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► To cite this version:

Jean-Denis Mathias, Nicolas Pellerin, Gustavo Carrero, Eric Raufaste, Michaël Dambrun. Running on the hedonic treadmill: a dynamical model of happiness based on an approach–avoidance framework. *Journal of Happiness Studies*, 2024, 25 (5), pp.58. 10.1007/s10902-024-00766-3 . hal-04637098

HAL Id: hal-04637098

<https://hal.science/hal-04637098v1>

Submitted on 30 Sep 2024

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Running on the Hedonic Treadmill: A Dynamical Model of Happiness Based on an Approach–Avoidance Framework

Jean-Denis Mathias¹ · Nicolas Pellerin² · Gustavo Carrero³ · Eric Raufaste⁴ · Michael Dambrun⁵

Accepted: 12 May 2024 / Published online: 11 June 2024
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Abstract

Describing the dynamical nature of happiness is crucial for understanding why individuals are constantly running on a hedonic treadmill around set levels of well-being. Based on the self-centeredness branch of the 'self-centeredness/selflessness happiness model', we present a dynamical model that focuses on unfolding the hedonic dimension of happiness dynamics through the use of the approach–avoidance framework. This numerical model enables us to understand and analyze emerging hedonic cycles caused by hedonic motivation and hedonic adaptation. In particular, hedonic motivation leads people to experience hedonic activities, which result in successes or failures and experiences of pleasure and afflictive affects; whereas hedonic adaptation causes individuals to return to a baseline level of pleasure and afflictive affects, more quickly for the former than the latter. The proposed dynamical model is based on the approach–avoidance framework that considers human behavior in two separate regulatory processes that contribute to homeostasis of individuals' happiness. We analyze these two processes independently and conjointly in order to highlight their effect on happiness levels. The analysis shows how individual characteristics and their combination may result in hedonic cycles, afflictive affects, (dis-)pleasure, and particular happiness dynamics. We also discuss how such a numerical model enables us to perform a multifactorial analysis which is hardly feasible outside the context of a simulation and how it may help us to narrow and design relevant experimental surveys from these preliminary numerical results.

Keywords Hedonic motivation · Hedonic cycles · Approach–avoidance framework · Dynamical model

1 Introduction

The pursuit of happiness has long been debated from philosophical and psychological perspectives (see Ryan and Deci (2001), for instance). Happiness and well-being are two closely related concepts that are sometimes used interchangeably. However, they are distinct (Raibley, 2012). In psychology, depending on the authors, well-being is interpreted as very large, "holistic" (Bornstein et al., 2003), but others consider well-being to be narrower.

For example, Seligman (2011) sees well-being as a measurable form of happiness. There is also no consensus on which aspects (Linton et al., 2016) or domains (Kauppi et al., 2023) constitute well-being. In philosophy, various approaches also compete, so there is no consensus either (Crisp, 2021). One of the most important approaches in psychology focuses on “subjective well-being” (Diener et al., 2002). Its first two components, the presence of positive emotions and the absence of negative emotions, refer to transient emotional states. For that matter they are called the ‘affective’ components. The third component, life satisfaction, is less a transient state than a cognitive assessment of a person’s life over a much longer period, and has been referred to as the ‘cognitive’ component for that reason. For some philosophers, life satisfaction can even cover a person’s entire life, the present, the past, and the future (Tatarkiewicz, 1966). Here, well-being is approached as a broad concept that encompasses various domains of an individual’s life, including—but not limited to, hedonic states.

However, this paper aims at modelling the interplay between emotional and motivational hedonic *states* rather than on long-term cognitive *evaluations*. This focus on hedonic functioning should be understood in the context of the distinction introduced by Dambrun and Ricard (2011) between two modes of psychological functioning leading either to a “fluctuating happiness” or to an “authentic-durable happiness”. Only the former is linked to the hedonic principle (research of pleasure and avoidance of displeasure). The latter is not. As these two modes of functioning are theoretically largely independent, they can be modelled independently. Our goal, here, is limited to providing a model of the short-term dynamics of such hedonic emotions/motivations, and their influence on the pursuit of happiness when individuals function according to the hedonic principle. Accordingly, in this paper, by “happiness” we refer to affective feelings, as in the first two components of Diener’s subjective well-being, or to what some philosophers call “episodic happiness” (e.g., (Raibley, 2012)).

Studying happiness requires an interdisciplinary approach in order to contribute to the debate of the pursuit of happiness, from psychology (Frawley, 2015) to economics of happiness (Powdthavee, 2007) to mathematics (Carrero et al., 2022), and philosophy, etc. In this context, our contribution relies on developing a numerical model of the dynamics of hedonic happiness. A numerical model of happiness may contribute to better understand psychological dynamics from different perspectives. First, we may perform a multifactorial analysis of happiness dynamics that encompass multiple integrated and interacting processes. Although modeling stylises the dynamics of happiness, it makes possible a multifactorial analysis that is generally impossible in practice. Secondly, modeling can allow us to test certain hypotheses in order to analyse the corresponding dynamics and, consequently, to refine and design relevant experimental studies on the basis of these preliminary numerical results. (Wang et al., 2016). From a modeling approach, happiness should probably be modeled as a dynamical process (Sprott, 2005; Carrero et al., 2022). To understand the dynamics of happiness, empirical researchers have studied its various contributing factors such as genetics (Haworth et al., 2016), activities (de Lima et al., 2018; Cloutier et al., 2020), and daily circumstances (Argyle, 1999), and their corresponding weights, (Lyubomirsky et al., 2005; Brown and Rohrer, 2020). Circumstances constitute inputs for internal processes that interact with the situation to create emotional outcomes (Jayawickreme et al., 2012). Among current psychological theories of happiness, the self-centeredness branch of the self-centeredness/selflessness happiness model (SSHM) proposed by Dambrun and Ricard (2011) states that the hedonic principle (Higgins, 1997) strongly influences happiness. This hedonic principle describes the pursuit of pleasure and the avoidance of pain, which

constitute the main foundations of the human functioning and the behavior of all animal life (Steiner et al., 2001). One key-process relies on motivation of individuals underlying this pursuit of pleasure and avoidance of pain. Among motivation theories, such as hedonic motivation or utilitarian motivation for instance (Zheng et al., 2019), we use hedonic motivation like the SSHM (Dambrun and Ricard, 2011). According to the principle of hedonic motivation, individuals are mainly motivated to obtain pleasure (i.e., approach) and to avoid displeasure (i.e., avoidance). This hedonic motivation is therefore an approach–avoidance motivation. Approach–avoidance motivation analyzes these interactions through the lens of three concepts: an approach concept defined as the driver to move forward to desirable stimuli, an avoidance concept defined as the driver to move away from an undesirable stimulus, and a motivation concept based on “the energization” and “direction” of behavior (Elliot, 2006). The (un)desirability of stimuli is characterized by their valence. Since the pioneering work of Arnold (Arnold, 1970), a positive valence has generally been considered to occur when a stimulus is pre-consciously deemed as “good”, which triggers an “action tendency” with a potential mobilization of approach behavior. A negative valence occurs when a stimulus is deemed as bad, triggering an avoidance tendency (Arnold, 1970).

As regards the possibility of sustainably changing one’s chronic level of happiness, an important challenge consists in understanding the class of mechanisms that drive happiness fluctuations. According to the SSHM, obtaining gratification (approach) and avoiding disagreeable stimuli successfully (avoidance) creates a feeling of pleasure, and transitory satisfaction. However, these stimulus-driven pleasures are contingent upon the appearance or disappearance of certain stimuli and of the success to obtain or avoid them (Wallace and Shapiro, 2006). The experience of pleasure is by nature fleeting and dependent upon circumstances. It is unstable and the sensations it evokes soon becomes neutral (i.e., hedonic adaptation; e.g., (Brickman et al., 1978)). This homeostatic mechanism of hedonic adaptation” or, metaphorically, the “hedonic treadmill” (Brickman and Campbell, 1971) has received strong empirical support (Frederick and Loewenstein, 1999) and explain conundrums such as why economic growth is not accompanied by a corresponding improvement in happiness (Easterlin, 1974) or why people experiencing strong gains or heavy losses return to their base-level in the long run (Diener et al., 2009). Furthermore, in the SSHM, failure to achieve valued goals gives rise to afflictive affects such as frustration, anger, hostility, or jealousy that impair well-being (Miller et al., 1996; Ekman et al., 2005; Dambrun and Ricard, 2011; Dambrun, 2017). Thus, by seeking to maximize pleasures and avoid displeasures, self-centeredness induces fluctuating happiness in which phases of pleasure and displeasure repeatedly alternate. Happiness can thus be, at least in part, characterized by the alternation of positive and negative phases that cause fluctuating happiness.

The purpose of studying this dynamic process is to understand, based on the existing SSHM psychological model of happiness, how exogenous and endogenous stimuli influence the levels of happiness; in particular, happiness set points and fluctuations around them. For example, whereas succeeding in the approach–avoidance strategy may create transitory pleasure (i.e., stimulus-driven pleasures), failing may cause afflictive affects. In turn, these pleasure and afflictive affects may impact the approach and avoidance strategy. Moreover, other interesting aspects to better understand the fluctuations in the levels of happiness are the frequency and amplitude of these hedonic cycles. Addressing these aspects through the lens of dynamical modeling has been barely addressed by scholars to the knowledge of the authors. For instance, Stutzer (2004) developed a simple autonomous mathematical model that enables simulating the dynamics of happiness according to income aspirations. Also, Sprott (2005) and Carrero et al. (2022) incorporated components

in their dynamical models of happiness to describe how the impact of external events and emotions, respectively, is reduced by a hedonic adaptation mechanism.

In what follows, we will focus on a dynamical model that distinguishes psychological processes of approach/avoidance motivation to describe the emergence of hedonic cycles in the dynamics of happiness. The main purpose of our modeling approach is to analyze the complex interplay between processes and psychological characteristics. Indeed, around thirty parameters are considered in our model, which limit our capacity to understand their influence on happiness dynamics in a qualitative way. Exploring parameter combinations in a numerical way provides us additional insights to complement those we already have with experimental survey. However, due to the complexity and high number of psychological processes involved in hedonic adaptation, the mathematical model is stylized by abstracting stimuli through their valence and built on the basis of psychological parameters and functional responses that describe the workings of an approach–avoidance motivation process.

2 The Hedonic Treadmill Mechanism

Individuals are continuously subjected to many stimuli in their environment. These stimuli are the driving force of people's hedonic behaviours. In what follows, we consider a flow of stimuli. These stimuli present different individual-dependent hedonic valences, and act in conjunction with a hedonic motivation system that is separated into two processes: an approach motivation (for stimuli with positive hedonic valence) and an avoidance motivation (for stimuli with negative hedonic valence). When the hedonic motivation reaches a threshold value, the approach–avoidance behaviour is activated, leading to the realization (approach or avoidance) of the hedonic activity associated with the stimuli. These hedonic activities provide (dis)pleasure as well as afflictive affects according not only to the hedonic valence of the stimuli but also to the expectations that individuals have about the stimuli. The resulting (dis)pleasure and afflictive affects will decrease due to the effect of hedonic adaptation and further contribute to increasing or decreasing the hedonic motivation. This mechanism is depicted in Fig. 1.

In order to dynamically analyze this mechanism, we consider a sequence of stimuli occurring at discrete times $\tau = 0, 1, 2, \dots, t$ (with a time unit associated to them; hours, for example), where $\tau = 0$ and $\tau = t$ denote the times of the first and last stimulus, respectively. Therefore, this discrete-time approach implies, without loss of generality, a constant time step between stimuli.

