) > 0$, and underestimate it when their BAC is decaying after the drinking stops, or $v_c^i(t) < 0$. Hence, the individual's perceived intoxication could be modelled as $x_c^i(t) + \beta_i v_c^i(t)$, where $\beta_i \geq 0$ represents the weight given to the BAC rate of change when assessing the intoxication. Furthermore, individuals with low BAC tend to overestimate their actual BAC, whereas those with moderate and high BAC levels tend to underestimate it (Grant, LaBrie, Hummer, & Lac, 2012; Kaestle et al., 2018). This acute effect of the BAC in the perception of intoxication has been also documented in the *alcohol myopia* literature (Steele & Josephs, 1990), where it is treated as a consequence of the limited information processing capabilities of the individuals with moderate and high levels of BAC. Hence, when intoxicated, the individual's attention resources are reduced, and the perceived 'wetness' is lower than the actual 'wetness' (see below for our definition of 'wetness'). The importance of the drinking rate $u^i(t)$ in drinking behaviour is highlighted in the works reviewed by Borsari and Carey (2001), where individuals observe, compare and try to match their drinking rate at drinking events. Considering all these elements, we assume that the individual aggregates the three components of his/her drinking behaviour into a single measure we call *wetness*, defined as

$$w_i^i(t) = p^i(t)\left(\alpha_i\varphi_i\left(x_c^i(t) + \beta_i v_c^i(t)\right) + (1-\alpha_i)u^i(t)\right),$$

where $w_i^i(t)$ is measured in g/min^2, the units of measurement of the drinking rate rate of change, and $\varphi_i \geq 0$ is the conversion term employed by the individual for the BAC in g/dl. The nonnegative scalar $\alpha_i \in [0,1]$ represents the weight, or bias, given to the intoxication variables. The acute effect of BAC on perception is modelled with the variable

$$p^i(t) = \max\{1-\rho_i x_c^i(t), 0\},$$

where $\rho_i \geq 0$ is the rate of perception's decline with respect to the individual's BAC $x_c^i(t)$.

Social perception (Aronson, Wilson, & Akert, 2010), which involves nonverbal, visual and body gesture cues, is the main process involving perception of intoxication and drinking rate of the group and the drinking event's environment. Social norms, and more specifically descriptive norms (Borsari & Carey, 2001), by which individuals perceive the quantity of drinking in a group, have also been cited as a risk factor for excessive drinking via overestimation of the group intoxication (Lewis & Neighbors, 2006). Descriptive norms have also been the target of interventions (Foxcroft, Moreira, Santimano, & Smith, 2015), with mixed results reported. We assume that the perceived group wetness $w_g^i(t)$ and environment wetness $w_e^i(t)$, from the individual's perspective, are computed in a similar manner with the same weight parameters, where $x_c^g(t)$, $v_c^g(t)$ and $u^g(t)$ are the group's BAC, BAC rate and drinking rate, respectively, and $x_c^e(t)$, $v_c^e(t)$ and $u^e(t)$ are the environment's BAC, BAC rate and drinking rate

$$w_g^i(t) = \psi_i p^i(t)\left(\alpha_i\varphi_i\left(x_c^g(t) + \beta_i v_c^g(t)\right) + (1-\alpha_i)u^g(t)\right)$$

$$w_e^i(t) = \psi_i p^i(t)\left(\alpha_i\varphi_i\left(x_c^e(t) + \beta_i v_c^e(t)\right) + (1-\alpha_i)u^e(t)\right),$$

where the parameter $\psi_i \geq 0$ represents the effect of descriptive social norms on the perception of the drinking behaviour, with $\psi_i > 1$ corresponding to the individual overestimating actual drinking behaviour elements due to misperceptions of the social norm.

2.2 | Individual-level intervention

The intervention at the individual level considered in this work consists of sending information about a *safe behaviour* trajectory to the agents, which is the desired intoxication trajectory from the intervention perspective (Gonzalez Villasanti et al., 2019). For example, an individual drinker may be cautioned that if he/she keeps drinking akin to their current behaviour, they may overshoot his/her intended level of drunkenness (i.e., to feel slightly buzzed). For the case of the individual agent, the safe behaviour trajectory employs the safe BAC $x_c^{fi}(t)$, the safe BAC rate of change $v_c^{fi}(t)$ and the safe drinking rate $u^{fi}(t)$, which are designed by the intervention such that the initial values of these variables at time t=0 match the ones observed for the agent. This safe behaviour is reinforced at various levels of persuasiveness: from passive SMS messages suggesting the adequate BAC and drinking rate at a given time to more active messages using the individual's intoxication feedback. The safe behaviour wetness as perceived by the individual, $w^i{}_f(t)$, is then computed with

$$w^i{}_f(t) = \alpha_i\left(x_c^{fi}(t) + \beta_i v_c^{fi}(t)\right) + (1-\alpha_i)u^{fi}(t), \qquad (2)$$

and we assume that the information is conveyed via objective channels, for example, smartphones or dedicated device, such that $w^i{}_f(t)$ is not affected by perception's decline via $p^i(t)$ or the social norms. An important aspect to mention is that we assume that the rate of change of the trajectories that are exogenous to the agents' decision-making block is computed internally. This is done to consider the fact that derivatives of a signal are estimated using approximations in the human brain (Levitan, Ban, Stiles, & Shimojo, 2015). For example, to compute the rate of change of the group's BAC $v_c^g(t)$, the individuals employ the previous values of the BAC $x_c^g(t)$ stored in the working memory to compute its rate of change. In the model implemented in STELLA v1.0, this computation is modelled employing a first-order filter (Passino & Quijano, 2002).

