Systems Research and Behavioral Science
Syst. Res **35**, 265–281 (2018)
Published online 15 January 2018 in Wiley Online Library
(wileyonlinelibrary.com) **DOI**: 10.1002/sres.2478

■ *Research Paper*

A System Dynamic Model of Drinking Events: Multi-Level Ecological Approach

John D. Clapp[1], Danielle R. Madden[1]*, Hugo Gonzalez Villasanti[2], Luis Felipe Giraldo[3], Kevin M. Passino[2], Mark B. Reed[4] and Isabel Fernandez Puentes[2]

[1] *USC Suzanne Dworak-Peck School of Social Work, University of Southern California, Los Angeles, CA, USA*
[2] *Electrical and Computer Engineering, The Ohio State University, Columbus, OH USA*
[3] *Department of Electrical and Electronics Engineering, Universidad de Los Andes, Bogota, Colombia*
[4] *School of Social Work, San Diego State University, San Diego, CA USA*

Drinking events are dynamic. The interactions of individuals, groups, and the environment as they relate to drinking behaviour are overwhelmingly complex. This paper presents an empirically grounded dynamic conceptual model to better understand drinking events. Using a collaborative mixed-methods approach, we developed an aggregated system dynamic model of drinking events. The process began with identification of system elements and boundaries. Once the first aspects of the model were completed, we constructed a causal loop diagram, an aggregated causal loop diagram, and stock and flow diagrams. Finally, we developed and ran computer simulations of the dynamical models. The model presented here can be used to guide future agent-based, system dynamics, or differential equation-based models. Such models can help inform future empirical work and modelling to increase the understanding of drinking events and provide solutions to the problems that happen proximal to these events. Copyright © 2018 John Wiley & Sons, Ltd.

Keywords conceptual models; drinking events; drinking behaviour; theoretical constructs

WHAT IS A DRINKING EVENT? TOWARD A SYSTEM DYNAMICS MODEL

Over the past half-century, a small but growing body of research has emerged with the goal of better understanding drinking behaviour as it naturally occurs. Researchers hoping to better understand how and why drinkers become intoxicated and experience related problems have struggled to untangle the complexities of an inherently ecological problem. Reflecting the multi-disciplinary nature of alcohol research, event studies vary in conceptual foci, methodology, and operational definitions. Independently, studies on 'drinking contexts', 'drinking situations', and 'drinking environments' offer related

*Correspondence to: Danielle R. Madden, College of Social Work, The Ohio State University, 1947 College Rd. N., Columbus, OH 43210, USA.
E-mail: madden.208@osu.edu

Received 5 December 2016
Accepted 5 July 2017

but unique insights into drinking behaviour *in situ*. As a collective body of work, such studies suggest the need for and offer the empirical basis of a conceptual modelling approach reflecting the complex and dynamic natures of drinking events.

Although conceptual models and theory have long guided social science in general (Lewin, 1951; Kuhn, 1974) and alcohol studies specifically (Denzin, 1987; Gusfield, 1996), models for drinking events rarely build on previous work, transcend theoretical streams, or acknowledge dynamics and complexity (e.g., nonlinearity, random effects, and feedback loops). Although there is a small body of system dynamic alcohol studies at the community level (Gorman *et al.*, 2001; Gruenewald, 2006; Holder, 2006; Scribner *et al.*, 2009) and some recent notable exceptions employing agent-based modelling (Gorman *et al.*, 2006; Fitzpatrick and Martinez, 2012) at the population and event levels, dynamical modelling in alcohol research is still largely underdeveloped. At the event level, this may well be an artefact of the difficultly of measuring drinking events (Clapp *et al.*, 2007; Kuntsche *et al.*, 2014).

Although recent advances in data collection technologies (Riley *et al.*, 2011; Leffingwell *et al.*, 2013) have the potential to advance our understanding of event-level drinking behaviour, Riley *et al.* (2011, p.54) note that our ability to collect individualized, context-specific data and to intervene *in situ* has surpassed our current theories. The authors note that 'health behavior models that have dynamic, regulatory system components to guide rapid intervention adaptation based on the individual's current and past behavior and situational context' are greatly needed. Recent studies have begun to embrace mobile continuous monitoring of physiological measures, like heart rate, as a means of monitoring drug and alcohol relapse triggers prior to having a solid theoretical understanding of the underlying relationship between this indicator and relapse triggers (Kennedy *et al.*, 2015). A clearer understanding of dynamical relationships during drinking events will likely complement the future uses of such technologies by identifying key leverage points for targeted intervention.

In this paper, we offer a dynamic conceptual model of drinking events that is grounded in the extant literature. Before presenting the conceptual framework, we briefly review the historical approaches to understanding drinking events. We also discuss the conceptual importance of drinking events for understanding drinking behaviour as a whole and preventing acute problems.

WHY ARE DRINKING EVENTS IMPORTANT?

Drinking events are direct antecedents to numerous acute alcohol-related problems including injuries, sexual and other violence, burns, falls, crashes, and crime, among many other problems (NIH, 2000). In aggregate, drinking events represent patterns of consumption that drive disease and premature death (Holder, 2006). Acute problems have a huge global impact (Rehm *et al.*, 2009); for instance, approximately 25% of all unintentional and 10% of intentional injuries in the world can be attributed to drinking events. When alcohol-related disease and death are considered, 3–4% of all deaths in the world are alcohol-related (Rehm *et al.*, 2009).

Although heavier drinkers or those with alcohol-use disorders are at higher risk to experience acute problems, lighter and moderate drinkers who engage in heavy episodic drinking account for the bulk of acute alcohol-related problems (Stockwell *et al.*, 1996). This so-called 'prevention paradox' (Kreitman, 1986) suggests that universal environmental approaches (e.g., driving under the influence campaigns, responsible beverage service, taxation, and regulation) have historically been the primary means for preventing acute alcohol problems. Although a solid evidence base exists for environmental alcohol interventions (Holder, 2006; Saltz *et al.*, 2010), newer 'smart' interventions (e.g., geofencing and SMS prompts) have the potential to complement universal environmental prevention efforts by targeting group-level or individual-level 'leverage points' (Stokols, 2000) in real time while considering the current behavioural environment.

DOI: 10.1002/sres.2478

PAST APPROACHES TO UNDERSTANDING DRINKING EVENTS

The conceptualization, definition, and measurement of drinking events have evolved little in recent decades. Over 30 years ago, the National Institute on Alcohol Abuse and Alcoholism published a monograph titled *Social Drinking Contexts* (Harford and Gaines, 1982). In the introduction to that collection of conference papers, Hartford and Gaines noted, 'While context, or frame of reference, may hold the key to understanding drinking behavior, no single idiom describes context' (p.1). The authors go on to note that the multi-disciplinary nature of alcohol studies related to context reflects a spectrum of terms and units of analysis. The nomenclature and taxonomies used to frame drinking events still reflect such diversity.

In that same volume, drawing from the basic social psychology theory of Lewin (1951), Jessor (1982) offered a simple multi-level representation:

$$DB = f\,(P, E)$$

In this formula, drinking behaviour is a function of the interaction of person-level variables and environment influences. Jessor explicitly defines 'context' as 'environment'. In his discussion, he notes two important considerations. First, '(the environment) persists in being a concept of disturbing *complexity*' (p.230; emphasis added). And then, 'the *dynamics* of situations give rise to changes in situations and behavior over time … an obvious source of such change is … alcohol ingestion … and its disinhibition effects' (p. 231; emphasis added).