Focusing on the time $\tau = t$ of the last stimulus, we notice that there are two consecutive hedonic precursors affecting both the levels of (dis)pleasure and afflictive affects, namely a hedonic motivation and a behavioural activation (see Fig. 1). First, people seek to approach pleasure and avoid displeasure in the presence of the stimulus occurring at time $\tau = t$ based on a hedonic motivation that has been built on the accumulated (dis)pleasure, and afflictive affects up to that time. Second, if the behavioural activation occurs in the presence of the stimulus, then the success or failure of the approach or avoidance (which depends on the context) will bring more (dis)pleasure or afflictive affects, and consequently, an experience of (un)happiness defined as

$$H(t) = P(t) - A(t), \quad (1)$$

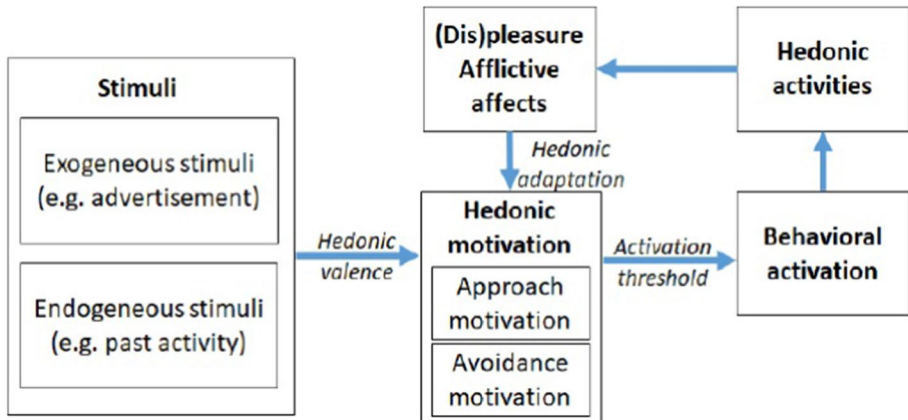


Fig. 1 The hedonic treadmill mechanism. Stimuli, in conjunction with the hedonic motivation, can activate the approach–avoidance behavior and consequently lead to hedonic activities which provide (dis-)pleasure and/or afflictive affects; these in turn will influence the hedonic motivation which will act in conjunction with future stimuli

where $P(t)$ and $A(t)$ denote the levels of pleasure (or displeasure) and afflictive affects, respectively. This dynamics persists as long as there are stimuli generating an approach–avoidance strategy. In the following sections, we will unfold the mathematical structure of the pleasure and afflictive affect functions, $P(t)$ and $A(t)$, by providing more details of the hedonic treadmill mechanism depicted in Fig. 1.

3 The Hedonic Adaptation Dynamics of Pleasure and Afflictive Affects

From the previous section, we learned that both pleasure and afflictive affects stem from the processing of stimuli. Since we are assuming a sequence of discrete stimuli, it seems reasonable to define $P(t)$ and $A(t)$ in terms of the stimuli-pleasure, $P_s(\tau)$, and the stimuli-afflictive affects, $A_s(\tau)$, which arise from all the discrete sequence of stimuli occurring at discrete times $\tau \leq t$, i.e., $\tau = 0, 1, 2, \dots, t$. Thus, considering first the hedonic adaptation effect on the sequence of stimuli-pleasure, we define the total pleasure of an individual at time $\tau = t$, $P(t)$, as the following sum of stimuli-pleasure $P_s(\tau)$ (over all $\tau \leq t$) reduced over time by a hedonic adaptation parameter γ_P ,

$$P(t) = \sum_{\tau=0}^t P_s(\tau) e^{-\gamma_P(t-\tau)} \tag{2}$$

Analogously, considering the hedonic adaptation effect on the sequence of stimuli-afflictive affects, we define the total afflictive affects of an individual at time $\tau = t$, $A(t)$, as the sum of stimuli-afflictive affects $A_s(\tau)$ (over all $\tau \leq t$) reduced over time by a hedonic adaptation parameter γ_A ,

$$A(t) = \sum_{\tau=0}^t A_s(\tau) e^{-\gamma_A(t-\tau)} \tag{3}$$

The parameters γ_P and γ_A are individual characteristics of the hedonic adaptation of pleasure activities and afflictive affects, respectively. The higher their values, the higher the hedonic adaptation, which means that old activities have lower influence on the current pleasure or afflictive affects of the individual. Conversely, if the hedonic adaptation is low, past activities have higher influence on the individual’s current pleasure or afflictive affects. Thus, the pleasure hedonic adaptation, γ_P , and the afflictive-affects hedonic adaptation, γ_A , reflect the tendency of an individual to be satisfied or annoyed for longer or shorter lengths of time following positive or negative experiences.

Note that by separating the last term in the summations of Eqs. (2) and (3) (mathematical details in the SI), they can be rewritten, respectively, as:

$$P(t) = e^{-\gamma_P} P(t - 1) + P_s(t), \tag{4}$$

and

$$A(t) = e^{-\gamma_A} A(t - 1) + A_s(t). \tag{5}$$

Thus, if we define, respectively,

$$P_m(t) = e^{-\gamma_P} P(t - 1), \tag{6}$$

and

$$A_m(t) = e^{-\gamma_A} A(t - 1), \tag{7}$$

as the accumulated pleasures and afflictive affects that have been subjected to hedonic adaptation up to time $\tau = t$, Eqs. (4) and (5) can be rewritten as

$$P(t) = \underbrace{P_m(t)}_{\text{Accumulated pleasure at time of current stimulus}} + \underbrace{P_s(t)}_{\text{Pleasure contribution of current stimulus}}, \tag{8}$$

and

$$A(t) = \underbrace{A_m(t)}_{\text{Accumulated afflictive affect at time of current stimulus}} + \underbrace{A_s(t)}_{\text{Afflictive affect contribution of current stimulus}}. \tag{9}$$

This last formulation enables us to see that the dynamics of pleasure and afflictive affects is determined by the hedonic adaptation of these emotions updated by emotions provided by the current stimuli. This dynamical nature of the total pleasure and afflictive affects, and consequently of the levels of happiness, is depicted in a schematic model in Fig. 2. In this figure, it becomes apparent that it is necessary to unfold the details of the approach–avoidance motivation mechanism in order to find out the stimuli-pleasure and the stimuli-afflictive affects resulting from the stimuli-valence. More specifically, it is necessary to describe all causalities of our dynamical model: how given psychological inputs may cause changes in other psychological outputs through dynamical equations that describe psychological processes. The next sections are devoted to this task. In particular, using the hedonic branch of the SSHM (Dambrun and Ricard, 2011), Sects. 4 and 5 will focus on the approach and avoidance hedonic behaviours separately, and Sect. 6 will focus on the

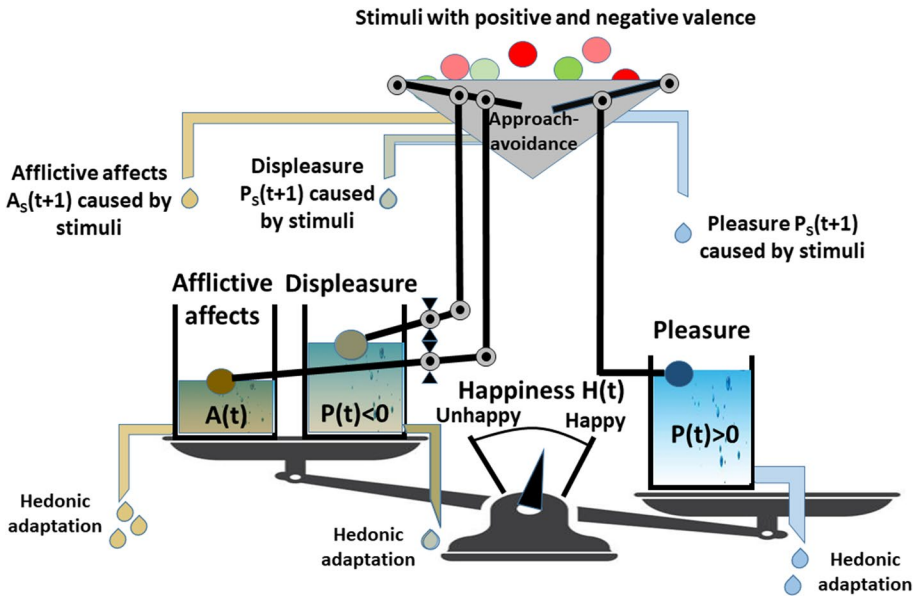


Fig. 2 Happiness dynamics. We consider happiness as a combination of continuous flows of pleasure and afflictive affects with a continuous loss of these flows caused by hedonic adaptation. The levels of afflictive affects and pleasure drive the motivation to adopt an approach–avoidance behavior. Note that we use the same variables $P(t)$ and $P_s(t)$ for describing pleasure and displeasure according to their mathematical sign

combined approach–avoidance behaviour. Finally, we discuss our results and future avenues in the last section.

4 Approach Hedonic Behaviour

In this section, we focus on processes involved in approach behavior. We base our analysis on the impulse to go toward positive stimuli. Even though we do not discuss the origin of the stimuli, we recognize that they can be born from external goal objects (Lang and Bradley, 2008) or from internal processes (Harmon-Jones et al., 2013). Also, we are aware that in some specific cases, approach behavior may arise from negative stimuli (Harmon-Jones et al., 2013); however, without loss of generality in our approach, we do not consider these latter cases.

4.1 From Hedonic Approach Motivation to Behavioural Activation

If an individual was subjected to a positive stimulus at time t , then the only type of motivation driving a possible approach behaviour would be an approach hedonic motivation. It is reasonable to think that this motivation, denoted as $M_{ap}(t)$, depends on the accumulated pleasure, $P_m(t)$, and accumulated afflictive affect, $A_m(t)$, at the time t of the stimulus (see Eqs. (6) and (7)). For this reason, we assume that the approach hedonic motivation is composed of two emotion-based motivations, namely a pleasure-based approach motivation, $M_{ap}^P(P_m(t))$, and an

afflictive affect-based approach motivation, $M_{ap}^A(A_m(t))$. Thus, we define the approach hedonic motivation as

$$M_{ap}(P_m(t), A_m(t)) = \alpha_{ap}M_{ap}^P(P_m(t)) + (1 - \alpha_{ap})M_{ap}^A(A_m(t)). \tag{10}$$

Note that the contribution of each of the emotion-based motivations is weighted by a coefficient $\alpha_{ap} \in [0, 1]$. We shall see shortly that this motivation has a normalized value between 0 and 1; a motivation of 0 means that an individual has no motivation to approach hedonic activities (an extreme case), whereas a value of 1 indicates high motivation for approaching hedonic activities that are perceived as potentially providing pleasure. Moreover, if α_{ap} equals 1 (respectively, 0), the approach motivation only depends on pleasure (respectively, afflictive affect) level.

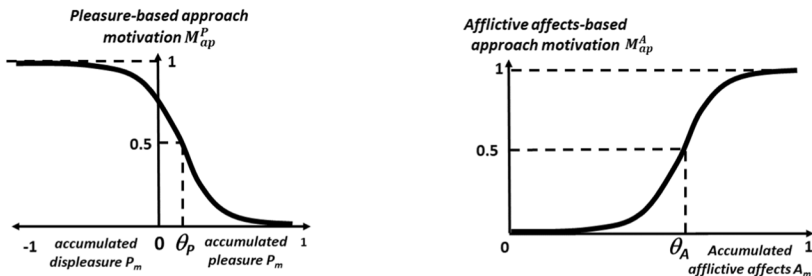
We first consider the pleasure-based approach motivation, $M_{ap}^P(P_m(t))$, that only depends on the accumulated pleasure, $P_m(t)$, as follows

$$\begin{cases} M_{ap}^P(P_m(t)) = 1 - \frac{(P_m(t) + 1)^{q_{ap}}}{(P_m(t) + 1)^{q_{ap}} + (1 + \theta_p)^{q_{ap}}}, \\ \qquad \qquad \qquad \text{if } P_m(t) \geq -1; \\ M_{ap}^P(P_m(t)) = 1, \quad \text{if } P_m(t) < -1, \end{cases} \tag{11}$$

where the pleasure threshold, θ_p , represents the value of pleasure for which the pleasure-based approach motivation, $M_{ap}^P(P_m(t))$, equals 0.5 (see Fig. 3a), and the parameter q_{ap} tunes how the hedonic approach motivation increases or decreases around this threshold. Note that the pleasure-based approach motivation, $M_{ap}^P(P_m(t))$, is normalized between 0 and 1.