The individual's goal-seeking behaviour requires the computation and constant update of the target wetness $w_r^i(t)$ that the individual will follow, based on the individual's initial planned wetness trajectory $w_p^i(t)$, the perceived group and environment wetness trajectories and the safe behaviour wetness $w^i{}_f(t)$ promoted by the intervention at the individual level. The individual's target wetness is computed with

$$w_r^i(t) = s_p^i(t)w_p^i(t) + s_g^i(t)w_g^i(t) + s_e^i(t)w_e^i(t) + s^i{}_f(t)w^i{}_f(t),$$

where $s_p^i(t), s_g^i(t), s_e^i(t), s^i{}_f(t)$ are nonnegative, time-varying weights that the individual assigns to the initial planned, group, environment and safe behaviour wetness, respectively. To represent the individual's *limited resource* on decision-making, proposed in Baumeister and Vohs (2003) to account for failures on self-regulation, we assume that

$$s_p^i(t) + s_g^i(t) + s_e^i(t) + s^i{}_f(t) = 1. \tag{3}$$

Hence, the computation of the target wetness becomes a linear combination of the different influences involved in the decision on the drinking rate. The weight assigned to follow the initial planned wetness at time t, $s_p^i(t)$ depends on the individual's commitment to follow the initial plan $\gamma_i \in [0,1]$. For example, an individual who strongly opposes drinking at an event has a commitment of γ_i close to one, with a planned wetness $w_p^i(t) = 0$ for all $t \geq 0$. However, the ability to successfully follow the initial plan decreases with the increase of the BAC, as reported in Hull and Bond (1986), thus reducing the value of $s_p^i(t)$ and increasing the value of the weight assigned to external cues. On the other hand, we assume that during the drinking event, the intervention is able to actively monitor the individual's intoxication and adjust the *persuasive effort* of the intervention, $\delta^i(t) \geq 0$, to increase or decrease the weight assigned to the safe behaviour $s^i{}_f(t)$. Considering these concepts, and the constraint in Equation(3), the influence weights are updated with

$$s^i{}_f(t) = \frac{\delta^i(t) m^i(t)}{1 + \delta^i(t) m^i(t)}$$

$$s_p^i(t) = \frac{\gamma_i m^i(t)}{1 + \delta^i(t) m^i(t)}$$

$$s_g^i(t) = \frac{\zeta_i (1 - \gamma_i m^i(t))}{1 + \delta^i(t) m^i(t)}$$

$$s_e^i(t) = \frac{(1 - \zeta_i)(1 - \gamma_i m^i(t))}{1 + \delta^i(t) m^i(t)},$$

where $\zeta_i \in [0,1]$ represents the allocation of attentional resources between the group and the environment wetness assuming no intervention, with $\zeta_i = 1$ describing an individual not being influenced by the environment wetness. Also, the effect of alcohol in decision-making is captured with

$$m^i(t) = \max\{1 - \eta_i x_c^i(t),\ 0\},$$

where $\eta_i \geq 0$ is the rate of decrease of the individual's commitment to the initial plan. Thus, it is seen that an intoxicated individual with high $x_c^i(t)$ will have assigned lower attentional resources to the initial planned and safe behaviour wetness and instead allocates to the more salient cues of group and environment wetness trajectories.

Finally, the dynamics of the individual's drinking rate are driven by the mismatch between the target wetness $w_r^i(t)$ and the current wetness $w_i^i(t)$. It has been reported in Field, Wiers, Christiansen, Fillmore, and Verster (2010) that alcohol consumption stimulates alcohol-seeking behaviour, that is, alcohol craving and consumption increase while intoxicated. This third acute effect of alcohol is added to the drinking rate dynamics, which are formulated as

$$\dot{u}^i(t) = \max\{w_r^i(t) - w_i^i(t) + \xi_i x_c^i(t), 0\}, \tag{4}$$

where $\xi_i \geq 0$ is the alcohol craving parameter, and it is assumed that the individual is able to react immediately to the stimulus and change his/her drinking rate accordingly. The nonlinearity imposed by the nonnegativity of the drinking rate $u^i(t)$ accounts for the fact that the individuals cannot, in general, reduce their BAC by eliminating alcohol via processes other than alcohol metabolism characterized in Equation (1). Figure 3 depicts the diagram for the individual's decision-making process, where the above computations are being carried on inside the modules in the diagram. Table 1 summarizes the variables employed in the individual model in the manuscript, as well as in the model included in the supporting information.

2.3 | Group and environment drinking behaviour subsystem

Following our socio-ecological models, we assume that the group's drinking behaviour aggregates the drinking behaviour of all individuals in the group, with the exception of the individual agent described above. Also, the environment drinking behaviour aggregates, among other physical aspects (i.e., built environment) to be described below, the behaviour of all individuals in the drinking event, except the ones included in the group and the individual agent. For these reasons, we choose to model their drinking behaviour dynamics using the same equations governing the metabolism and decision-making from the previous section, while employing different parameters to account for different behaviour dynamics. In the case of the group agent, we introduce the concept of a *virtual weight* $z_g \geq 0$, which affects the central and peripheral volumes by scaling the corresponding volumes of the individual agent, with $V_{g,c} = z_g V_{i,c}$ and $V_{g,p} = z_g V_{i,p}$. With respect to the environment drinking behaviour, it models both physical and social aspects of the drinking event environment. The