Some three decades later, understanding drinking events from a system perspective remains a vexing problem. Since the publication of *Social Drinking Contexts* (Harford and Gaines, 1982), there has been great variation in the conceptualization, measurement, and analysis of drinking events. To start, it is important to note that there is no standard definition of 'drinking event'. Consistent with Jessor's (1982) basic model, we conceptualize drinking events as including a drinker interacting socially with a network of other drinkers (and non-drinkers), embedded in larger social and physical environments. Conceptually, we view the event as a system that activates when drinking begins and achieves entropy when both active drinking has ceased and the social purpose of the event has concluded. This approach differs from the now-common practice of segmenting drinking events into time-specific (e.g., pre-gaming), social (e.g., drinking games), and/or geospatial (e.g., bars) elements. Although analytically useful, such segmentation may obscure our understanding of the system as a whole and the complex nature of these events (Miller and Page, 2007). For instance, over the course of an individual's drinking event, pre-gaming can occur in a small private setting, followed by drinking games in a larger party setting and culminating with drinking in a public setting like a bar. Each activity and setting comes with its own dynamics (Clapp *et al.*, 2008; Clapp *et al.*, 2009; Fitzpatrick and Martinez, 2012), resulting in complexity (i.e., multi-level) and transitory risk (and protection) across an entire event. Individuals interact socially with peers, while their personal decisions and desires are potentially influenced by group dynamics, the larger environment, and their own level of intoxication. Segmented approaches to studying drinking events miss much of this behaviour.

This paper hopes to further the scientific understanding of the dynamics surrounding drinking behaviour as it naturally occurs. There are several dynamic problems related to drinking. First, although the biological dynamics associated with metabolism and blood alcohol content (BAC) have been modelled, little is known about how individual desires relate to drinking effects (i.e., the rate of drinking, peak blood alcohol levels, and blood alcohol concentration curves) or how the consumption of alcohol impacts one's personal desires over the course of an event. Further, our model addresses the dynamical problem related to how a drinker's drinking companions influence a drinker's desires; in turn, the model postulates the dynamics of how a drinker influences their drinking companions. Finally, the model addresses how the drinking group influences, and is influenced by, the drinking environment. As a system, we view these dynamics as being critical to better understanding the

Syst. Res **35**, 265–281 (2018)
DOI: 10.1002/sres.2478

complex nature of drinking as a social behaviour that is inherently ecological.

METHODS

Our general approach to developing a dynamic-driven framework for drinking events is consistent with Pentland's (2014, pg. 5) approach to social physics: 'Just as the goal of traditional physics is to understand how the flow of energy translates into changes in motion', our aim is to understand how different social or environmental factors translate into changes in the dynamics of a drinking event. While there is no standard approach to developing dynamical models, we followed an approach similar to others (Richardson and Pugh, 1981; Sterman, 2002) by engaging in the following steps to develop our model: (i) problem definition; (ii) system conceptualization; (iii) model formulation; (iv) testing and simulation; and (v) model evaluation. We note that steps ii–v follow an iterative process.

The model presented in the succeeding texts represents our work to date. Consistent with others (Richmond, 2004; Sterman, 2002), we are approaching this modelling as an ongoing process that includes both conceptual and empirical stages. Here, we present our conceptual work in a form we hope will facilitate its use by others.

Modelling Context

Our team consists of two full professors (one in social work, one in engineering) and four doctoral students (one in social work, three in engineering) working at the same university. In addition, we have a social work professor working at another institution who did not participate in all modelling activities but served as a reviewer—evaluating the logic of the models relative to the existing literature, in addition to other tasks as the model developed. The social work members of the team have extensive experience in studying drinking events and drinking behaviour *in situ* (Clapp and Shillington, 2001; Clapp *et al.*, 2003; Clapp *et al.*, 2007; Clapp *et al.*, 2008; Clapp *et al.*, 2009), and the engineering members have extensive experience in system dynamic modelling of behaviour (Passino and Seeley, 2006; Passino *et al.*, 2008).

The team met twice monthly (about 90 min per session) to work on modelling. Group members took extensive notes and minutes, including graphic depictions of concepts, and those notes were circulated regularly. It was common for group members to take on assignments between meetings. An in-depth description of the team science aspects of this process is currently in progress.

Problem Definition

In the early phases of the collaboration, the social work partners presented alcohol research related to drinking events (Clapp *et al.*, 2008; Wells *et al.*, 2008; Thombs *et al.*, 2010; Neighbors *et al.*, 2011; Clapp *et al.*, 2014; Kuntsche *et al.*, 2015). These presentations helped to define the problem by specifically identifying the key elements of the drinking event system. Examples related to the influence of variables at different levels of abstraction were discussed in depth. For instance, the relationship between a drinker's motivation and BAC at the individual level (see: Neal and Carey, 2007; Wetherill and Fromme, 2009; O'Grady *et al.*, 2011) was discussed. Similarly, studies related to group influence on drinking (see Cullum *et al.*, 2012; Reed *et al.*, 2013; Wells *et al.*, 2015) and environmental influences on drinking (see Clapp *et al.*, 2008; Clapp *et al.*, 2009) were discussed. Additionally, the engineering team read key papers related to BAC metabolism (Lundquist and Wolthers, 1958; Wilkinson, 1980; Norberg *et al.*, 2003; Jones, 2010).

System Conceptualization

Consistent with Richmond (2004), we developed hypothesized dynamical 'behavior over time graphs' and causal loop diagrams (CLDs) along with other visuals to illustrate concepts and potential dynamics during this stage of the work. In turn, the engineering members presented simulations of computational models—based on the materials presented by the social work members

Syst. Res **35**, 265–281 (2018)
DOI: 10.1002/sres.2478

—and explained underlying mathematical concepts. Early simulations were based on field data collected by one of the team members in a previous project (Clapp *et al.*, 2009). Mathematical models, proofs, and simulations related to the conceptual elements of the model presented in this paper have been published in engineering journals (Giraldo *et al.*, 2017a, 2017b).

Model Formulation

During this phase of the work, the group jointly constructed stock and flow diagrams based on the CLDs. We discussed the dynamics relative to what would be expected logically—for example, one with strong motives to become 'drunk' would likely have a higher BAC than a drinker with motives to become 'buzzed'. Once the qualitative assessment of the initial stock and flow diagrams was complete, the engineering team developed a computational model to illustrate the dynamics of BAC metabolism and the group influence aspects of the model (Giraldo *et al.*, 2017a).

Testing and Simulation

Computational models were built for environmental dynamics as well. Those models and simulations were all performed in Simulink. To facilitate the social work team's understanding of mathematical models, and to ensure that the engineering team had gotten drinking concepts correctly represented, generic versions using representative parameters of variables were constructed in STELLA and Vensim, collaboratively by our team.

Model Evaluation

The final stage of the initial modelling process involved qualitative and quantitative assessments of the simulation results. Qualitatively, the team assessed simulation results relative to the extant literature on drinking events. For instance, researchers (Trim *et al.*, 2011) have shown that a drinker's desired level of intoxication at the beginning of an event often fails to match the outcome (i.e., they become more or less intoxicated than they intended), suggesting that the interaction of the individual's drinking and endogenous factors (i.e., group influences or environmental influences) are dynamically linked. As such, our model needed to allow for both 'under-shooting' and 'over-shooting' of BAC over the course of an event. The models developed in previous stages were reviewed for this characteristic and others described in the results. Mathematically, the underlying differential equations had to have sound and demonstrated proofs (Giraldo *et al.*, 2017a, 2017b).

RESULTS

Figure 1 represents an overall conceptual model of drinking events. The figure depicts individuals during a drinking event (smallest circles), who are situated in groups (enclosed in the same medium-sized circle), drinking in specific environments (the largest circles). Lines between individuals represent communication between group members, across groups, or between people in different locations. Our model focuses on the aspects of a drinking event for only one of these hypothetical drinkers (for example, the individual marked A). The model is conceptually an extension of Jessor's simple heuristic path model of drinking behaviour. That is, we have begun to fill in the various ecological elements at the person level (i.e., biological variables and psychological variables) that theoretically drive the dynamics within the overall drinking event system.