We now consider the afflictive affect-based approach motivation, $M_{ap}^A(A_m(t))$, that only depends on the accumulated afflictive affect, $A_m(t)$, as follows

$$M_{ap}^A(A_m(t)) = \frac{A_m(t)^{q_{ap}}}{A_m(t)^{q_{ap}} + \theta_A^{q_{ap}}}, \tag{12}$$



a - Pleasure-based motivation $M_{ap}^P(P(t))$ b - Afflictive affects-based motivation $M_{ap}^A(A(t))$

Fig. 3 Approach motivation, $M_{ap}(P(t), A(t))$, is the weighted sum of pleasure-based $M_{ap}^P(P(t))$ and afflictive affects $M_{ap}^A(A(t))$ approach motivations. Parameters θ_p and θ_A correspond to values of pleasure and afflictive affects for which motivations are equal to 0.5

where the afflictive affect threshold, θ_A , represents the value of accumulated afflictive affect, $A(t)$, for which $M_{ap}^A(A_m(t))$ equals 0.5 (see Fig. 3b), and the parameter q_{ap} tunes how the hedonic motivation increases or decreases around this threshold.

Notice that the afflictive affect-based approach motivation, $M_{ap}^A(A_m(t))$, is also normalized between 0 and 1. Therefore, the approach motivation, $M_{ap}(P_m(t), A_m(t))$, defined by the contribution of the two normalized emotion-based approach motivations, $M_{ap}^P(P_m(t))$ and $M_{ap}^A(A_m(t))$, according to Eq. 10, is normalized as well.

Figure 3a–b depict the pleasure and afflictive affect-based motivations, $M_{ap}^P(P_m)$ and $M_{ap}^A(A_m)$, as functions of the accumulated pleasure and afflictive affect, P_m and A_m , respectively. As both the accumulated pleasure and afflictive affect, P_m and A_m , depend on time, we will also use the notation $M_{ap}(t) = M_{ap}(P_m(t), A_m(t))$ for the approach hedonic motivation.

As mentioned in Sect. 2, an approach behaviour is activated in the presence of a positive stimulus only if the approach hedonic motivation, $M_{ap}(P_m(t), A_m(t))$, reaches a certain threshold value. We call this value the approach behaviour activation threshold and denote it as θ_B .

On the one hand, if the value of the approach hedonic motivation, $M_{ap}(P_m(t), A_m(t))$, is lower than the activation threshold, θ_B , then the approach behavior is not activated. Nonetheless, the individual may still experience the stimulus according to a contact probability, $p_{contact}$, without an active behaviour effort. Therefore, if the individual experiences the stimulus because of this contact, the stimulus pleasure will be equal to the hedonic valence (i.e., $P_s(t) = V(t)$ and $A_s(t) = 0$); and if there is no contact with the stimulus, no emotion will appear ($P_s(t) = A_s(t) = 0$).

On the other hand, if the value of the approach hedonic motivation, $M_{ap}(P_m(t), A_m(t))$, is higher than an activation threshold, θ_B , then the approach behavior is activated. Therefore, behavior activation threshold θ_B directly influences hedonic cycle: hedonic motivation has to be always higher than this threshold θ_B for having hedonic cycles. However it is a necessary but not sufficient condition for hedonic cycle.

According to the value of α_{ap} , pleasure and afflictive affects are more or less influential in the behaviour activation.

To illustrate this, we consider fixed values $q_{ap} = 5$ and $\theta_A = \theta_P = 0.25$ of the emotion-based approach motivations, a fixed value $\theta_B = 0.5$ for the activation threshold, let α_{ap} vary between 0 and 1, and show the regions in the $P(t)A(t)$ -plane where the approach behaviour is activated (Fig. 4).

Note that these regions are given by the area left to the black curves determined by different values of α_{ap} . For example, when $\alpha_{ap} = 1$, activation is only driven by pleasure, and the approach behavior is activated when the accumulated pleasure, $P_m(t)$, is lower than the pleasure threshold, $\theta_P = 0.25$, regardless of the accumulated afflictive affect (blue dashed rectangle in Fig. 4). Analogously, when $\alpha_{ap} = 0$, activation is only driven by afflictive affect and the approach behavior is activated when the accumulated afflictive affect, $A_m(t)$, is higher than afflictive affect threshold, $\theta_A = 0.25$, regardless of the accumulated pleasure (brown dashed rectangle in Fig. 4).

Also, notice that the red area in Fig. 4 corresponds to a systematic activation of the behavior caused by a combination of low pleasure and high afflictive affects, regardless of the value of the parameter α_{ap} ; whereas the green area corresponds to a low value of afflictive affects and high pleasure, resulting in no behavioral activation regardless of the value of α_{ap} .

In the next section, we will discuss the expectation of pleasure created by an individual when the approach hedonic behaviour is activated by a stimulus.

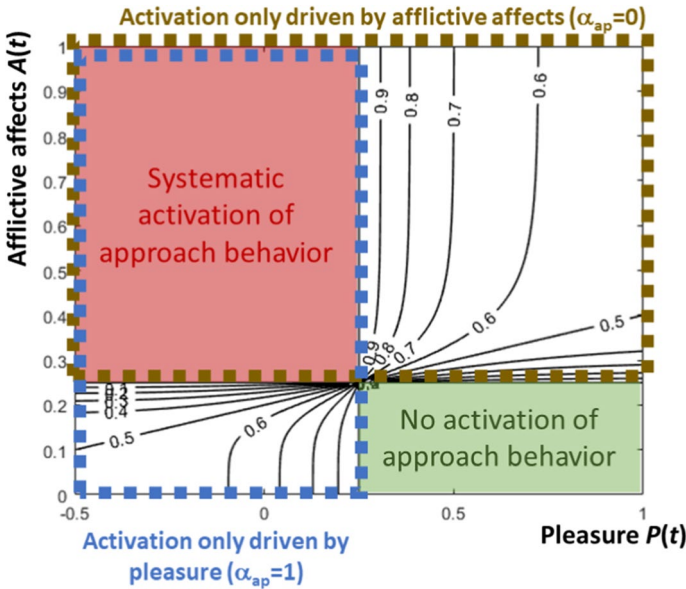


Fig. 4 Behavioral activation according to different values of α_{ap} ($q_{ap} = 5$, $\theta_A = \theta_p = 0.25$, and $\theta_B = 0.5$). It highlights areas of systematic activation and non activation of approach behavior for given combinations of pleasure and afflictive affects

4.2 Expectations of Pleasure from Stimulus Approach

Once the approach behaviour is activated due to a stimulus, it is reasonable for an individual to expect levels of pleasure around those of the valence of the stimulus. For this reason, we define the expectations of pleasure as the following function of the stimulus valence, $V(t)$, and the hedonic approach motivation, $M_{ap}(t)$,

$$E_{ap}(V(t), M_{ap}(t)) = V(t) + (M_{ap}(t) - \mu_{ap})V(t)(1 - V(t)), \tag{13}$$

where μ_{ap} denotes an approach hedonic motivation coefficient that allows for the possibility of having levels of expectation higher or lower than those of the valence of the stimulus.

Specifically, if the hedonic motivation $M_{ap}(t)$ is higher (lower) than μ_{ap} , then the expected levels of pleasure are higher (lower) than those of the stimulus valence $V(t)$; and if $M_{ap}(t) = \mu_{ap}$, then the expected level of pleasure is equal to the valence of the stimulus, i.e., $E_{ap}(V(t), M_{ap}(t)) = V(t)$. These cases are illustrated in Fig. 5 using $\mu_{ap} = 0.5$. This hedonic motivation coefficient μ_{ap} depends on individual and influence hedonic cycle: high value will decrease expectations and therefore mitigate hedonic cycles.

4.3 Effect of Approach Success and Failure on the Stimulus Pleasure and Afflictive Affects

Depending on the context and individual skills, one succeeds (or not) in the stimulus approach. For this reason, we consider a probability of success of the strategy equal to $p_{success}$. We will account for this probability in the simulations by generating a random number from a uniform

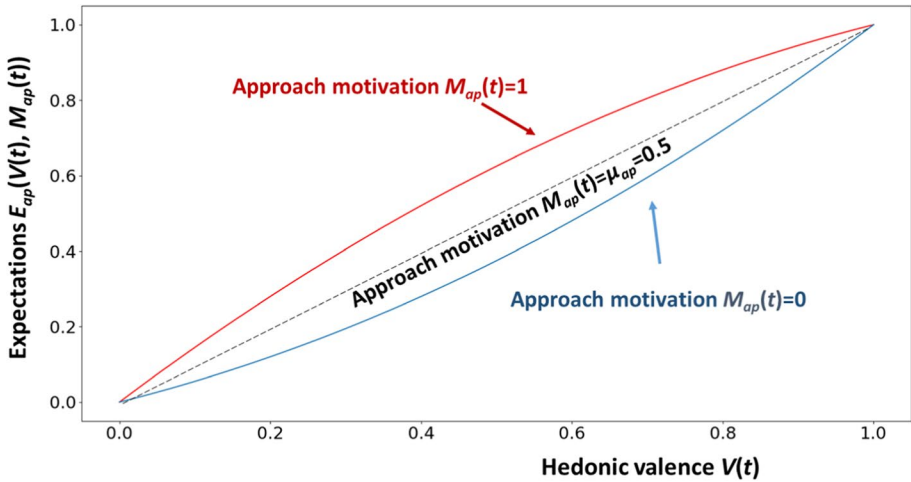


Fig. 5 Value of expectations $E_{ap}(V(t), M_{ap}(t))$ according to the stimulus valence, $V(t)$, for three values of the approach motivation $M_{ap}(t)$ and $\mu_{ap} = 0.5$; $M_{ap}(t) = 1 > \mu_{ap}$ (red curve), $M_{ap}(t) = 0 < \mu_{ap}$ (blue curve), and $M_{ap}(t) = 0.5 = \mu_{ap}$ (black curve)

distribution; if the value is lower than $p_{success}$, we assume that the individual succeeds in the approach. This probability may depend on the environment and the context of the stimuli. For the sake of simplicity, we assume this probability of success to be the same for the avoidance strategy (see Sect. 5). The probability of failure is, therefore, equal to $(1 - p_{success})$.

If the individual succeeds in the approach, the stimulus pleasure obtained equals the hedonic valence of the activity increased (or decreased) by the difference with the expectations, i.e.,

$$P_s(t) = V(t) + (V(t) - E_{ap}(V(t), M_{ap}(t))). \tag{14}$$

Thus, lower expectations lead to higher pleasure (and *vice versa*).

If there is no success in the approach, the individual experiences unpleasant emotions, which we assume are composed of stimuli displeasure and stimuli afflictive affects. Moreover, if we suppose that individuals will generally experience less unhappiness, in absolute terms, when they do not obtain what they want (failure) compared to the amount of happiness they would have experienced if they did (success), we can assume the displeasure experienced to be a fraction of the expectation, i.e.,

$$P_s(t) = -\beta_{ap}^P E_{ap}(V(t), M_{ap}(t)), \tag{15}$$

where $0 < \beta_{ap}^P < 1$.

The arising afflictive affects after failure, $A_s(t)$, are described in a similar way,

$$A_s(t) = \beta_{ap}^A E_{ap}(V(t), M_{ap}(t)), \tag{16}$$

where $0 < \beta_{ap}^A < 1$.