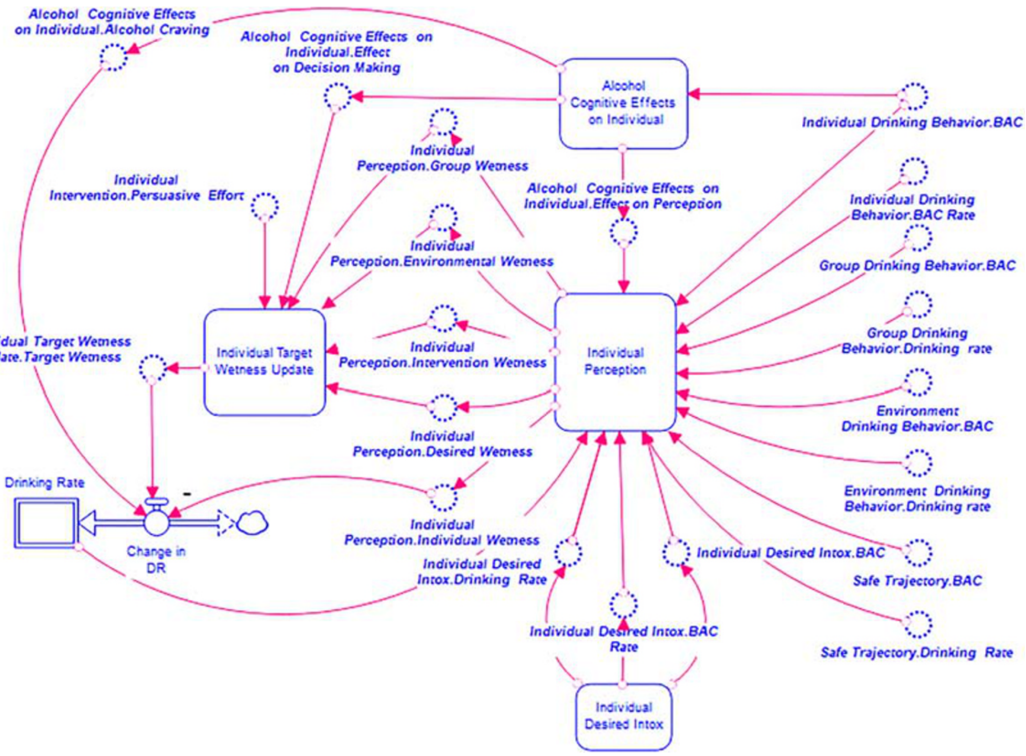

FIGURE 3 Diagram of the individual agent's decision-making model. BAC, blood alcohol content [Colour figure can be viewed at wileyonlinelibrary.com]

physical aspects include the price of drinks, presence of food, music, dancing and bartending services, among other protective and risk factors (Clapp, Min, Shillington, Reed, & Croff, 2008; Clapp et al., 2009). The presence of physical risk factors increases the environment's initial BAC $x_c^e(0)$ and increases its virtual weight z_e, affecting the central and peripheral volumes with $V_{e,c} = z_e V_{i,c}$ and $V_{e,p} = z_e V_{i,p}$. Higher virtual weights allow higher drinking rates $u^e(t)$, which exert a negative influence towards risky drinking behaviours in the group and individual. The social aspect of the environment drinking behaviour represents the average wetness of all individuals in the drinking event, and its importance increases when the number of individuals at the event is small (e.g., a typical party in a private location) where the group and individual agents can perceive the other individuals' drinking behaviour more accurately. Hence, an environment with high social component is modelled with a small virtual weight, close to the virtual weight of the group, and high influence weight on decision-making for the group and individual wetness (i.e., a low commitment γ_e).

3 | SENSITIVITY ANALYSIS

In this section, we study the effects of the three main components of our model that are relevant to the quest to identify possible leverage points, useful when designing interventions in drinking events. Clearly, individuals motivated to drink at higher rates will achieve higher BACs, and individuals with higher initial BAC due to predrinking (i.e., consuming alcohol prior to attending a bar or party) constitute a risk factor, and we are not going to analyse them in detail here. We focus on exploring the elements that contribute to risky drinking behaviour in a dynamical setting. The elements to be studied are the acute cognitive effects of alcohol, the impact of peer pressure on self-regulation and the influence of social norms on perception. A more detailed analysis of the interplay between the different exogenous and endogenous stimuli on the individual agent's decision-making can be found in Gonzalez Villasanti et al. (2019). We assume that the individual agent has a lower weight and, consequently, lower volume of distribution, than the group and environment agent, with $z_g = 1.4$ and $z_e = 14$. We also consider $\alpha_i = \alpha_g = \alpha_e = 0.9$, indicating that agents assign more attentional resources to follow their intoxication rather than their drinking rate.