Figure 2 presents the CLD for the drinking event system. Conceptually, our model included four key stocks: (i) BAC; (ii) desired state (of intoxication) or desired BAC; (iii) group wetness, and (iv) environmental wetness. From a social ecological framework, BAC and desired state are micro-level variables, group wetness is a mezzo-level variable, and environmental wetness is a macro-level variable. Together, these stocks represent the various levels of abstraction found in the literature examining drinking events (Jessor, 1982; Clapp *et al.*, 2009; Reed *et al.*, 2013) in a highly aggregated model consistent with a 10 000 foot view of the system (Richmond, 2004).

Syst. Res 35, 265–281 (2018)
DOI: 10.1002/sres.2478

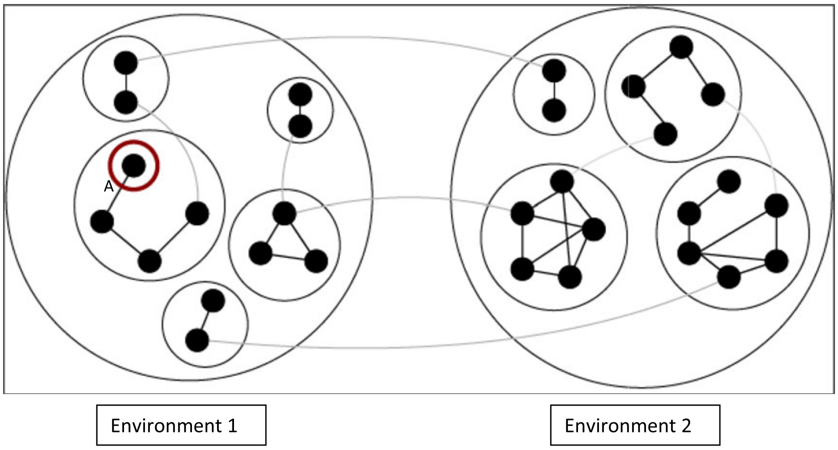

Figure 1 Conceptual model of drinking events. [Colour figure can be viewed at wileyonlinelibrary.com]

Beginning from the bottom of the CLD (micro-level) in Figure 2, there is a balancing causal feedback loop between the BAC stock and the metabolic rate (Giraldo *et al.*, 2017a). A delay is introduced before the BAC stock, representing the transit of alcohol through the gastrointestinal tract before entering the blood by an absorption process (it could also be delayed further by food intake). Put in practical terms, decisions by drinkers whether to have another drink to maintain or obtain a 'buzz' are often based on a misperception of the amount of alcohol they have in their system (Richmond, 2004).

Moving up a level, the feedback loop related to drinking motives, perceptions of intoxication, and drinking behaviour is represented. This loop segment of the CDL can be thought of as the 'goal seeking' segment of the model. As noted in the structure of the CLD, there is a tension between the rational desire to obtain a desired state of intoxication and maintain it (in a balancing feedback loop) and the 'alcohol myopia' or the disinhibitory effects of alcohol on cognitive control (reinforcing loop), where an individual's desire to drink might increase *in vivo* with the net effect of over-shooting their original desired state of intoxication (Steele and Josephs, 1990; Field *et al.*, 2010). A full operational model including all stocks, flows, and connectors is presented in the appendix.

Continuing with Figure 2 and moving up a level of abstraction, the drinker's desired BAC stock is also influenced by the group wetness stock in a reinforcing feedback structure. As described in Table 1, group wetness is a form of social influence that includes the average BAC of a drinker's companions at the drinking event, the average desired BAC of the drinker's companions, and the relative influence of each member of the group on the drinker. In our earlier work (Giraldo *et al.*, 2017a), we modelled how peer influence varies in strength and interacts with a drinker's own desired state to alter drinking trajectories. Through a series of computer simulations, we showed that a strong influence within a peer network pulls all but those with very strong desires toward a BAC trajectory similar to the peer exerting the influence. In turn, completing this reinforcing feedback loop as a member of the group, the drinker's BAC and desired BAC also influence the group wetness stock.

Finally, moving to the top of the CLD in Figure 2 to the group and environmental levels, we posit a reinforcing feedback loop between group wetness and environmental wetness. Our earlier studies of drinking events (Clapp *et al.*, 2000; Clapp *et al.*, 2009) found that the presence of 'many intoxicated people' (whether observed by researchers or reported by survey respondents) consistently contributed to high BAC or self-reported heavy drinking. We also found that heavier drinkers seek out wetter environments (Trim *et al.*, 2011), suggesting that influence flows

Syst. Res **35**, 265–281 (2018)
DOI: 10.1002/sres.2478

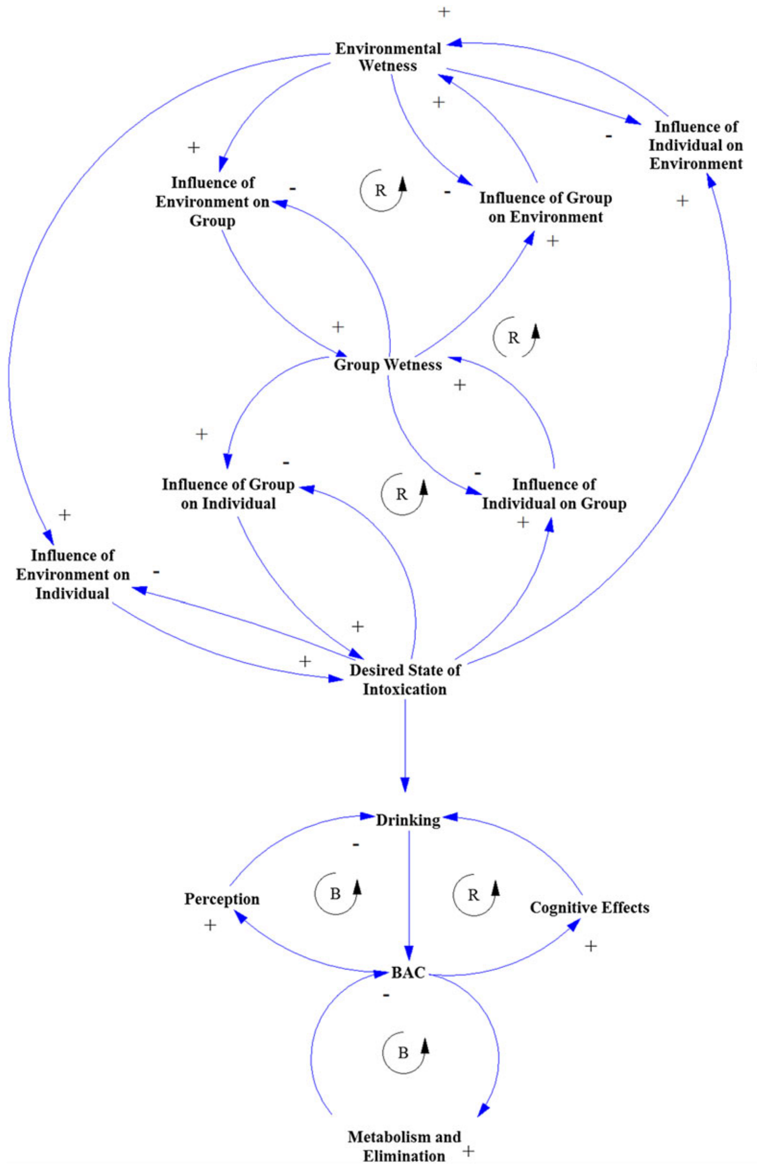

Figure 2 Causal loop diagram for drinking event system. [Colour figure can be viewed at wileyonlinelibrary.com]

in both directions. As group wetness increases, environmental wetness increases. In turn, environmental wetness, which represents the overall average BAC among bar patrons coupled with alcohol availability in the environment (Clapp *et al.*, 2009), influences group wetness in a reinforcing way.