For the sake of simplicity and without any loss of generality, we will assume, from hereon, equal fraction proportionality constants for the displeasure and afflictive affects, i.e.,

$$\beta_{ap} = \beta_{ap}^P = \beta_{ap}^A \tag{17}$$

These coefficients represents how people have displeasure and afflictive affects from their expectations. Having a coefficient β_{ap} equal to 0 (limit case) means that even if individual has mobilized an approach with high expectations, she will not have any displeasure and afflictive affects in case of failure of her approach behavior. Therefore, low values of β_{ap} mitigate hedonic cycles.

4.4 Hedonic Dynamics of Happiness Based on an Approach Behaviour

The scheme of the numerical dynamical model of happiness for an approach behaviour is described in Fig. 6, and can be summarized as follows. Depending on the approach hedonic

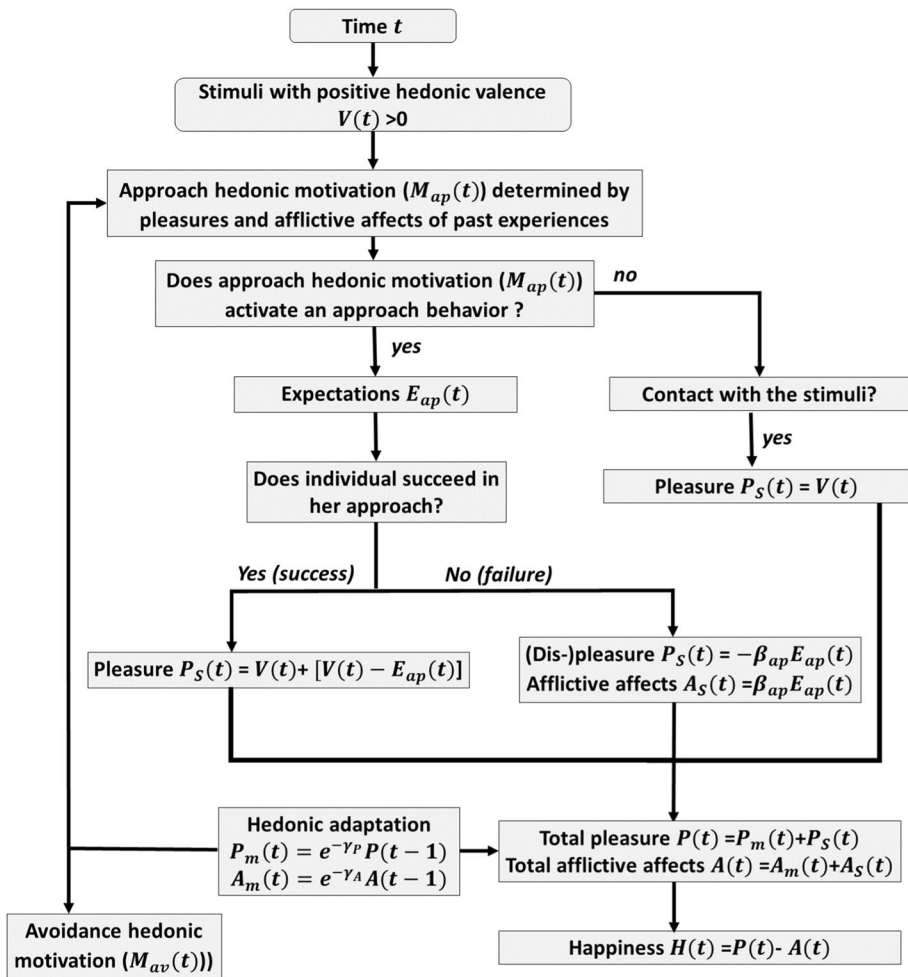


Fig. 6 Dynamical model of happiness based on approach behaviour. It highlights the different causal loops of the different psychological processes

motivation, $M_{ap}(t)$, an individual exposed to a stimulus with hedonic valence $V(t)$ can activate an approach strategy. If the approach behaviour is activated, the individual will have some expectations of the level of pleasure that can be obtained from the stimulus, $E_{ap}(V(t), M_{ap}(t))$, that depend on the approach hedonic motivation $M_{ap}(t)$ and the hedonic valence $V(t)$. According to the context and environment, the individual obtains (or not) pleasure or afflictive affects. If there is success in the approach behaviour, the individual obtains pleasure equal to the hedonic valence of the stimuli increased (or decreased) by the difference with the expectations. In case of failure, there is a displeasure equal to the expectation; this displeasure feeds the pleasure dynamics and the afflictive affects dynamics.

All the state variables and parameters of this numerical mathematical model, described in Fig. 6, as well as all the parameter values used for the subsequent numerical simulations, are detailed in Table 2 of the SI. The code for generating the simulations can be downloaded at <https://github.com/jdmathias/happiness>

4.5 Hedonic Self-Regulation in the Case of Permanent Success: Opposite Regulating Roles of Behavioural Activation and Hedonic Adaptation

In the case of approach hedonic behavior, individual’s behavior is continuously driven by a trade-off between pleasure and hedonic motivation. A decrease in the levels of pleasure (caused by hedonic adaptation) increases the levels of hedonic motivation, and may push the individual to activate an approach behavior in order to increase the levels of pleasure, as shown in Fig. 7. This process of hedonic self-regulation, driven by the opposite regulating roles of behavioural activation and hedonic adaptation (depicted with green boxes in Fig. 7) yields a hedonic treadmill with alternative peaks of pleasure. We illustrate this effect in Fig. 8 by considering an individual (i) continuously subjected to stimuli with the same hedonic valence ($V(\tau) = 0.5$), (ii) who always succeeds

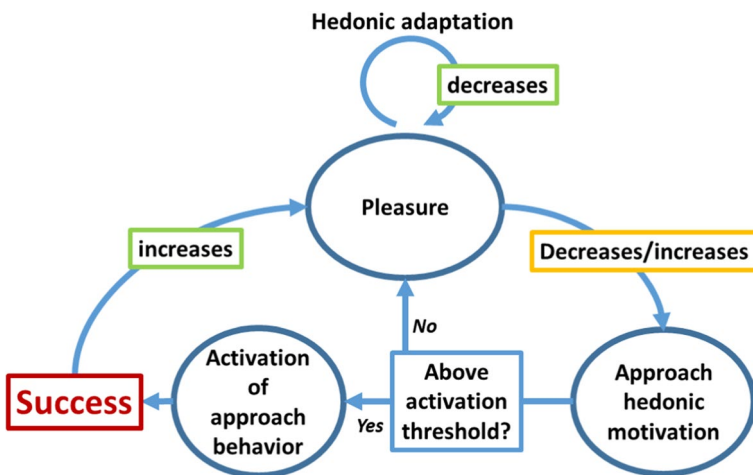


Fig. 7 Hedonic self-regulation in the case of permanent success. Hedonic adaptation decreases pleasure, while success in the approach behavior increases pleasure (green boxes). Depending on the pleasure resulting from these opposite regulating components, hedonic motivation can either decrease or increase (orange box), leading, or not, to behavioral activation. Note that if the behavior is not activated, pleasure will necessarily decrease due to hedonic adaptation. (Color figure online)

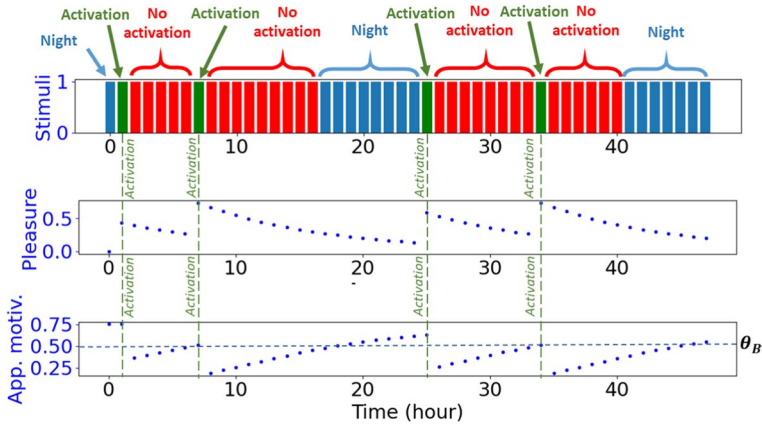


Fig. 8 Dynamics of pleasure and approach motivation in the case of permanent success. When the approach motivation exceeds the activation threshold θ_B , approach behavior is activated, yielding pleasure of the hedonic activity

in their approach behavior when this latter is activated, (iii) with a probability of contact with the stimuli equal to 0 when the behavior is not activated, and (iv) with a pleasure hedonic adaptation $\gamma_p = 0.1$ (it takes approximately one day for removing 90% of the stimuli pleasure). In this scenario, such individual only experiences pleasure with its associated hedonic adaptation, and the pleasure dynamics is fully controlled by the activation of the approach strategy. Also, no afflictive affects nor displeasure emerge because there is no failure.

The numerical results of the dynamics of pleasure and approach motivation for this scenario are plotted in Fig. 8 for a reference case (using the parameter values of Table 2 of the SI and the scheme of the numerical dynamical model of happiness for an approach behaviour described in Fig. 6), where only two days are considered for the sake of clarity. Stimuli are also reported; blue bars represent the night hours when the individual is sleeping and not subjected to stimuli. Red and green bars represent stimuli for which the approach behavior has been activated, or not, according to the level of pleasure and motivation as explained hereafter.

Note the self-regulation of pleasure and hedonic motivation; when pleasure decreases, hedonic motivation increases. Moreover, the peak of hedonic motivation is reached when the minimum of pleasure is reached and vice versa (see Fig. 8). When the approach motivation exceeds the activation threshold θ_B , approach behavior is activated, yielding pleasure of the hedonic activity.

In order to show the effect that changes in parameter values can have on the behaviour of the hedonic treadmill resulting from the self-regulation of pleasure and hedonic adaptation, we present the results of a sensitivity analysis in Fig. 9. The dynamics of the reference case is shown in Fig. 9a (same results of Fig. 8 but for a longer time), and the dynamics after varying the pleasure threshold, θ_p , the activation threshold, θ_B , and the hedonic adaptation, γ_p , are shown in Fig. 9b–d, respectively.

When the pleasure threshold θ_p (value below which the pleasure-based approach motivation is always higher than 0.5) is increased, one would expect high levels of pleasure to be maintained, as shown in Fig. 9b, since the hedonic motivation is kept at high levels with higher levels of pleasure in comparison to the reference case.