The acute effects of alcohol in cognition are modelled via the parameters affecting perception ρ_i, target update η_i and alcohol-seeking behaviour ξ_i. The following correspondence between these parameters is obtained to match the initial and final BAC recorded in Clapp et al. (2009): $\eta_i = \rho_i$ and $\xi_i = 0.1\rho_i$. We adopt the same

TABLE 1 Parameters and variable descriptions corresponding to the individual agent, as referred in the manuscript and in the computer model in the supporting information

Manuscript	Model	Role	Range
Z_i	Vmax	Maximum metabolic rate	$Z_i > 0$
$x_c^i(t)$	BAC	Alcohol concentration in central compartment (BAC) at time t	$x_c^i \geq 0$
$x_p^i(t)$	Peripheral Concentration	Alcohol concentration in peripheral compartment at time t	$x_p^i(t) \geq 0$
$u^i(t)$	Drinking rate	Oral alcohol intake (drinking rate) at time t	$u^i(t) \in \mathbb{R}$
a_i	Intercompartmental Flow rate	Intercompartmental flow rate	$a_i > 0$
$V_{i,p}$	Peripheral Volume	Volume of peripheral compartment	$V_{i,p} > 0$
$V_{i,c}$	Central Volume	Volume of central compartment	$V_{i,c} > 0$
$v_c^i(t)$	BAC Rate	BAC rate of change at time t	$v_c^i \in \mathbb{R}$
β_i	Rate weight	Weight assigned to BAC rate of change	$\beta_i \geq 0$
$w_i^i(t)$	Individual Wetness	Perceived self-wetness at time t	$w_i^i(t) \geq 0$
φ_i	Conversion term	Conversion term	$\varphi_i \geq 0$
α_i	Intox weight	Weight assigned to BAC	$\alpha_i \in [0,1]$
$p^i(t)$	Effect on Perception	Acute effect of BAC on perception at time t	$p^i(t) \geq 0$
ρ_i	Attention deficit parameter	Rate of perception's decline with respect to BAC	$\rho^i \geq 0$
ψ_i	Social Bias	Effect of descriptive social norms on perception	$\psi_i \geq 0$
$x_c^{fi}(t)$	Safe Trajectory.BAC	Safe BAC trajectory for agent i at time t	$x_c^{fi}(t) \geq 0$
$v_c^{fi}(t)$	Safe Trajectory.BAC Rate	Safe BAC rate of change for agent i at time t	$v_c^{fi}(t) \in \mathbb{R}$
$u^{fi}(t)$	Safe Trajectory.Drinking Rate	Safe drinking rate for agent i at time t	$u^{fi}(t) \in \mathbb{R}$
$w^i{}_f(t)$	Intervention Wetness	Perceived safe wetness at time t	$w^i{}_f(t) \geq 0$
$w_r^i(t)$	Target Wetness	Target wetness at time t	$w_r^i(t) \geq 0$
$w_p^i(t)$	Desired Wetness	Planned wetness at time t	$w_p^i(t) \geq 0$
$s^i{}_j(t)$	Influence Weights	Cognitive biases j=p,g,e,g for planned, group, env, and safe	$s^i{}_j(t) \in [0,1]$
γ_i	Commitment	Commitment to initial plan	$\gamma_i \in [0,1]$
$\delta^i(t)$	Individual Intervention.Persuasive Effort	Intervention's persuasive effort at time t	$\delta^i(t) \geq 0$
ζ_i	zeta	Attentional resources allocation parameter	$\zeta_i \in [0,1]$
$m^i(t)$	Effect on Decision Making	Effect of alcohol in decision-making at time t	$m^i(t) \geq 0$
η_i	Self regulation deficit parameter	Rate of decrease of commitment to initial plan	$\eta_i \geq 0$
ξ_i	Alcohol craving parameter	Alcohol craving parameter	$\xi_i \geq 0$
z_g	Included in volume block	Group agent's virtual weight	$z_g \geq 0$
z_e	Included in volume block	Environmental agent's virtual weight	$z_e \geq 0$
K_i	Individual Intervention.Proportional gain	Intervention strength parameter	$K_i \geq 0$
$\bar{u}_i$	Individual Intervention.Safe DR	Safe drinking rate	$\bar{u}_i \geq 0$
$\bar{x}_i$	Individual Intervention.Safe BAC	Safe peak BAC level	$\bar{x}_i \geq 0$
α_{fi}	Individual Intervention.Intox weight	Weight assigned to BAC by the intervention	$\alpha_{fi} \in [0,1]$
β_{fi}	Individual Intervention.Rate weight	Weight assigned to BAC rate of change by the intervention	$\beta_{fi} \geq 0$

Note: The parameters and variables corresponding to the group and environment agents follow the same naming convention.
Abbreviation: BAC, blood alcohol content.

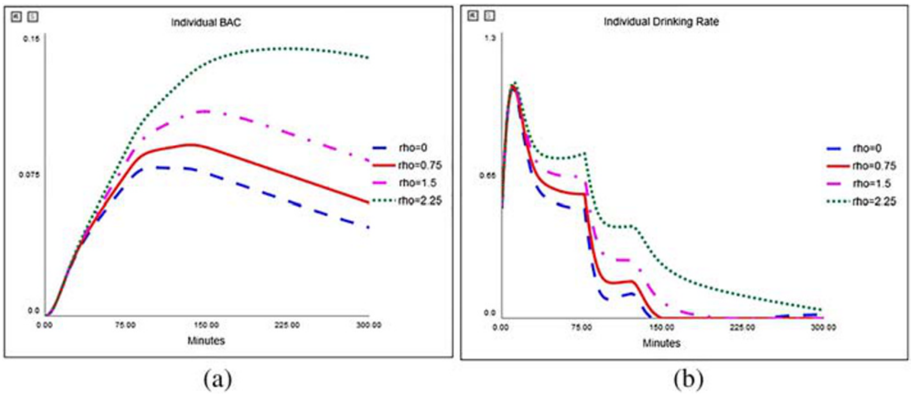

FIGURE 4 (a) Individual BAC $x_c^i(t)$ and b) individual drinking rate $u^i(t)$ trajectories for various values of the myopia parameter ρ_i. BAC, blood alcohol content [Colour figure can be viewed at wileyonlinelibrary.com]