Table 1 describes each element in the model, except for the GAC stock, which simply represents the aggregate amount of alcohol (for example, the unit of measure could be standard drinks) residing in the gastrointestinal tract. We offer basic definitions of each element, theoretical parameters (based on our mathematical models), how the elements might be measured (or have been), and some assumptions about how each element operates in the system based on the literature and our previous research.

DOI: 10.1002/sres.2478

Table 1 Description of elements in the model

	BAC	Desired BAC	Group wetness	Environmental wetness
Ecological level of abstraction	Biological Micro	Psychological Micro	Social Mezzo	Social/physical Macro
Definition	Represents the drinker's blood alcohol concentration	The state of intoxication a drinker hopes to obtain at any given point during the drinking event	Represents the mean BAC of the peer group over the event. Could also include mean of group's desired state	Represents the extent the environment promotes heavy drinking
Parameters	Grams of ethanol/100 ML of blood Values range from 0.0 to 0.30 (bounded not to go below 0.0 or above 0.30 to reflect typical values) A standard drink = 0.02 (+) in BAC Metabolism = 0.02 ( ) in BAC per hour (Dubowski, 1985)	Measured on Likert scale with values ranging from 'drink but not get buzzed' to 'drink to get very drunk' Can also measure *strength* of desire by Likert scale (Clapp *et al.*, 2009; Thombs *et al.*, 2010)	Mean values ranging from 0.0 to 0.30	Measured by an index of availability including average dollar amount per standard drink, average time to obtain a drink, and the number of fixed and temporary servers. Could also include the social aspects of the environment such as the presence of many intoxicated people (Clapp *et al.*, 2009)
Assumptions	Influenced by rate and volume of drinking Influences desired state Food delays metabolism. Delay drinking and ability to perceive BAC level	May be conscious or subconscious Can shift over the course of event Initial strength of desire relates to likelihood of change Influences and is influenced by group wetness Some group members might have more influence than others.	Influences individual drinker's BAC and desired state Is influenced by individual drinker's BAC and desired state Influences and is influenced by environmental wetness and selection	Influences and is influenced by group wetness Influences and is influenced by individual drinker BAC and desired state Is selected based on the weighted mean of a group's desired state (giving more weight to influential group members

Figure 3 shows a series of our hypothesized reference behaviour of time graphs for various BAC outcomes generated via simulation of the model found in Figure A.1. Although we are interested in conceptually understanding the entire drinking event system, understanding how different elements of the model affect the BAC is particularly important for guiding prevention efforts. The graphs shown in Figure 3A portray the effect of metabolism on BAC. The plots in Figure 3B shed light on the reinforcing cognitive effects on BAC, while the plots in Figure 3C show the effect of peer and environment influence on individual's intoxication. In all cases, it is assumed that the drinking period lasts for 3 h. The model parameters are provided in Table 2.

DOI: 10.1002/sres.2478

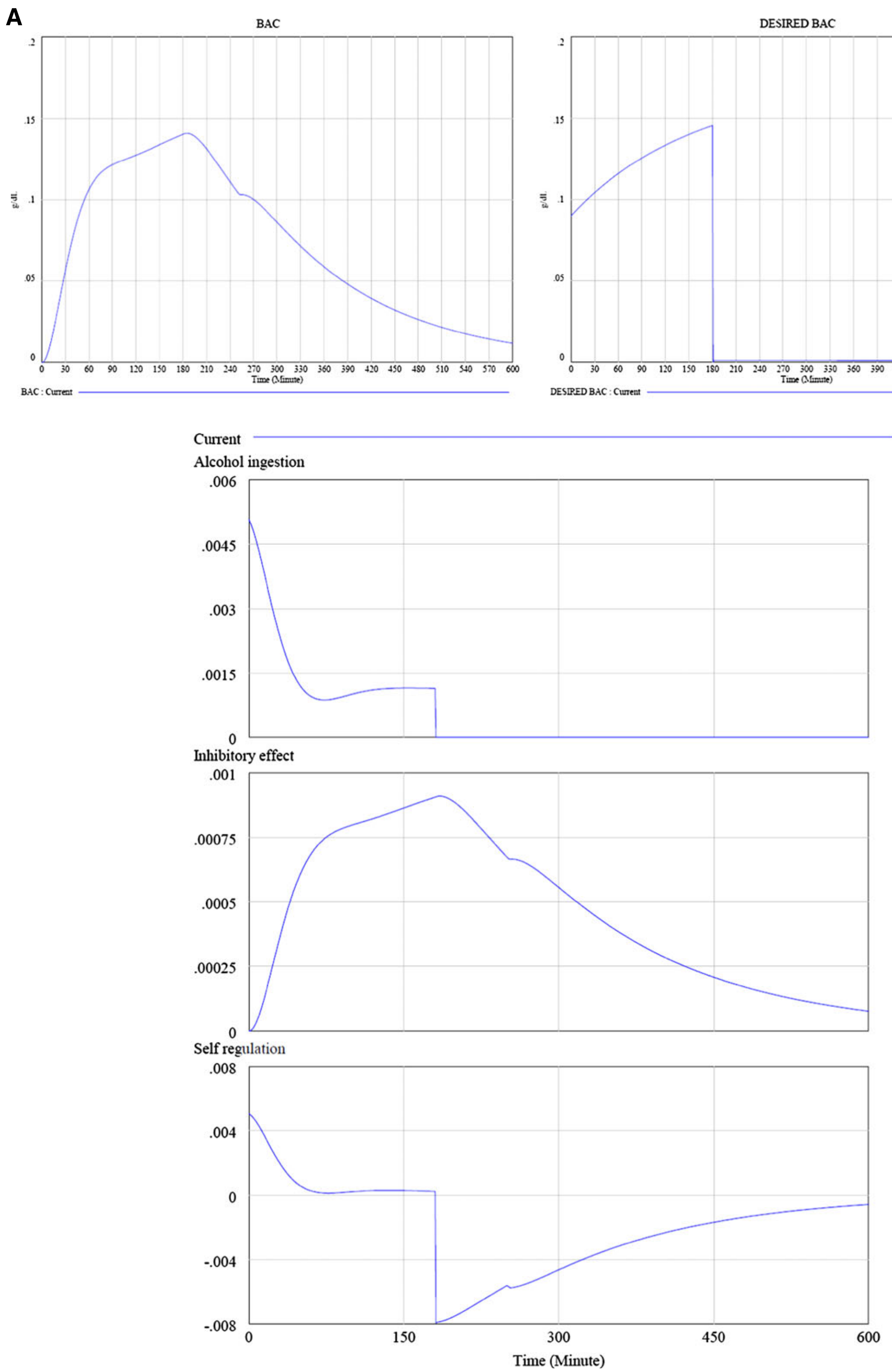

Figure 3 Blood alcohol content (BAC) curves under different conditions. [Colour figure can be viewed at wileyonlinelibrary.com]