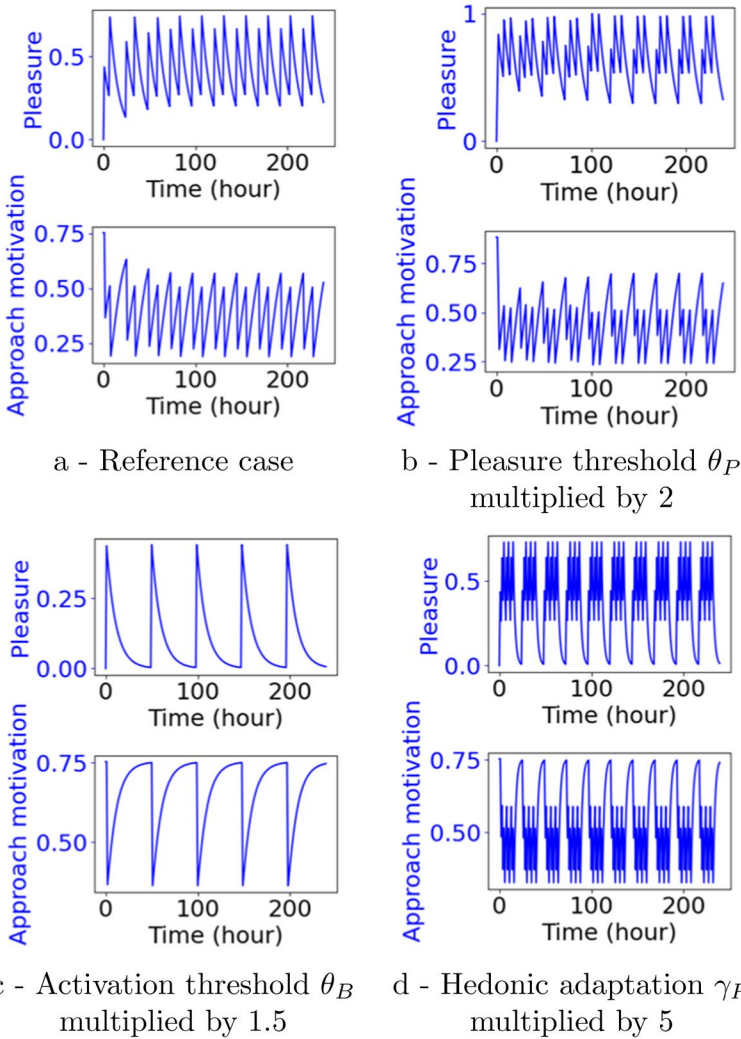


Fig. 9 Sensitivity analysis in the case of permanent success of approach behavior. A high value of θ_P -parameter (**b**) leads to maintain a high level of pleasure. Increasing θ_B -parameter (**c**) slows down hedonic cycles whereas increasing γ_P -parameter (**d**) accelerate them

When the activation threshold θ_B is increased, a higher hedonic motivation is required for activating an approach behavior, which in turn slows down the hedonic treadmill cycles as shown in Fig. 9c.

Finally, when the hedonic adaptation γ_P is increased, the level of pleasure decreases quickly after experiencing a positive stimulus. This results in rapid variations of pleasure (individual quickly adapts to stimuli pleasure) and shorter hedonic treadmill periods as shown in Fig. 9d. Note in the same figure, that around every twenty four hours the level of pleasure decreases near to zero, which corresponds to the night time when the individual is only subjected to hedonic adaptation.

In Fig. 10, we tested different values of the contact probability, $p_{contact}$ (probability that the individual may still experience an stimulus without activation of the approach behaviour). In practice, the contact with stimuli without behavioural activation may depend on the environment. For instance, physical stimuli for citizens may impact their happiness in their daily life (Samavati and Ranjbar, 2017) and may constitute a major role in urban design. Having a very high contact probability, $p_{contact}$, means that citizens are more exposed to unwanted stimuli, in which case the environment can play a major role in the happiness dynamics of individuals regardless of their psychological characteristics. Notice in Fig. 10, that adding a contact probability creates stochasticity in the pleasure dynamics except when the probability equals 0 or 1. Moreover, the higher the probability of contact, the lower the approach motivation. Nonetheless, the individual’s pleasure increases when the probability of contact with positive stimuli increases; the individual experiences pleasure without any approach motivation or behavioral activation.

4.6 Regime Shift in Hedonic Cycles Due to Appearance of Affective Affects in Case of Failure

Instead of having permanent success ($p_{success}=1$), we now consider the case of a time frame of continuous failure ($p_{success}=0$) in the dynamical model of happiness described in Fig. 6. In particular, we illustrate the pleasure dynamics of an individual subjected to the previous reference case (Fig. 9a), who suddenly faces continuous failure during two days. In case of failures, displeasure and affective affects arise as depicted in Fig. 11; for this reason, we need to consider the hedonic adaptation of affective affects, and set it to $\gamma_A = 0.05$ (it takes approximately two days for removing 90% of the stimuli affective affects). In order to guarantee complete failure during the two days, we also consider a contact probability, $p_{contact} = 0$, when there is no behavioral activation.

The simulations for the hedonic dynamics in this case are shown in Fig. 12a (this is now, our new reference case). After six days of continuous success, the individual experiences two days of continuous failure, before experiencing continuous success again. Notice that the two days of constant failure produce an increase of affective affects (red curve) and a collapse in the levels of pleasure, which in turn make the hedonic motivation reach its highest level and the levels of happiness decrease to negative levels (unhappiness).

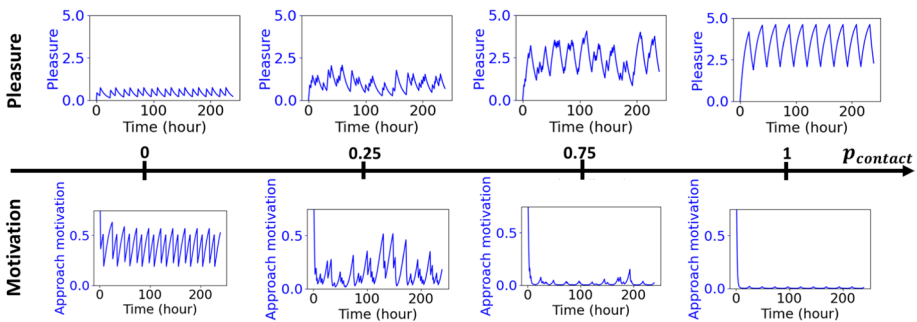


Fig. 10 Effect of the contact probability, $p_{contact}$ when the approach behavior is not activated. Adding a contact probability creates some stochasticity in the pleasure dynamics (except when the probability equals 0 or 1). The higher the contact probability, the lower the approach motivation; however, the individual experiences pleasure without an approach strategy



Fig. 11 Hedonic self-regulation in the case of failure in the approach behavior. Hedonic adaptation decreases displeasure and afflictive affects, while failure in the approach behavior increases displeasure and afflictive affects (green boxes). Depending on the pleasure and afflictive affects resulting from these opposite regulating components, hedonic motivation can either decrease or increase (orange boxes), leading, or not, to behavioral activation. (Color figure online)

The highest level of motivation during the two days of failure is solely due to the high levels of displeasure since in this reference case, the presence of the of afflictive affects does not affect the approach motivation; in other words $\alpha_{ap} = 1$ in Eq. (10). However, note that the afflictive affects have a significant effect on the levels of happiness, not only during the 2 days of failure but also after the individual starts experiencing successes again (after the 8th day). Even though displeasure does not last much longer after successes come back (due to the high levels of hedonic motivation), afflictive affects persist for some time, preventing the levels of happiness to increase as rapidly as the levels of pleasure. This is consistent with the fact that afflictive affects influence people longer than pleasure (Baumeister et al., 2001); around 2 days against 1 day (Sheldon et al., 1996).

Due to this longer influence of afflictive affects, it is reasonable to ask whether there is an effect on the hedonic treadmill dynamics when incorporating the dependence on the afflictive affect-based approach motivation, $M_{ap}^A(A_m(t))$, into the approach hedonic motivation, $M_{ap}(P_m(t), A_m(t))$ (Eq. (10)); in other words, we would like to know what happens to the hedonic treadmill dynamics when $\alpha_{ap} \neq 1$.

To answer this question, we carry out the simulations of the dynamical model of happiness with $\alpha_{ap} = 0.75$ and $\theta_A = 0.05$, while keeping the value of the rest of the

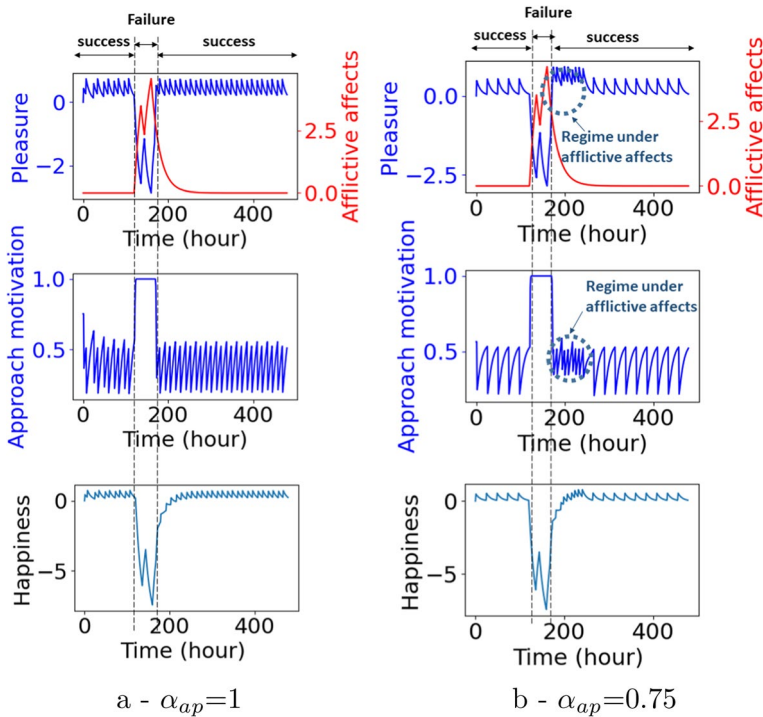


Fig. 12 Approach dynamics in the case of two days of failures. **a** (left column) Dynamics of the reference case. **b** (right column) dynamics for $\alpha_{ap} = 0.75$, i.e., 75% of the hedonic motivation is driven by (dis-)pleasure and 25% by afflictive affects, and $\theta_A = 0.05$. A regime under afflictive affects appears with shorter hedonic cycles

parameters the same as in the reference case. Note that now, 75% of the hedonic motivation is driven by (dis-)pleasure and 25% by afflictive affects. The choice of $\theta_A = 0.05$ helps us highlight the influence of afflictive affects. The results are shown in Fig. 12b.

The first difference we notice from the reference case (Fig. 12a) appears during the first 6 days of continuous success; due to the absence of afflictive affects and the lower influence of the pleasure-based approach motivation ($\alpha_{ap} = 0.75 < 1$), the approach hedonic motivation experiences longer cycles, producing as a consequence, also longer hedonic cycles in pleasure.

The second and most interesting difference is the appearance of a new hedonic regime once successes restart. The persistence of afflictive affects after the two days of constant failure increases the hedonic motivation and keeps the baseline motivation high (middle plot in Fig. 12b). This produces a new regime for the hedonic treadmill with higher levels of pleasure and higher frequency for about two days after successes resume (top plot in Fig. 12b), and a faster recovery to positive levels of happiness (bottom plot in Fig. 12b). As the afflictive affects decrease to a level lower than the afflictive affects threshold, θ_A , the hedonic motivation decreases and the hedonic cycles based only on displeasure come back.

5 Avoidance Hedonic Behaviour

Avoidance behaviour occurs when there is a negative valence stimulus. In the presence of such a stimulus, people seek to avoid the displeasure that the negative stimulus may cause. Moreover, stimuli with negative valence can be fear-inducing and may lead to avoidance behavior (Bandura, 1969).

Even though avoidance behavior may produce anxiety as well as depression in some specific cases (Dymond, 2019), avoidance behavior does not necessarily involve dysfunctional behavior in daily life. Hereafter, we consider this latter case, and we assume that avoidance behavior is not associated with anxiety or dysfunctional behaviors.

We shall see that, similarly to the approach strategy, the dynamics of pleasure and afflictive affects contribute to the motivation of people to adopt an avoidance strategy.

5.1 From Hedonic Avoidance Motivation to Behaviour Activation

As in Sect. 4, we consider a stylized case in order to analyze the psychological dynamics that contribute to the avoidance approach. In particular, we consider the case of an individual only subjected to constant negative stimuli ($V(\tau) = -0.5$). The analysis is similar to that of the approach hedonic behavior. Since the individual is only subjected to negative stimuli, the hedonic motivation to be considered is the avoidance hedonic motivation, $M_{av}(t)$, which is defined as

$$M_{av}(P_m(t), A_m(t)) = \alpha_{av}M_{av}^P(P_m(t)) + (1 - \alpha_{av})M_{av}^A(A_m(t)). \tag{18}$$

where $M_{av}^P(P_m(t))$ and $M_{av}^A(A_m(t))$ denote the pleasure- and afflictive-based avoidance motivations, respectively, and the coefficient $\alpha_{av} \in [0, 1]$ weights the contribution of both emotion-based avoidance motivations.