interdependence between the parameter corresponding to the group and environment agents, and $\rho_e = \rho_g = \rho_i$. This allows us to explore the effect of alcohol in decision-making and intoxication via the parameter ρ_i. Figure 4 shows time trajectories for BAC $x_c^i(t)$ and drinking rate $u^i(t)$ for the individual agent, for values of $\rho_i \in [0,2.25]$. The nonlinear effect of alcohol in decision-making is noticed after the BAC goes beyond 0.05 g/dl. This is driven by higher drinking rates, even after the individual has reached his/her initial planned peak BAC around $t = 75$ min. The implications for interventions are clear, as influencing the individual's decision-making towards a safe behaviour trajectory, after his/her fact reaches 0.05 g/dl, becomes a harder task and will require more effort, as exposed in the following section concerning intervention design. Thus, the ideal 'leverage point' occurs early in a drinking event.

Another important parameter that affects the decision-making of the agents in a drinking event is their degree of commitment γ_i to the initial plan, or inversely, how susceptible is the individual to any influence from the group or environment when deciding how much to drink. We select $\zeta_i = 0.7$, to model an individual where the group's influence is greater than the rest of the environment's influence, while the individual's influence on the group is $\zeta_g = 0.3$ and $\zeta_e = 0.95$ on the environment. Figure 5 shows results for time trajectories of BAC and drinking rate for various values of commitment γ_i. It can be seen that the highly committed individual with $\gamma = 1$ closely follows his/her initial plan, which is drink at a rate of 0.5 g/min until the BAC level reaches 0.05 g/dl. As the commitment decreases, the individual tries to model (i.e., mimic) the higher drinking rates from the group and the environment, obtaining higher peak BAC levels. A decrease of 25% on the commitment parameter leads to an increase of 50% in peak BAC. Interestingly, in the case for very low commitment across individuals, the group and environment, agents with low initial intoxication make a great effort to match their drinking behaviour at the beginning, but converge to lower drinking rates later on. This is as a consequence of the low initial BAC of the agents. Drinking before the event (i.e., higher initial BAC) would increase the final BAC of less committed individuals. Interventions targeting individuals susceptible to peer pressure, or with initial plans that include high drinking rates and BAC, may lower risky drinking behaviour at drinking events, as seen in Figure 5.

Figure 6 shows BAC and drinking rate time trajectories for various values of the social norm parameter ψ_i, where we considered $\psi_g = \psi_e = \psi_i$. It can be seen that overestimating other agents' intoxication by as little as 20% leads to higher drinking rates and a 30% increase in the peak BAC, which in turn reinforces the risky

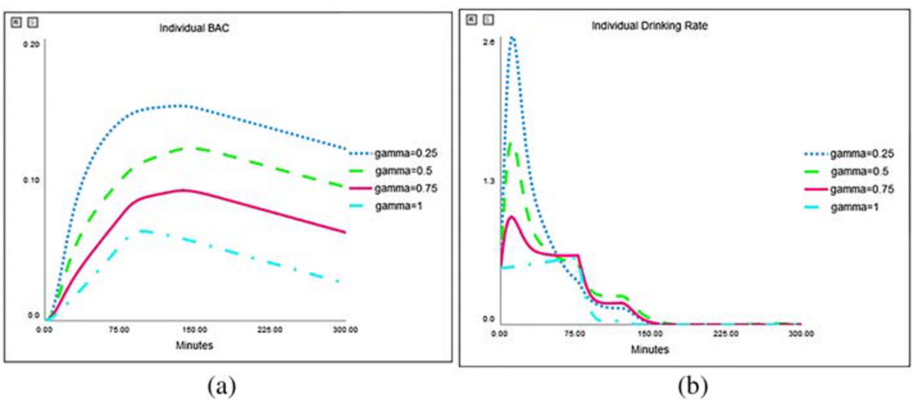

FIGURE 5 (a) Individual BAC $x_c^i(t)$ and (b) individual drinking rate $u^i(t)$ trajectories for various values of the commitment parameter γ_i. BAC, blood alcohol content [Colour figure can be viewed at wileyonlinelibrary.com]

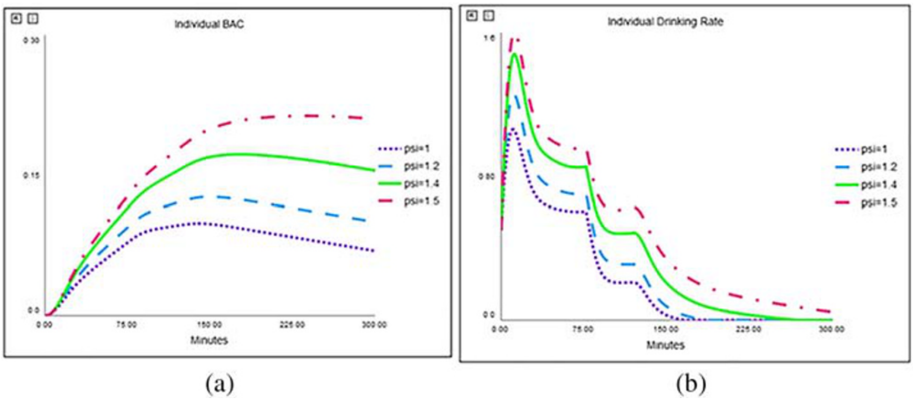

FIGURE 6 (a) Individual BAC $x_c^i(t)$ and (b) individual drinking rate $u^i(t)$ trajectories for various values of the descriptive norm parameter ψ_i. BAC, blood alcohol content [Colour figure can be viewed at wileyonlinelibrary.com]

drinking behaviour of the group and the whole environment. Higher values of overestimation also greatly increase intoxication levels, with 50% of this overestimation corresponding to 110% higher peak BAC. Interventions aimed to accurately inform the individual of his/her peers and the whole environment's actual intoxication could reduce risky drinking behaviours, especially in cases where descriptive norms affect the perception of intoxication by a factor greater than 40%.