Syst. Res **35**, 265–281 (2018)
DOI: 10.1002/sres.2478

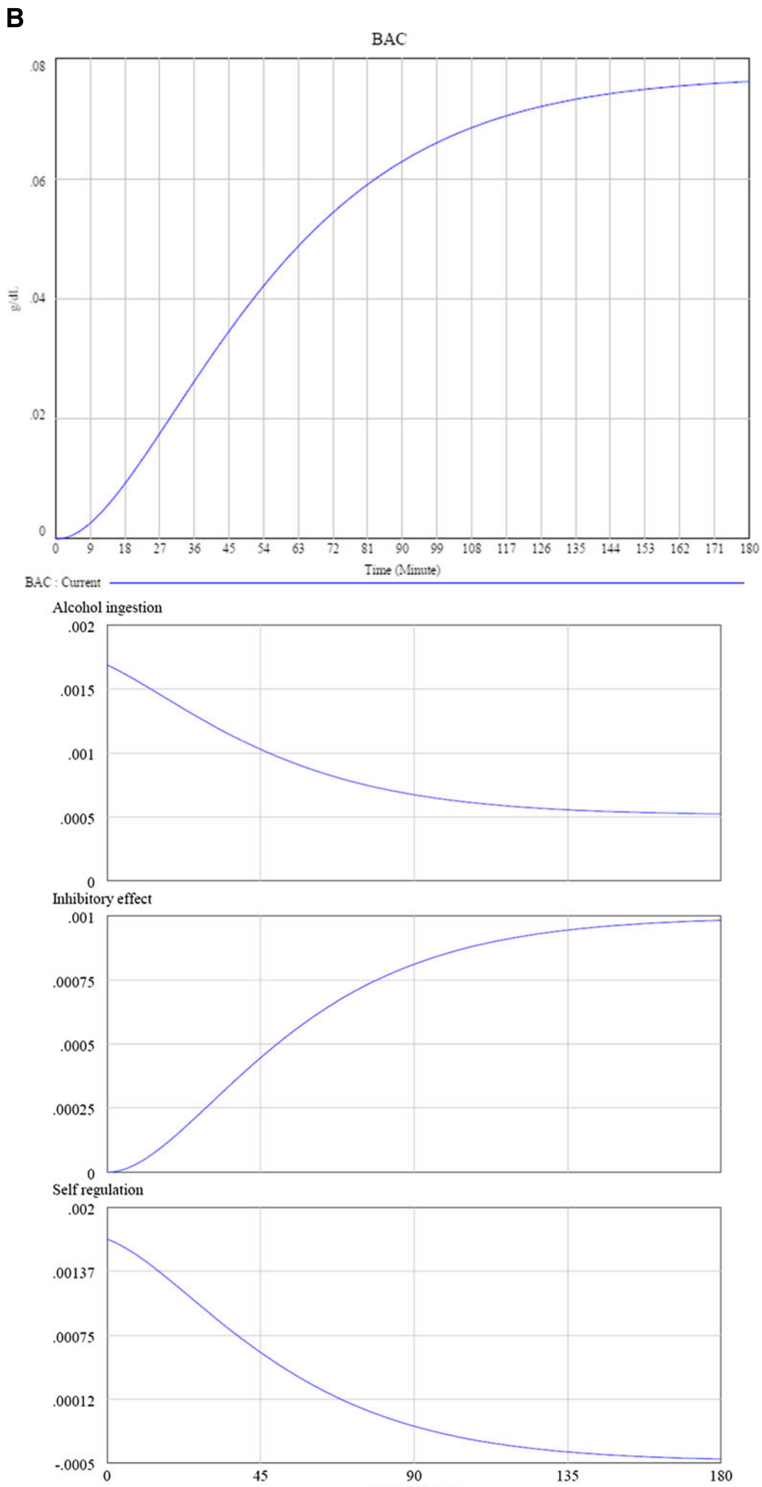

Figure 3 Continued

Syst. Res **35**, 265–281 (2018)
DOI: 10.1002/sres.2478

C

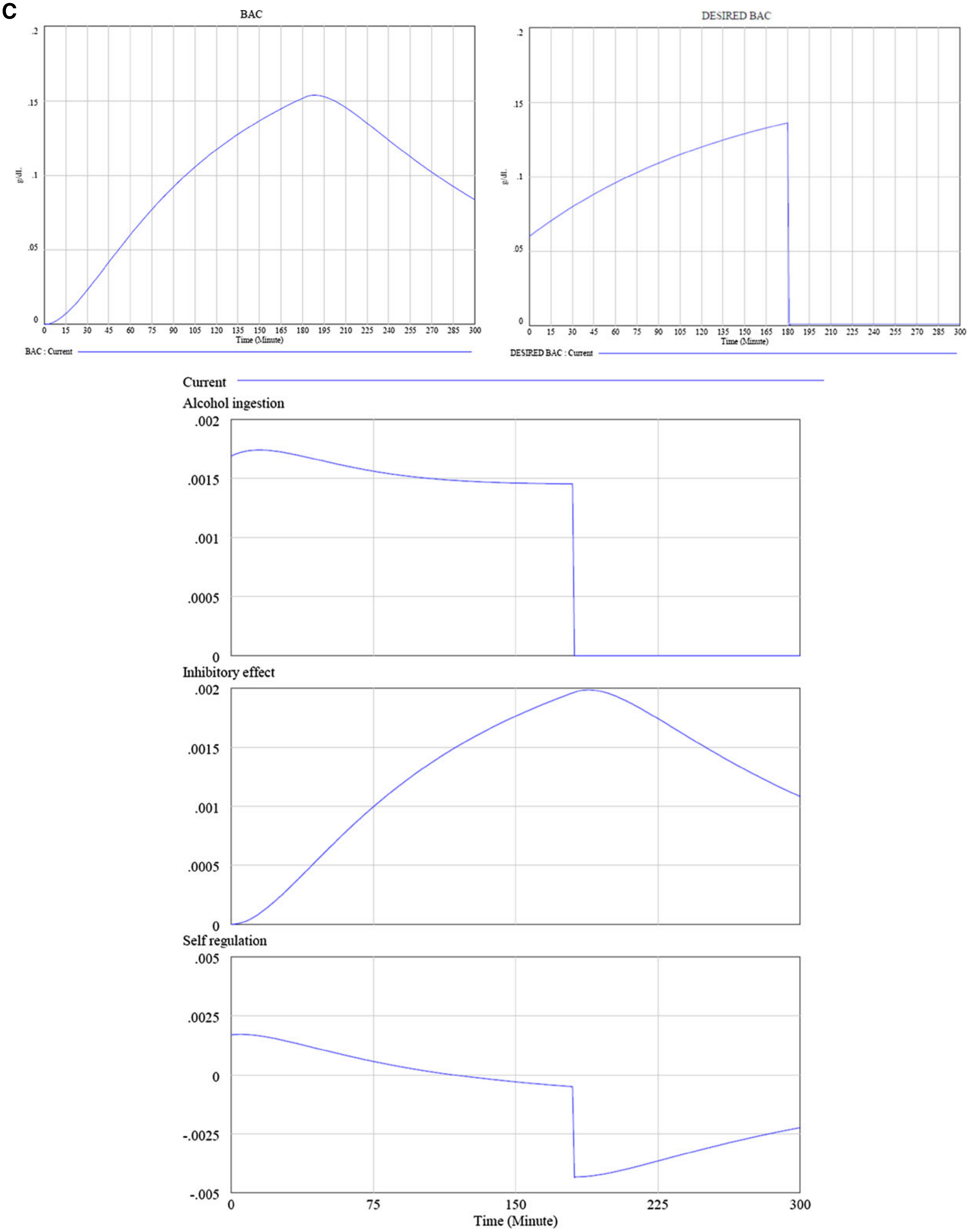

Figure 3 Continued

DOI: 10.1002/sres.2478

Table 2 Model parameters

Figure	Parameter	Value
3A	Elimination parameter	0.0067
	Absorption parameter	0.05
	Effect of food	0
	BAC rate perception parameter	0.1
	Decision commitment	0.0225
	Alcohol in CNS/blood ratio	0.6451
	Inhibitory effect parameter	0.01
	Env strength on individual	0
	Group strength on individual	0
	Initial desired BAC	0.1
	Initial GAC and BAC	0
3B	Inhibitory effect parameter	0.02
	Initial desired BAC	0.03
3C	Env strength on individual	0.002
	Group strength on individual	0.005
	Ind strength on group	0.0005
	Ind strength on Env	0.0005
	Group strength on Env	0.0005
	Env strength on group	0.002
	Initial desired BAC	0.06