The pleasure-based approach motivation, $M_{av}^P(P_m(t))$, only depends on accumulated pleasure $P_m(t)$ as follows

$$\left\{ \begin{array}{l} M_{av}^P(P_m(t)) = 1 - \frac{(P_m(t) + 1)^{q_{av}}}{(P_m(t) + 1)^{q_{av}} + (1 + \theta_p)^{q_{av}}}, \\ \quad \text{if } P_m(t) \geq -1; \\ M_{av}^P(P_m(t)) = 1, \quad \text{if } P_m(t) < -1. \end{array} \right. \tag{19}$$

The afflictive affect-based approach motivation, $M_{av}^A(A_m(t))$, only depends on the afflictive affects, $A_m(t)$, accumulated over time as follows

$$M_{av}^A(A_m(t)) = \frac{A_m(t)^{q_{av}}}{A_m(t)^{q_{av}} + \theta_A^{q_{av}}}. \tag{20}$$

If the avoidance hedonic motivation, $M_{av}(P_m(t), A_m(t))$, given by Eq. (18), is higher than the activation threshold, θ_B , the avoidance behaviour is activated. If the avoidance behavior is not activated, the individual may experience the stimuli according to a contact probability, $p_{contact}$. If the individual experiences the stimuli because of this contact, the pleasure will be equal to the hedonic valence (i.e., $P_s(t) = V(t)$ and $A_s(t) = 0$), whereas no emotion

appears in the case of no contact with the stimuli ($P_s(t) = A_s(t) = 0$). In what follows, and for the sake of clarity, we simplify the notation of the avoidance hedonic motivation as $M_{av}(P_m(t), A_m(t)) = M_{av}(t)$.

5.2 Expectations of Pleasure from Stimulus Avoidance

In the case of avoidance behavior, expectations refer to the levels of expected levels of displeasure (i.e., negative valued pleasure) around those of the negative valence of the stimulus. Thus, the expectations depend on the hedonic valence $V(t)$ of the stimuli and the avoidance hedonic motivation, $M_{av}(t)$, as follows

$$E_{av}(V(t), M_{av}(t)) = V(t) + (M_{av}(t) - \mu_{av})V(t)(1 + V(t)), \quad (21)$$

where μ_{av} denotes an avoidance hedonic motivation coefficient that allows for the possibility of having levels of expectation of displeasure higher or lower than those determined solely by the valence of the stimulus.

Specifically, if the avoidance hedonic motivation $M_{av}(t)$ is higher (lower) than μ_{av} , then the expected levels of displeasure are higher (lower) than those determined by the stimulus valence $V(t)$; and if $M_{av}(t) = \mu_{av}$, then the expected level of displeasure from the negative stimulus is equal to its valence, i.e., $E_{av}(V(t), M_{av}(t)) = V(t)$. For the purpose of the numerical simulations, we set $\mu_{av} = 0.5$.

5.3 Effect of Avoidance Success and Failure on the Stimulus Pleasure and Affective Affects

Similarly to the approach behaviour, we consider a probability of success, $p_{success}$, of the avoidance strategy. However, the consequence of failure and success in the avoidance strategy does not lead to the same emotional mechanisms. In particular, an individual who succeeds in the avoidance behaviour, will obtain a stimulus pleasure (referring to the pleasure from having avoided the negative stimulus) proportional and opposite in sign to the expectations, i.e.,

$$P_s(t) = -\beta_{av}E_{av}(V(t), M_{av}(t)), \quad (22)$$

whereas failure to avoid the negative stimulus will bring the individual an experience of displeasure (negative stimulus pleasure) and affective affects equal to the hedonic valence of the stimulus increased (or decreased) by the difference with the expectations, i.e.,

$$P_s(t) = -A_s(t) = V(t) + (V(t) - E_{av}(V(t), M_{av}(t))). \quad (23)$$

Thus, both success and failure mechanisms in the avoidance and approach strategies are different. Also, if the avoidance behavior is not activated, we consider a probability of contact, $p_{contact}$, with the stimuli; if such contact occurs, the individual will experience the associated displeasure, but not affective affects, i.e., $P_s(t) = V(t)$ and $A_s(t) = 0$.

5.4 Hedonic Dynamics of Happiness Based on an Avoidance Behaviour

The scheme of the numerical dynamical model of happiness for an avoidance behaviour is described in Fig. 13, and can be summarized as follows. Depending on the avoidance hedonic motivation, $M_{av}(t)$, an individual can activate an avoidance strategy

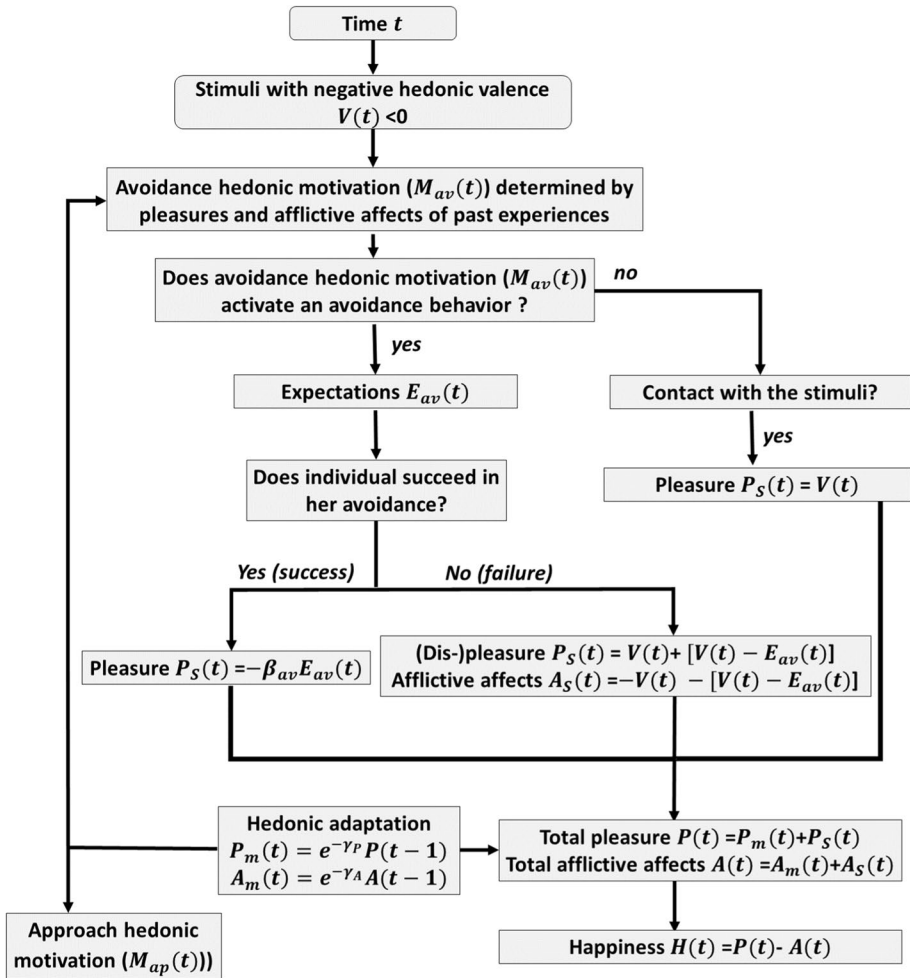


Fig. 13 Dynamical model of happiness based on avoidance behaviour. It highlights the different causal loops of the different psychological processes

in order to avoid the displeasure from a stimulus with a negative hedonic valence, $V(t)$. If the avoidance behaviour is activated, the individual will have some expectations, $E_{av}(V(t), M_{av}(t))$, given by Eq. (21), of the level of displeasure that can be experienced from the negative stimulus.

If the negative stimulus is avoided, the individual will experience a stimulus pleasure proportional and opposite in sign to the expectation, according to Eq. (22). In case of failure, the individual experiences levels of displeasure and afflictive affects equal to the hedonic valence of the stimulus increased (or decreased) by the difference with the expectations, according to Eq. (23).

5.5 Hedonic Self-Regulation in the Case of Permanent Success in an Avoidance Strategy

In this case of avoidance hedonic behavior, just like in the approach behavior, individual’s behavior is continuously driven by a trade-off between pleasure and hedonic motivation. A decrease in the levels of pleasure (caused by hedonic adaptation) increases the levels of hedonic motivation, and may push the individual to activate an avoidance behavior in order to increase the levels of pleasure, as shown in Fig. 14. This process of hedonic self-regulation, driven by the opposite regulating roles of behavioural activation and hedonic adaptation (depicted with green boxes in Fig. 14) yields a hedonic treadmill with alternative peaks of pleasure.

We illustrate this effect in Fig. 15 by considering an individual (i) continuously subjected to negative stimuli with the same hedonic valence ($V(\tau) = -0.5$), (ii) who always succeeds in their avoidance behavior when this latter is activated, (iii) with a probability of contact with the stimuli equal to 0 when the behavior is not activated, and (iv) with a pleasure hedonic adaptation $\gamma_p = 0.1$ (it takes approximately one day for removing 90% of the stimuli pleasure). In this scenario, such individual only experiences pleasure with its associated hedonic adaptation, and the pleasure dynamics is fully controlled by the activation of the avoidance strategy. Also, no afflictive affects nor displeasure emerge because there is no failure.

In order to show the effect that changes in parameter values can have on the behaviour of the hedonic treadmill resulting from the self-regulation of pleasure, we present the results of a sensitivity analysis in Fig. 15. The dynamics of the reference case is shown in Fig. 15a, and the dynamics after varying the pleasure threshold, θ_p , the activation threshold, θ_B , and the hedonic adaptation, γ_p , are shown in Fig. 15b–d, respectively.

Results are quite similar to those of the approach behavior. An increase in the pleasure threshold θ_p (value below which the pleasure-based approach motivation is always higher than 0.5) leads to higher levels of pleasure, as shown in Fig. 15b, since the

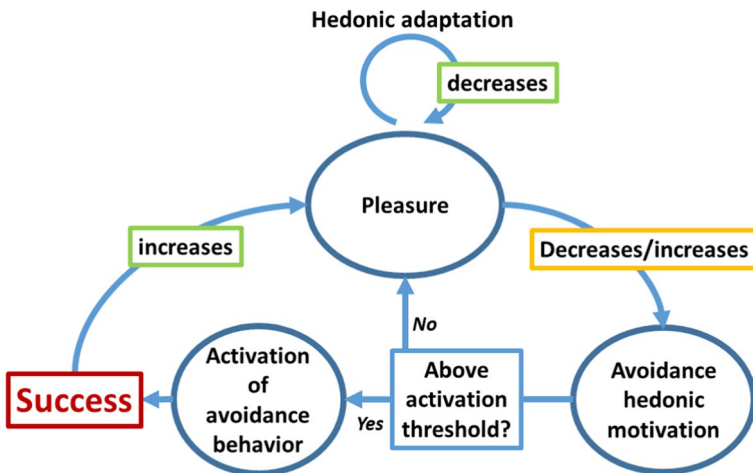


Fig. 14 Hedonic self-regulation in the case of constant success in the avoidance behavior. Hedonic adaptation decreases pleasure, while success in the avoidance behavior increases pleasure (green boxes). Depending on the pleasure resulting from these opposite regulating components, avoidance hedonic motivation can either decrease or increase (orange box), leading, or not, to behavioral activation. (Color figure online)