In summary, we have identified that the nonlinear acute effect of alcohol in cognition manifests itself at moderate BAC levels, 0.05 g/dl in our case. After reaching that point, the BAC increases as a result of higher drinking rates, surpassing the initial planned drinking behaviour. Individuals susceptible to peer and environment influence also result with higher BAC levels, as a consequence of their effort to match the higher drinking rates of the group and environment agents. Descriptive social norms that cause individuals to overestimate their group's drinking behaviour and environmental wetness also negatively affect the individual's peak BAC, and its effects are seen across the time horizon of the event. Future experiments should be aimed to accurately measure these parameters and its effects using measured field data in order to inform event-based drinking interventions.

4 | EVENT-BASED INTERVENTION DESIGN

In this section, we take advantage of the lessons learned in the previous section and design an event-based intervention to mitigate risky drinking behaviours for individuals at a bar/party. We will not consider strategies aimed at modifying the model parameters a priori, as these interventions can be analysed in a straightforward manner from a modelling perspective. Strategies of the mentioned type include interventions altering the environmental initial wetness such as higher drink prices and responsible serving training (i.e., training to pour standard drinks sizes among other social control strategies) and social norm interventions to decrease the value of the overestimation parameter ψ_i via feedback of the objective (i.e., actual) drinking behaviours of individuals (Lewis & Neighbors, 2006). Instead, we focus on behavioural strategies that try to influence the decision-making of the agents towards the safe behaviour trajectory via adjustments in the persuasive effort $\delta_i(t)$, employing information about the agents' wetness value at each time t during the drinking event.

We explore a closed-loop strategy intervention, one that uses information on current drinking behaviour to adjust the value of $\delta^i(t)$, $\delta^g(t)$ and $\delta^e(t)$. For simplicity, we formulate the next variables with respect to the individual agent, noting that the variables corresponding to the intervention among the group and environmental agents are formulated accordingly. The closed-loop strategy to obtain $\delta_i(t)$ can be formulated with

$$\delta^i(t) = \max\left\{K_i\left(w_i^{fi}(t) - w_f^{fi}(t)\right), 0\right\}, \tag{5}$$

where

$$w_f^{fi}(t) = \alpha_{fi}\left(x_c^{fi}(t) + \beta_{fi} v_c^{fi}(t)\right) + \left(1 - \alpha_{fi}\right) u^{fi}(t) \tag{6}$$

is the safe behaviour wetness, computed according to Equation (2), where the values of α_{fi}, β_{fi} and K_i are chosen by the intervention design. The individual wetness as seen by the intervention, $w_i^{fi}(t)$ is computed with the same parameters as in Equation (6), and we assume that the drinking behaviour elements are measured accurately via sensors, for example, via alcohol-tracking wearables (see Marques & McKnight, 2009for a description of devices that can measure intoxication transdermally). The intervention strength parameter $K_i \geq 0$ scales the mismatch between the safe behaviour wetness and individual wetness. The value of this parameter depends on the methods employed by the intervention to suggest or enforce the safe behaviour trajectory. Small K_i values correspond to *softer* or passive interventions, with low cost of implementation in general (e.g., the safe trajectory being fed back via SMS to the individual's mobile phone as described earlier). High K_i values represent active interventions that produce a greater response from the individual, usually involving higher costs. Note that $K_g = K_i$ does not imply that the costs associated to intervene with a group are the same as the costs to intervene with an individual, which are probably higher for the group agent, given the higher number of individuals that it represents. However, the previous equality represents that the group intervention is able to produce a similar persuasion effort obtained with a single individual, but in all its members. A similar reasoning applies to the case of $K_e = K_i$.

We begin analysing the design of the safe behaviour trajectories and its corresponding enforcement efforts. In Gonzalez Villasanti et al. (2019), it has been shown that the mismatch between the safe drinking trajectory and the actual BAC trajectory is reduced by employing an accurate model of the individual metabolism when designing the safe drinking trajectory. Therefore, in this work, we design the safe trajectory employing the agent's metabolism model in Equation (1), where the drinking rate is chosen as

$$u^{fi}(t) = \begin{pmatrix} \bar{u}_i & \text{when} \;\; x_c^{fi}(t) \le \bar{x}_i \;\; \text{and} \;\; v_c^{fi}(t) > 0 \\ 0 & \text{else,} \end{pmatrix}$$