Note: Parameters not listed in Figures 3B and 3C remain the same as in Figure 3A

While the graphs in Figures 3B and 3C only illustrate 'peak' BAC and do not show the decline of BAC back to zero, Figure 3A shows the entire BAC curve for a drinker who desired to become 'very buzzed or drunk'. As presented, the drinker reaches a peak BAC of over 0.1 by hour 3 of the event, before the BAC begins to decrease slowly. The fluctuations in the decreasing BAC are due to consumption of more alcohol after stopping drinking for a period. The steep growth of BAC in the early hours of the event is related to the rate of drinking. That is, to obtain the BAC shown, the rate of drinking would be fairly fast.

The graph shown in Figure 3B illustrates the BAC curve for a drinker with the desire to 'get buzzed (desired BAC = 0.06)', with low influence from the group and environment wetness, so his desired BAC remains constant. In this graph, the drinker reaches the desired intoxication level after 80 min of drinking. However, due to the disinhibitory effect that increases his desire to drink, the individual does not decrease the drinking rate to zero but continues drinking at a lower rate, increasing his BAC level.

The final graph in the series, Figure 3C, illustrates a drinker who desires to 'get buzzed (desired BAC = 0.06)' but is pulled off that trajectory later in the event. Conceptually, such 'overshooting' is a function of group and/or environmental dynamics. Empirically, we found this to be fairly common during drinking events (Clapp *et al.*, 2009; Giraldo *et al.*, 2017a; Trim *et al.*, 2011). The mathematics underlying the dynamics of overshooting or undershooting desired intoxication levels is presented in our more technical work (Giraldo *et al.*, 2017a).

Finally, Appendix presents potential random variables (disturbances), at each level of abstraction that, theoretically, might alter the dynamics in the model. The list is provided as both a means to set the exogenous boundaries of the model and to guide potential simulations in the future.

DISCUSSION

Drinking events remain an important area of study for alcohol researchers. Understanding drinking events and the complex dynamics that underlie them is important both conceptually and to help guide prevention efforts that utilize 'smart' technologies *in situ*. Our model and previous work (Giraldo *et al.*, 2017a, 2017b) advance a conceptual approach, which we hope will aid understanding of drinking behaviour while guiding the development of prevention approaches.

By considering the underlying interactions among the biological, psychological, social, and environmental interactions related to drinking behaviour as it occurs, the model presented here is one of the few attempts to address the inherent complexity of drinking events noted by Jessor (1982) and Harford and Gaines (1982), over three decades ago. Our conceptual and mathematical results thus far begin to illustrate the potential of dynamics at several levels resulting in individuals drinking heavily and more than they initially intended. Initial intentions are important. In our model, we posit a reinforcing feedback loop among perceptions/cognitive effects, desired state, drinking, and BAC. In theory, a

DOI: 10.1002/sres.2478

drinker with the motivation to have a 'no buzz' or a 'slight buzz' who drank slowly enough to have fairly accurate perceptions of their intoxication (or stopped drinking after a drink or two) could be represented by a balancing feedback loop where equilibrium is achieved. However, as noted by other researchers (Trim *et al.*, 2011; Giraldo *et al.*, 2017a), drinkers' initial motives for a level of 'buzz' often do not reflect their actual BAC (i.e., drinkers become more intoxicated than intended). Further field work is needed to better understand how these dynamics might differ based on initial desires for intoxication.

The modelling efforts and simulation results presented here (fig. 3) illustrate the importance of dynamics in drinking behaviour. For instance, figure 3B shows how a drinker's desire impacts and is impacted by BAC levels. The issue of how one's BAC curve impacts an overall drinking event was raised by Jessor over 30 years ago (Jessor, 1982), yet little work to date has focused on this issue. Figure 3B illustrated an example of 'overshooting' where the drinker ends up drinking more than intended, resulting in a higher BAC. Figure 3C illustrates how the GI tract results in a delay in BAC, the mechanism that theoretically accounts for overshooting. Taken together, the simulation leaves in a manner consistent with the CLD presented in figure 2.

Future work—both empirical and computational—will be needed to validate and refine the conceptual model. Field studies with high ecological validity (Clapp *et al.*, 2007) are needed to examine social network influences as they relate to desired intoxication and actual drinking outcomes. Similarly, more work is needed to biologically validate BAC curves as they relate to elements of the drinking event system. Likewise, better understanding of how individuals decide to continue or stop drinking to achieve a desired level of intoxication must be better developed. Better measures of environmental wetness must also be created and tested. Finally, applying the knowledge generated by the dynamical modelling and validation process must identify leverage points to guide the development and testing of preventive interventions. Such work is never complete; nor is it easy.

Our approach required the collective effort of a team of scientists from disparate disciplines working together in a highly collaborative manner for a considerable period. Pulling together the relevant aspects of the drinking event, literature with appropriate mathematical formulations drawn from physics and engineering required both parties to be simultaneously open and critical. The extant literature on drinking events, with a few notable exceptions (Gorman *et al.*, 2006; Fitzpatrick and Martinez, 2012), rarely considers multiple levels of abstraction and is almost exclusively grounded in static linear models—making the jump to developing a dynamical model challenging. Similarly, the application of principles related to physics (like force and attraction) used in our computational work (Giraldo *et al.*, 2017a) had to be carefully applied to a social behaviour. As this line of work continues and, we hope, expands to other groups, the multi-disciplinary method described here must evolve into a transdisciplinary approach.

In this spirit, others have noted that system dynamic maps and CLDs are essentially heuristic devices to explain complex behaviour in an elegant and aggregate form (Richmond, 2004) and guide applied intervention work (BeLue *et al.*, 2012). One challenge of both the current work presented and future work will be to develop a common system of visual explanation (e.g., conventions for drawing CLDs, stock, and flow diagrams). CLDs and stock and flow diagrams can be useful when carefully presented. They can, however, be overly complex and confusing. Finding the correct balance of system specification that is ecologically valid without sacrificing accessibility can be challenging. Similarly, developing a common nomenclature for discussing and studying drinking events will be important. Beyond the scientific community, using collaborative model building approaches (BeLue *et al.*, 2012; Hovmand, 2013) and visual simulations using free software packages like Vensim and Mental Modeller might facilitate the understanding of these complex systems. Like others working on collaborative models to tackle important real-world problems, we hope that such efforts will help move science into applied situations faster and in a more ecologically valid way.

Syst. Res **35**, 265–281 (2018)
DOI: 10.1002/sres.2478

ACKNOWLEDGEMENTS

This study was conducted, in part, through funding from the College of Social Work at The Ohio State University.

REFERENCES

BeLue R, Carmack C, Myers KR, Weinreb-Welch L, Lengerich EJ. 2012. Systems thinking tools as applied to community-based participatory research: a case study. *Health Education & Behavior* **39**(6): 745–751.

Clapp JD, Shillington AM. 2001. Environmental predictors of heavy episodic drinking events. *The American Journal of Drug and Alcohol Abuse* **27**(2): 310–313.