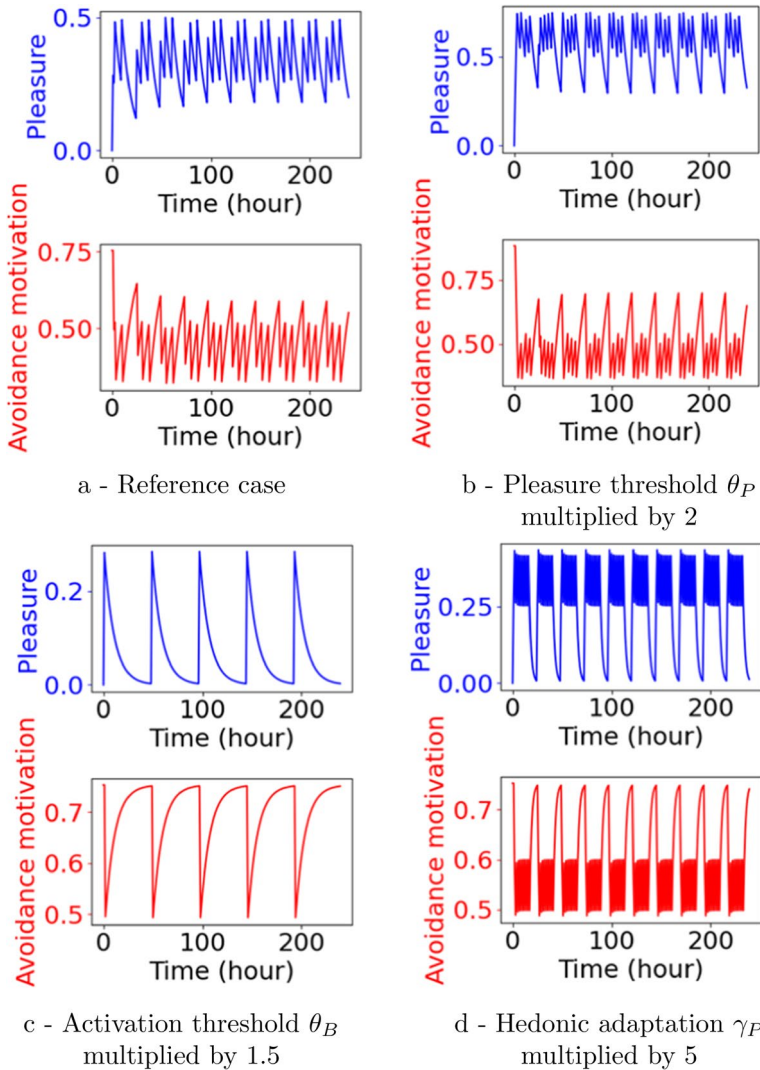


Fig. 15 Sensitivity analysis in the case of permanent success of avoidance behavior. Effects are similar to the ones obtained in the case of approach behavior (see Fig. 9)

hedonic motivation is kept at high levels with higher levels of pleasure in comparison to the reference case.

An increase of the activation threshold θ_B requires a higher hedonic motivation for activating an avoidance behavior. This delays such activation and slows down the hedonic treadmill cycles as shown in Fig. 15c.

When the hedonic adaptation γ_P is increased, the level of pleasure obtained from a successful avoidance behavior decreases quickly, causing an increase in the hedonic cycles as shown in Fig. 15d. Note in the same figure, that around every twenty four

hours the level of pleasure decreases near to zero, which corresponds to the night time when the individual is only subjected to hedonic adaptation.

Unlike the constant successful approach strategy, in which the experienced pleasure comes from the contact with stimuli, the pleasure from a constant successful avoidance strategy comes from avoiding contact with the stimuli and is determined by a fraction of the expectations. For this reason, a constant successful avoidance strategy results in lower levels of pleasure and higher hedonic cycles than those of a constant successful approach strategy.

We now consider the possibility of having contact with the stimuli when the avoidance behavior is not activated. Since having a probability of contact with negative stimuli involves displeasure (negative pleasure), this case can lead to a stochastic hedonic treadmill behaviour caused by the pleasure of a successful avoidance and the displeasure caused by a probable contact with the negative stimuli when the avoidance behavior is not activated. This is illustrated in Fig. 16, that shows the influence of different values of the probability of contact, $p_{contact}$, on the dynamics of pleasure.

Unlike contact with stimuli when the approach behavior is not activated (Fig. 10), which increases pleasure and decreases approach motivation, contact with negative stimuli when the avoidance behavior is not activated decreases pleasure and increases avoidance motivation (Fig. 16). For instance, while an individual, who has always contact with positive stimuli when the approach behaviour is not activated, does not need to activate an approach strategy due to the lack of approach motivation ($p_{contact} = 1$ in Fig. 10), an individual, who has always contact with negative stimuli when the avoidance behaviour is not activated, needs to continuously activate the avoidance strategy ($p_{contact} = 1$ in Fig. 16).

5.6 Effect of Affective Affects on the Hedonic Cycles in the Case of Avoidance Failure

Instead of having permanent success ($p_{success}=1$), we now consider the case of a time frame of continuous failure ($p_{success}=0$) in the dynamical model of happiness described in Fig. 13. In particular, we illustrate the pleasure dynamics of an individual subjected to the previous reference case (Fig. 15a), who suddenly faces continuous failure during two days. In case of failures, displeasure and affective affects arise as depicted in Fig. 17; for this reason,

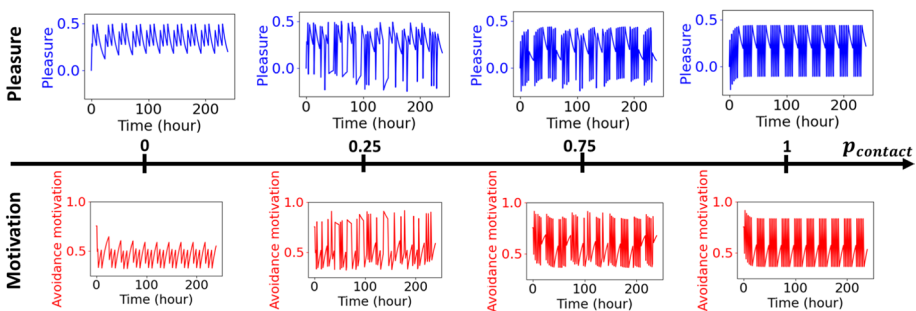


Fig. 16 Effect of the contact probability, $p_{contact}$, when the avoidance behavior is not activated. Adding a contact probability creates some stochasticity in the pleasure dynamics (except when the probability equals 0 or 1). The higher the contact probability, the higher the avoidance motivation and the experience of displeasure



Fig. 17 Hedonic self-regulation in the case of failure in the avoidance behavior. Hedonic adaptation decreases displeasure and afflictive affects, while failure in the avoidance behavior increases displeasure and afflictive affects (green boxes). Depending on the pleasure and afflictive affects resulting from these opposite regulating components, hedonic motivation can either decrease or increase (orange boxes), leading, or not, to behavioral activation. (Color figure online)

we need to consider the hedonic adaptation of afflictive affects, and set it to $\gamma_A = 0.05$ (it takes approximately two days for removing 90% of the stimuli afflictive affects). Also, we assume a contact probability, $p_{contact} = 0$, when there is no behavioral activation.

The simulations for the hedonic dynamics in this case are shown in Fig. 18a (this is now, our new reference case). After six days of continuous success in the avoidance strategy, the individual experiences two days of continuous failure, before experiencing continuous success again. Notice that the two days of constant failure produce an increase of afflictive affects (red curve) and a collapse in the levels of pleasure, which in turn make the avoidance motivation reach its highest level and the levels of happiness decrease to negative levels (unhappiness). This highest level of motivation during the two days of failure is solely due to the high levels of displeasure since in this reference case, the presence of the of afflictive affects does not affect the approach motivation; in other words $\alpha_{ap} = 1$ in Eq. (18). However, note that the afflictive affects have a significant effect on the levels of happiness, not only during the 2 days of failure but also after the individual starts experiencing successes again (after the 8th day). Even though displeasure does not last much longer after successes come back (due to the high levels of avoidance motivation), afflictive affects persist for some time, preventing the levels of

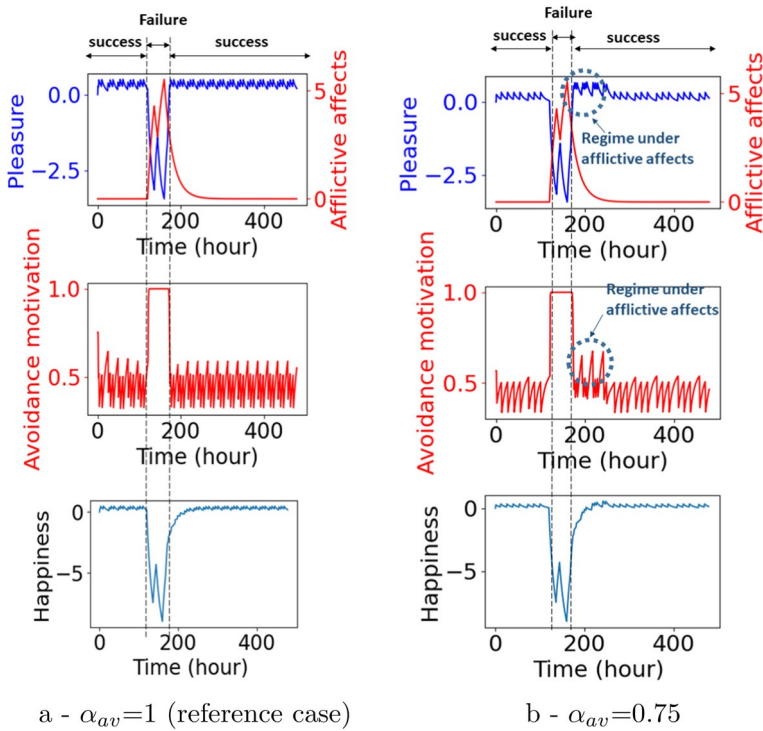


Fig. 18 Avoidance dynamics in the case of two days of failures. **a** (left column) Dynamics of the reference case. **b** (right column) Dynamics for $\alpha_{av} = 0.75$, i.e., 75% of the hedonic avoidance motivation is driven by (dis-)pleasure and 25% by afflictive affects, and $\theta_A = 0.05$. A regime under afflictive affects appears with shorter hedonic cycles

happiness to increase as rapidly as the levels of pleasure. As mentioned previously, this is consistent with the fact that afflictive affects influence people longer than pleasure (Baumeister et al., 2001); around 2 days against 1 day (Sheldon et al., 1996).

Due to this longer influence of afflictive affects, it is reasonable to ask, just as we did for the case of failure in the approach behavior, whether there is an effect on the hedonic treadmill dynamics when incorporating the dependence on the afflictive affect-based avoidance motivation, $M_{av}^A(A_m(t))$, into the avoidance hedonic motivation, $M_{av}(P_m(t), A_m(t))$ (Eq. (18)); in other words, we would like to know what happens to the hedonic treadmill dynamics when $\alpha_{ap} \neq 1$.

To answer this question, we carry out the simulations of the dynamical model of happiness based on avoidance behaviour (Fig. 13) with $\alpha_{ap} = 0.75$ and $\theta_A = 0.05$, while keeping the value of the rest of the parameters the same as in the reference case. Note that now, 75% of the hedonic motivation is driven by (dis-)pleasure and 25% by afflictive affects. The choice of $\theta_A = 0.05$ helps us highlight the influence of afflictive affects. The results are shown in Fig. 18b.

The first difference we notice from the reference case (Fig. 18a) appears during the first six days of continuous success; due to the absence of afflictive affects and the lower influence of the pleasure-based avoidance motivation ($\alpha_{av} = 0.75 < 1$), the avoidance

hedonic motivation experiences longer cycles, producing as a consequence, also longer hedonic cycles in pleasure.