where $\bar{u}_i \ge 0$ is a safe drinking rate and $\bar{x}_i \ge 0$ is a safe peak BAC level. The lowest mismatch values between the safe and actual wetness were achieved by using $\alpha_{fi} = 3$, $\beta_{fi} = 60$ and $\gamma_{fi} = 0$. These values highlight the importance of accurate measurement or estimation of the individuals' intoxication variables, the BAC and its rate of change in a drinking event. For the next simulations, we fixed $\bar{x}_i = \bar{x}_g = \bar{x}_e$, $\bar{u}_i = \bar{u}_g = \bar{u}_e$ and $K_i = K_g = K_e = 20$, which produce values of the intervention weight $s^i{}_f(t) \le 0.5$. Figure 7 shows results for the individual's BAC $x_c^i(t)$ and persuasive effort $\delta^i(t)$ trajectories for various values of safe peak BAC $\bar{x}_i$, while maintaining $\bar{u}_i = 0.6$ g/min constant, which corresponds to 2.6 standard drinks per hour. It can be seen that the no-drinking safe behaviour trajectory, with $\bar{x}_i = 0$, demands a higher persuasive effort at the beginning of the simulation, than the other higher $\bar{x}_i$ safe trajectories. The value of that peak is largely set by the rate of change weight β_{fi}, which acts as a derivative gain, reacting to changes in the rate of the BAC. Note that the peak effort is higher for $\bar{x}_i = 0.025$, despite the higher peak BAC, and it occurs close to the highest point in safe BAC trajectory. The higher effort is required to counteract the acute cognitive effects of alcohol. Safe behaviour trajectories with peak BAC higher than $\bar{x}_i = 0.05$ intuitively require lower persuasive efforts, although the individual's BAC trajectory approaches unsafe drinking behaviour values above 0.08 g/dl. Note that with the limited value of the strength parameter K_i, the intervention is not able to fully counteract the influences from the group and environment's riskier drinking behaviour, which is depicted in the higher individual's peak BAC values, compared with the $\bar{x}_i$ values. The design of the safe trajectories should consider this mismatch and the effort required to persuade the agents to follow the safe drinking behaviour, favouring lower values of peak safe BAC $\bar{x}_i$.

Figure 8 shows results of the individual, group and environment's BAC trajectories under no intervention and under intervention with each of these three agents. It can be noted that the intervention at the individual agent has a negligible effect on the group and environment, whereas intervention at the group agent significantly reduces the peak BAC level of both the group and the individual agent and slightly reduces the environment's BAC, which remains almost unchanged due to its larger virtual weight. Intervention at the environment level

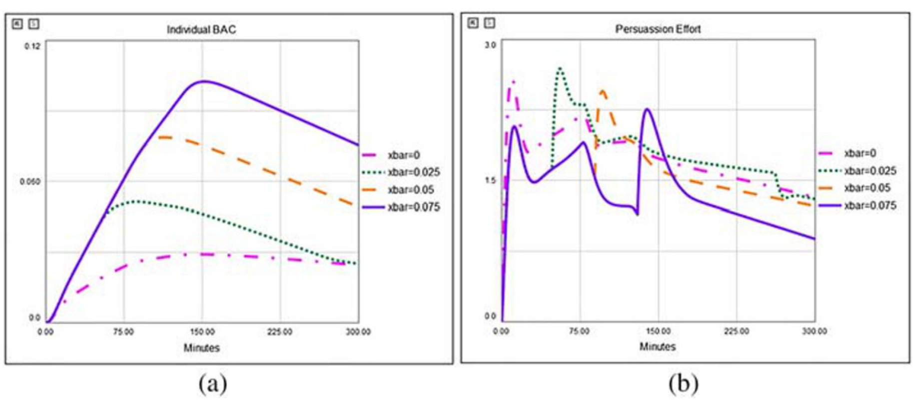

FIGURE 7 (a) Individual BAC trajectories and (b) persuasive effort $\delta^i(t)$ trajectories, for various values of the peak safe behaviour trajectory $\bar{x}_I$. BAC, blood alcohol content [Colour figure can be viewed at wileyonlinelibrary.com]

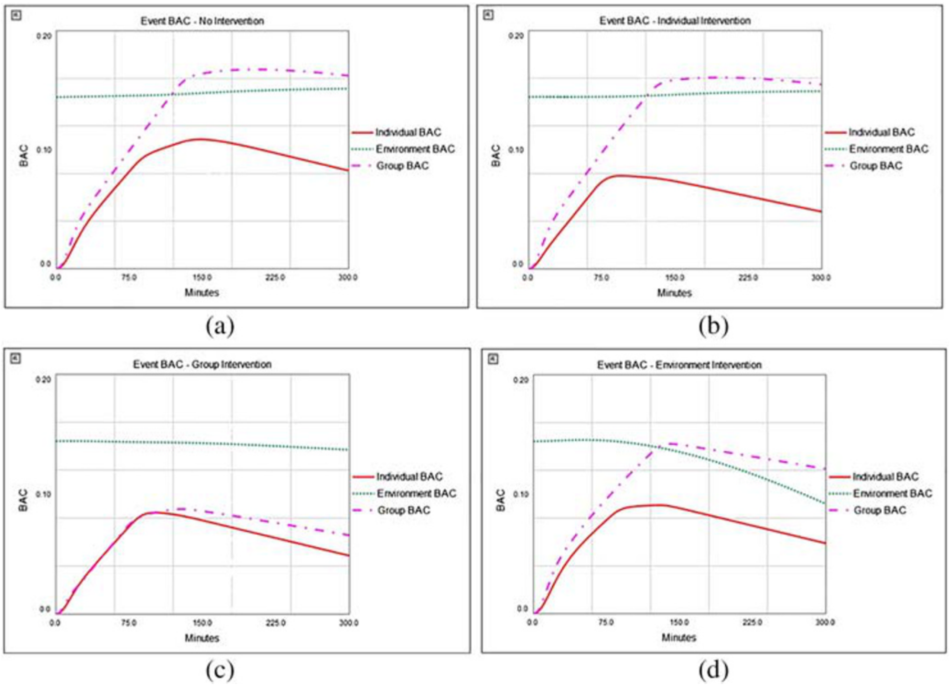

FIGURE 8 Event BAC trajectories with (a) no intervention interventions and with interventions at the (b) individual, (c) group, and (d) environment levels. BAC, blood alcohol content [Colour figure can be viewed at wileyonlinelibrary.com]