Clapp JD, Shillington AM, Segars L. 2000. Deconstructing contexts of binge drinking among college students. *The American Journal of Drug and Alcohol Abuse.* **26**(1): 139–154.

Clapp JD, Lange J, Min JW, Shillington A, Johnson M, Voas R. 2003. Two studies examining environmental predictors of heavy drinking by college students. *Prevention Science* **4**(2): 99–108.

Clapp JD, Holmes MR, Reed MB, Shillington AM, Freisthler B, Lange JE. 2007. Measuring college students' alcohol consumption in natural drinking environments: field methodologies for bars and parties. *Evaluation Review* **31**(5): 469–489.

Clapp JD, Min JW, Shillington AM, Reed MB, Croff JK. 2008. Person and environment predictors of blood alcohol concentrations: a multi level study of college parties. *Alcoholism: Clinical and Experimental Research* **32**(1): 100–107.

Clapp JD, Reed MB, Min JW *et al.* 2009. Blood alcohol concentrations among bar patrons: a multi-level study of drinking behavior. *Drug and Alcohol Dependence* **102**: 41–48.

Clapp JD, Reed MB, Ruderman DE. 2014. The relationship between drinking games and intentions to continue drinking, intentions to drive after drinking, and adverse consequences: results of a field study. *The American Journal of Drug and Alcohol Abuse* **40**(5): 374–379.

Cullum J, O'Grady M, Armeli S, Tennen H. 2012. Change and stability in active and passive social influence dynamics during natural drinking events: a longitudinal measurement-burst study. *Journal of Social and Clinical Psychology* **31**(1): 51–80.

Denzin NK. 1987. *The Alcoholic Self*. Sage Publications: Thousand Oaks, CA.

Dubowski KM. 1985. Absorption, distribution and elimination of alcohol: highway safety aspects. *Journal of Studies on Alcohol, Supplement No.* **10**: 98–108.

Field M, Wiers RW, Christiansen P, Fillmore MT, Verster JC. 2010. Acute alcohol effects on inhibitory control and implicit cognition: implications for loss of control over drinking. *Alcoholism: Clinical and Experimental Research* **34**(8): 1346–1352.

Fitzpatrick B, Martinez J. 2012. Agent-based modeling of ecological niche theory and assortative drinking. *Journal of Artificial Societies and Social Simulation* **15**(2): 4–17.

Giraldo LF, Passino KM, Clapp JD. 2017a. Modeling and analysis of group dynamics in alcohol-consumption environments. *IEEE Transactions on Cybernetics* **47**(1): 165–176.

Giraldo LF, Passino KM, Clapp JD, Ruderman D. 2017b. Dynamics of metabolism and decision making during alcohol consumption: modeling and analysis. *IEEE Transactions on Cybernetics* **47**(11): 3955–3966.

Gorman DM, Speer PW, Gruenewald PJ, Labouvie EW. 2001. Spatial dynamics of alcohol availability, neighborhood structure and violent crime. *Journal of Studies on Alcohol and Drugs* **62**: 628–636.

Gorman DM, Mezic J, Mezic I, Gruenewald PJ. 2006. Agent-based modeling of drinking behavior: a preliminary model and potential applications to theory and practice. *American Journal of Public Health* **96**(11): 2055–2060.

Gruenewald PJ. 2006. The spatial ecology of alcohol problems: niche theory and assortative drinking. *Addiction* **102**(6): 870–878.

Gusfield JR. 1996. *Contested Meanings: The Construction of Alcohol Problems*. University of Wisconsin Press: Madison, WI.

Harford TC, Gaines LS. 1982. Social drinking contexts: an introduction. In Harford TC, Gaines LS, eds. Social Drinking Contexts: Proceedings of a Workshop. Research Monograph No 7. Rockville: NIAAA: 1-7.

Holder HD. 2006. *Alcohol and the Community: A Systems Approach to Prevention*. Cambridge University Press: Cambridge, UK.

Hovmand PS. 2013. *Community Based System Dynamics*. Springer: New York, NY.

Jessor R. 1982. Some problematic aspects of research on drinking contexts. In *Social Drinking Contexts: Proceedings of a Workshop*, Harford TC, Gaines LS (eds.), Research Monograph No 7. NIAAA: Rockville; 228–233.

Jones AW. 2010. Evidence-based survey of the elimination rates of ethanol from blood with applications in forensic casework. *Forensic Science International* **200**(1): 1–20.

Kennedy AP, Epstein DH, Jobes ML *et al.* 2015. Continuous in-the-field measurement of heart rate: correlates of drug use, craving, stress, and mood in polydrug users. *Drug and Alcohol Dependence* **151**: 159–166.

Kreitman N. 1986. Alcohol consumption and the preventive paradox. *British Journal of Addiction to Alcohol and Other Drugs* **81**: 353–363.

Kuhn A. 1974. *The Logic of Social Systems: A Unified Deductive System Based Approach to Social Science*. Jossey-Bass Publishers: San Francisco, CA.

Kuntsche E, Dietze P, Jenkinson R. 2014. Understanding alcohol and other drug use during the event. *Drug and Alcohol Review* **33**(4): 335–337.

Kuntsche E, Otten R, Labhart F. 2015. Identifying risky drinking patterns over the course of Saturday evenings: an event-level study. *Psychology of Addictive Behaviors* **39**(3): 744–752.

Leffingwell TR, Cooney NJ, Murphy JG *et al.* 2013. Continuous objective monitoring of alcohol use: twenty first century measurement using transdermal sensors. *Alcoholism: Clinical and Experimental Research* **37**(1): 16–22.

Lewin K. 1951. *Field Theory in Social Science: Selected Theoretical Papers*. Harpers: Oxford, UK.

Lundquist F, Wolthers H. 1958. The kinetics of alcohol elimination in man. *Acta Pharamcologica et Toxicologica* **14**(3): 265–289.

Miller JH, Page SE. 2007. *Complex Adaptive Systems: An Introduction to Computational Models of Social Life*. Princeton University Press: Princeton, NJ.

National Institute of Health. 2000. 10th special report to the U.S. congress on alcohol and health. U.S. Department of Health and Human Services.

Neal DJ, Carey KB. 2007. Association between alcohol intoxication and alcohol-related problems: an event-level analysis. *Psychology of Addictive Behaviors* **21**(2): 194–204.

Neighbors C, Atkins DC, Lewis MA *et al.* 2011. Event-specific drinking among college students. *Psychology of Addictive Behaviors* **25**(4): 702–707.

Norberg A, Jones AW, Hahn RG, Gabrielsson JL. 2003. Role of variability in explaining ethanol pharmacokinetics. *Clinical Pharmacokinetics* **42**(1): 1–31.

O'Grady MA, Cullum J, Tennen H, Armeli S. 2011. Daily relationship between event-specific drinking norms and alcohol use: a four-year longitudinal study. *Journal of Studies on Alcohol and Drugs* **72**: 633–641.

Passino K, Seeley TD. 2006. Modeling and analysis of nest-site selection by honey bee swarms: the speed and accuracy trade-off. *Behavioral Ecology and Sociobiology* **59**: 427–442.

Passino KM, Seeley TD, Visscher PK. 2008. Swarm cognition in honey bees. *Behavioral Ecology and Sociobiology* **62**: 401–414.

Pentland A. 2014. *Social Physics: How Good Ideas Spread—The Lessons From a New Science*. The Penguin Press: New York, NY.

Reed MB, Clapp JD, Martell B, Hidalgo-Sotelo A. 2013. The relationship between group size, intoxication and continuing to drink after bar attendance. *Drug and Alcohol Dependence* **133**: 198–203.

Rehm J, Mathers C, Popova S, Thavorncharoensap M, Teerawattananon Y, Patra J. 2009. Global burden of disease and injury and economic cost attributable to alcohol use and alcohol-use disorders. *The Lancet* **373**(9682): 2223–2233.

Richardson GP, Pugh AL. 1981. *Introduction to System Dynamics Modeling with Dynamo*. MIT Press: Cambridge, MA.

Richmond B. 2004. *An Introduction to Systems Thinking with STELLA*. isee systems, inc: Lebanon, NH.

Riley WT, Rivera DE, Atienza AA, Nilsen W, Allison SM, Mermelstein R. 2011. Health behavior models in the age of mobile interventions: are our theories up to the task? *Translational Behavioral Medicine* **1**(1): 53–71.

Saltz RF, Paschall MJ, McGaffigan RP, Nygaard PM. 2010. Alcohol risk management in college settings: the safer California universities randomized trial. *American Journal of Preventive Medicine* **39**(6): 491–499.

Scribner R, Ackleh AS, Fitzpatrick BG *et al.* 2009. A systems approach to college drinking: development of a deterministic model for testing alcohol control polices. *Journal of Studies on Alcohol and Drugs* **70**: 805–821.

Steele CM, Josephs RA. 1990. Alcohol myopia. Its prized and dangerous effects. *American Psychologist* **45**(8): 921–933.

Sterman JD. 2002. All models are wrong: reflections on becoming a systems scientist. *System Dynamics Review* **18**(4): 501–531.

Stockwell T, Hawks D, Lang E, Rydon P. 1996. Unravelling the preventive paradox for acute alcohol problems. *Drug and Alcohol Review* **15**(1): 7–15.

Stokols D. 2000. Creating health-promotive environments: implications for research and theory. In *Promoting Human Wellness: New Frontiers for Research and Practice*, Jamner MS, Stokols D (eds.). University of California Press: Berkeley, CA; 135–162.

Thombs DL, O'Mara RJ, Tsukamoto M *et al.* 2010. Event-level analyses of energy drink consumption and alcohol intoxication in bar patrons. *Addictive Behaviors* **35**: 325–330.

Trim RS, Clapp JD, Reed MB, Shillington A, Thombs D. 2011. Drinking plans and drinking outcomes: examining young adults' weekend drinking behavior. *Journal of Drug Education* **41**(3): 253–270.

Wells S, Mihic L, Tremblay PF, Graham K, Demers A. 2008. Where, with whom, and how much alcohol is consumed on drinking events involving aggression? Event-level associations in a Canadian national survey of university students. *Alcoholism: Clinical and Experimental Research* **32**(3): 522–533.

Wells S, Dumas TM, Bernards S, Kuntsche E, Labhart F, Graham K. 2015. Predrinking, alcohol use, and breath alcohol concentration: a study of young adult bargoers. *Psychology of Addictive Behaviors* **29**(3): 683–689.

Wetherill RR, Fromme K. 2009. Subjective responses to alcohol prime event-specific alcohol consumption and predict blackouts and hangover. *Journal of Studies on Alcohol and Drugs* **70**: 593–600.

Wilkinson P. 1980. Pharmacokinetics of ethanol; a review. *Alcoholism: Clinical and Experimental Research* **4**(1): 6–21.

Syst. Res **35**, 265–281 (2018)
DOI: 10.1002/sres.2478

APPENDIX A.

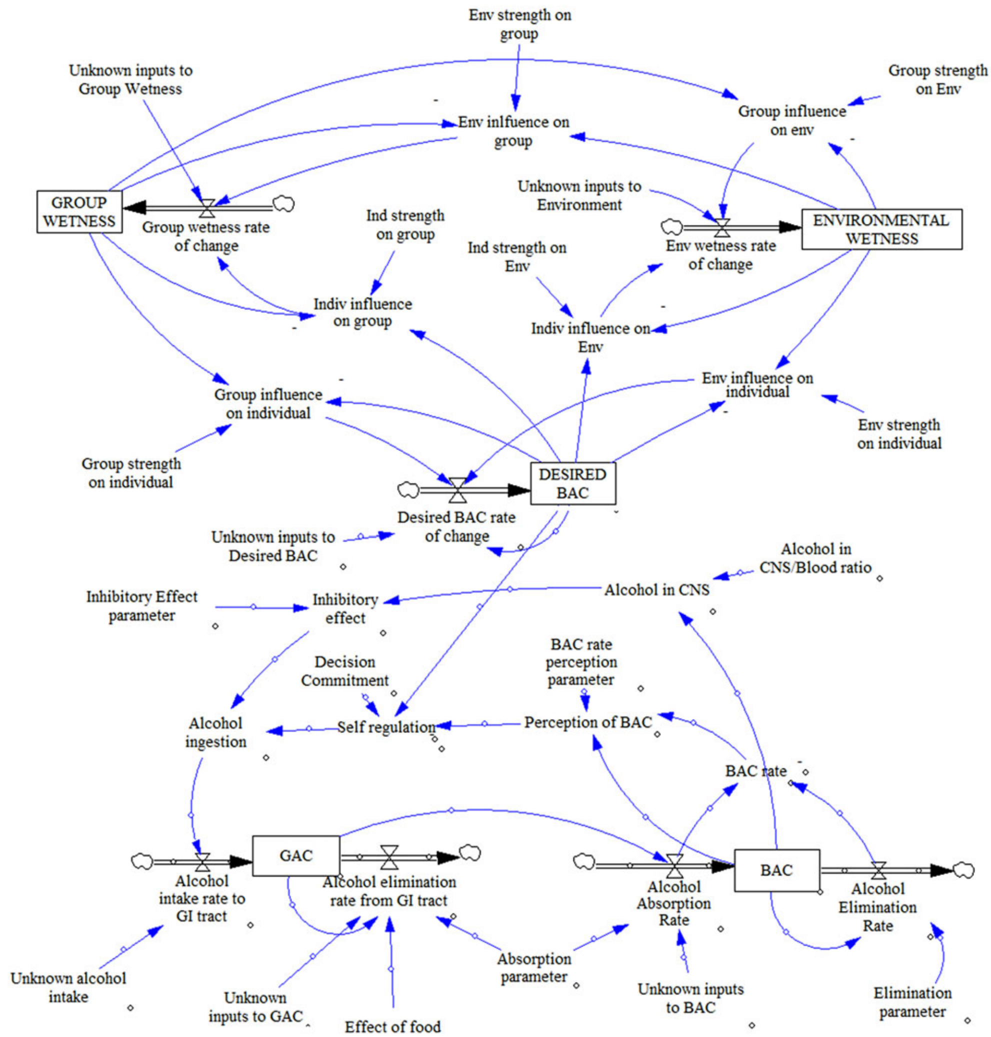

Figure A.1 Full stock and flow diagram for drinking event system. [Colour figure can be viewed at wileyonlinelibrary.com]

DOI: 10.1002/sres.2478

APPENDIX A.1.

TABLE B.1. POTENTIAL RANDOM VARIABLES AND DISTURBANCES BY LEVEL OF ABSTRACTION

Level	Random variable
Micro/individual	•Taking medication •Level of hydration •Level of rest •Drinking history (e.g., binge drinker) •Genetic markers •Tolerance
Mezzo/group	•New group member(s) during event •Exiting group members during event •Sexual attraction among group members •Social media or SMS connection among group members during event
Macro/environment	•Moving locations during event •Fights or aggression at events •Introduction of music or dancing during event •Influx or outflow of other groups during event

Note: This table provides potential variables and disturbances and does not reflect specifically what is in our model. This is not an exhaustive list.

Syst. Res **35**, 265–281 (2018)
DOI: 10.1002/sres.2478