results in a lower peak BAC for the individual, driven by the low environment's drinking rate produced by the intervention. However, this element is not enough to reduce the group's peak BAC in the same proportion as the individual's peak intoxication. In addition, the sluggish nature of the environment's wetness dynamics avoids higher rates of decrease of its BAC, with lower values occurring at the end of the simulation. Thus, in environments with a large number of individuals, represented with higher virtual weight as our case, the intervention at the group level could take advantage of the higher influence this agent exerts on the individual. Hence, it is plausible that this group intervention could alter peak BAC to values comparable with those obtained by a direct but possibly more expensive intervention at the individual level.

5 | CONCLUSION

Employing key references from pharmacokinetics, cognitive science and social psychology, a system dynamics model of a drinking event is formulated to represent the dynamics that underlie it. By considering the underlying interactions among the individual, group and environment drinking behaviours, the model is fit to employ the socio-ecological approach to aggregate the complex dynamics governing these three agents' interaction at the event. At the agent level, the model features a modified version of the second-order alcohol metabolism model employed in our earlier work (Giraldo, Passino, & Clapp, 2017; Giraldo, Passino, Clapp, & Ruderman, 2017) with parameter design using experimental data. A self-regulation approach is employed to model the agents' decision on their drinking rates. A particular agent computes the drinking rate based on the biased perception of his/her own and the other agents' drinking behaviours, defined here by the BAC, the BAC rate of change and the observable drinking rate. The acute cognitive effects on perception and goal setting are combined with the priming (craving) effect of alcohol to introduce nonlinearities in the model. The role of social norms is also considered in this model by allowing an agent to overestimate the other agents' drinking behaviour elements.

Sensitivity analysis performed on the individual agent at a drinking event revealed the incremental impact on the peak BAC of the acute cognitive effect of alcohol. Individuals more susceptible to show cognitive effects were unwilling to stop drinking after reaching their initial peak BAC and continue drinking, reaching higher BAC levels. The literature of alcohol myopia (Steele & Josephs, 1990) suggests similar results. The potential for social norm intervention was highlighted when analysing the incremental effect on the individuals' peak BAC due to the overestimation of the drinking behaviour elements by the agents. Also, individuals with low abilities to self-regulate towards their initial planned drinking behaviour are prone to exceed their planned peak BAC, influenced by the group and the environment to drink at a faster rate.

This work studied potential leverage points for interventions that provide behavioural input to persuade individuals to follow safe drinking behaviours tailored for each agent. When exploring the implications of the sensitivity analysis results for the design of in situ interventions during drinking events, it is seen that lower peak BAC employed in the safe behaviour trajectories results in more effective interventions, as measured by the lower persuasive effort employed to maintain low alcohol consumption in the agents. For the case analysed in this work, intermediate levels of peak BAC, between 0.025 and 0.075 g/dl, in the safe trajectory resulted in higher persuasive efforts, attempted to counteract the acute cognitive effect of alcohol, which increases with the agent's BAC. Results in this work suggest that intervention at the group level could lower risky drinking behaviour at the event level, with lower implementation effort. This is achieved by taking advantage of the influence of the group in the individuals' decision-making.

The calibration of the model parameters employed data from experiments that were recorded in discrete time with large sample time (e.g., before and after the event; see Gonzalez Villasanti et al., 2019 for details on the calibration process). The parameter estimation process would improve if the data employed were sampled with smaller intervals. This highlights the need for developing drinking event experiments that leverage strategies such as ecological momentary assessments or transdermal monitors that can capture the agents' BAC and drinking rate per second during the event (see Clapp, Madden, Mooney, & Dahlquist, 2017 for an example). Rigorous theoretical and practical assessments of sensors and actuators are also needed for implementing the behavioural feedback-based interventions described in this work. The use of wearables and the need for environment-level sensing may require the use of state observers, employed in control theory to provide estimates of unobservable variables. In Gonzalez Villasanti et al. (2019), it was shown that the controllability of the intervened event depended greatly on the influence of the environment agent's drinking behaviour in the individuals. However, a proper design and implementation of the actuators needed for this intervention at the individual and group level (e.g., smartphone application or dedicated device) will require more sophisticated cognitive models that capture the agents' behaviour change dynamics and the limits on persuasiveness of these actuators. Furthermore, with minor transformations, the model presented in this paper could be employed to analyse interventions aimed at reducing the abuse of other controlled substances (Wakeland, Nielsen, & Geissert, 2015).

Expanding our understanding of drinking events and the dynamics that underlie them is important in order to inform prevention efforts. These interventions can take advantage of technological advances to accurately sense the drinking behaviour variables and actuate in situ to reduce excessive alcohol consumption. Our model and previous work (Giraldo, Passino, & Clapp, 2017; Giraldo, Passino, Clapp, & Ruderman, 2017; Clapp et al., 2018; Gonzalez Villasanti et al., 2019) advance a conceptual approach, which we hope will assist in the development of prevention approaches.

ORCID

Danielle Madden https://orcid.org/0000-0001-5145-8116

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SUPPORTING INFORMATION

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