The second and most interesting difference is the appearance of a new hedonic regime once successes restart. The persistence of afflictive affects after the two days of constant failure increases the hedonic avoidance motivation and keeps the baseline motivation high (middle plot in Fig. 18b). This produces a new regime for the hedonic treadmill with higher levels of pleasure and higher frequency for about two days after successes resume (top plot in Fig. 18b), and a faster recovery to positive levels of happiness (bottom plot in Fig. 18b). As the afflictive affects decrease to a level lower than the afflictive affects threshold, θ_A , the hedonic motivation decreases and the hedonic cycles based only on displeasure come back.

6 Approach–Avoidance Hedonic Behaviour

In this section, we analyze a more complex behavior that involves both approach and avoidance behaviours, i.e., we consider a whole approach–avoidance behavior. In order to show the hedonic dynamics of an approach–avoidance behavior, we consider an individual subjected to stimuli with random hedonic valences between -1 and 1 . The purpose is to show the opposite effects of the approach and avoidance behaviours on the hedonic treadmill dynamics as a response to the random valences of stimuli. To better understand the interacting effects and outcomes of both behaviors, we summarized, in Table 1, the main and different effects of the approach and avoidance behaviors on pleasure and afflictive affects in the cases of success, failure, and no behavioral activation.

6.1 Permanent Success in an Approach–Avoidance Hedonic Behavior

In the case of permanent success in an approach–avoidance behavior, an individual exposed to stimuli with random valences may or may not activate an approach or avoidance behavior. When a behaviour is activated, there is always success (first row in Table 1), and when there is no behavioral activation, there might be contact with the stimuli (third row in Table 1).

Thus, the only outcome resulting in displeasure is when an individual exposed to a negative stimulus does not activate the avoidance behaviour and has contact with the stimulus (last case in Table 1). We show the effect of such contact on the pleasure and happiness dynamics in Fig. 19.

On the one hand, when there is no contact with the stimuli ($p_{contact} = 0$) after no behavioural activation, there is no source of displeasure and, therefore, the levels of pleasure and happiness are always positive due to the constant success in both approach and avoidance strategies, as shown in Fig. 19a. Moreover, since the individual does not experience failure, the afflictive affects are null and only the levels of pleasure will drive the hedonic motivations, which in turn will activate an approach or an avoidance behaviour when the levels of pleasure are low. This self-regulating dynamics of pleasure keeps the minimum level of pleasure around 0.25 in Fig. 19a.

On the other hand, when there is always contact with the stimuli ($p_{contact} = 1$) after no behavioural activation, contact with positive stimuli will cause an increase of pleasure and happiness whereas contact with the negative stimuli will decrease them. This will result in higher variations in the levels pleasure and happiness, as seen in Fig. 19b; there are levels of pleasure and happiness higher than those when there is no contact, and also levels

Table 1 Main outcomes of the approach and avoidance strategies

	Approach (to positive stimuli)	Avoidance (of negative stimuli)
Success	Pleasure increases depending on positive stimulus valence and expectations	Pleasure increases depending on expectations
Failure	Displeasure and afflictive affects increase depending on expectations	Displeasure and afflictive affects increase depending on the negative stimulus valence and expectations
No behavioral activation	If there is contact with the positive stimulus (according to a probability of contact) pleasure has an increase equal to the stimulus valence	If there is contact with the negative stimulus (according to a probability of contact) displeasure has an increase equal to the stimulus valence

of displeasure (negative pleasure) and unhappiness (negative happiness) caused by contact with negative stimuli.

6.2 Effect of Failures in an Approach–Avoidance Hedonic Behavior

Instead of having permanent success ($p_{success}=1$), we now consider the case of a time frame of continuous failure ($p_{success}=0$), and its effect on the pleasure and happiness dynamics. In particular, we illustrate these dynamics for an individual exposed to stimuli with random valences who, after six days of continuous success in the approach–avoidance strategy, suddenly faces two days of continuous failure before experiencing constant success again. The numerical simulations for this case, shown in Fig. 20, assume a null contact probability, $p_{contact} = 0$, when there is no behavioral activation, $\alpha_{ap} = \alpha_{av} = 0.75$ (i.e., 75% of the hedonic motivation is driven by (dis-)pleasure and 25% by afflictive affects), and $\theta_A = 0.05$, in order to highlight the effect of both afflictive affects and displeasure in the resulting dynamics of happiness.

During the 2 days of failure, both approach and avoidance motivations are at the highest level. While this may trigger the activation of corresponding behaviors, continuous failure does not result in a subsequent decrease of afflictive affects or in an increase of pleasure, thus maintaining the levels of hedonic motivations at its highest level. The persistence of afflictive affects after the two days of constant failure keeps the baseline motivations high (bottom plots in Fig. 20), which in turn produces a new regime for the hedonic treadmill with higher levels of pleasure and higher frequency for about two days after successes resume (top left plot in Fig. 20), and a steady recovery to positive levels of happiness (top right plot in Fig. 20). Eventually, the afflictive affects decrease to a level lower than the afflictive affects threshold, $\theta_A = 0.05$, causing the hedonic motivations to decrease and the hedonic cycles based only on displeasure to come back.

In order to illustrate the stochastic nature of the hedonic treadmill dynamics, we now add a random success, i.e., a probability of success different from zero or one, in particular, $p_{success}=0.5$. We consider two cases: the case when the contact probability is null, $p_{contact} = 0$, if a behaviour is not activated and the case when there is always contact ($p_{contact} = 1$) with the stimuli if the behavior is not activated (Fig. 21).

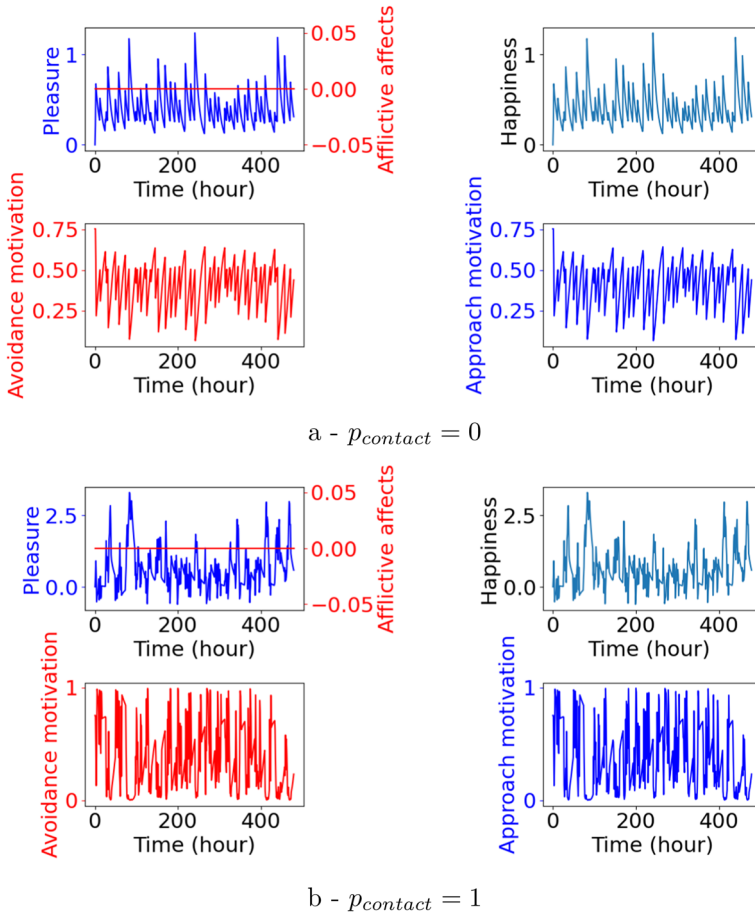


Fig. 19 Approach–avoidance dynamics in case of constant success, when **a** there is no contact with the stimuli if the approach or avoidance behavior is not activated ($p_{contact} = 0$), and **b** there is always contact with stimuli if behavior is not activated ($p_{contact} = 1$); the higher contact with positive stimuli increases happiness while the higher contact with negative stimuli decreases it

Note that in this case of random success, a higher probability of contact does not cause higher variability in the levels of happiness or pleasure, which differs to the effect of increasing the contact probability in the case of constant success (Fig. 19). The reason for this is that the individual can now experience both afflictive affects and displeasure (due to failure) whether there is contact or not with the stimuli when a behaviour is not activated. However, it is worth mentioning that having contact with the stimuli when the behaviour is not activated contributes to the high peaks of (un-)happiness and (dis-)pleasure and increases the stochasticity of the hedonic treadmill dynamics (Fig. 21b).

Finally, note that these simulations in the case of random success can be interpreted as the contribution to the approach–avoidance dynamics of psychological processes (Fig. 21a) and of the environment (Fig. 21b). In both cases, as predicted by the SSHM model of happiness, the individual experiences fluctuating happiness.

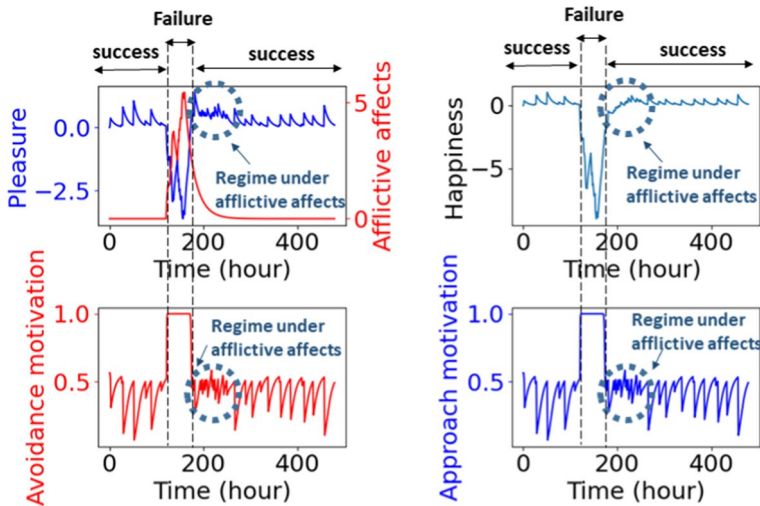


Fig. 20 Approach–avoidance dynamics in the case of two days of failures for $\alpha_{ap} = \alpha_{av} = 0.75$, i.e., 75% of the hedonic motivation is driven by (dis-)pleasure and 25% by afflictive affects, and $\theta_A = 0.05$. A regime under afflictive affects appears with shorter hedonic cycles

7 Conclusion and Discussions

The use of computational modeling may help build theories in psychological science by better understanding causality relationships and dynamic effects of psychological processes on people in the long term (Guest and Martin, 2021). In this work, we develop a dynamical model of happiness based on the approach–avoidance framework by translating part of its complex psychological processes into equations.

Our results show how the hedonic treadmill may emerge from interactions between several of the psychological processes considered. The model enables us to understand the role of isolated and interacting processes in the hedonic dynamics of happiness. Even though a mathematical modelling approach may not capture all the psychological complexity of the dynamics of happiness; it may, however, provide new insights for developing new theories through the operationalization of a causality structure. In fact, assessing the dynamical long-term effect of interacting processes is a major issue for discriminating causality from correlation (Peyrot, 1996; Marken and Horth, 2011). Specific surveys can be carried out for this purpose (Marken and Horth, 2011), but we argue that a modeling approach can provide a relevant complementary tool for helping researchers on this issue.

In this work, we focused on the hedonic dynamics coming from an approach–avoidance behavior and its homeostatic properties. A reasonable future task to carry out is to extend this work by incorporating the eudaimonic dimension of happiness (Ryff and Singer, 2008; Ryan and Deci, 2001) into the model and studying the dynamics of such dimension alone. According to these authors, while the hedonic approach of happiness focuses on pleasure attainment and pain avoidance, the eudaimonic approach focuses on meaning, self-realization and optimal functioning. Eudaimonic motivations include seeking excellence, authenticity and meaning while doing various activities (Huta, 2016). Therefore, eudaimonic activities are different from hedonic activities: we may cite volunteering at community center, arts, sharing knowledge with others for instance. The analysis of both eudaimonic and hedonic dimensions and

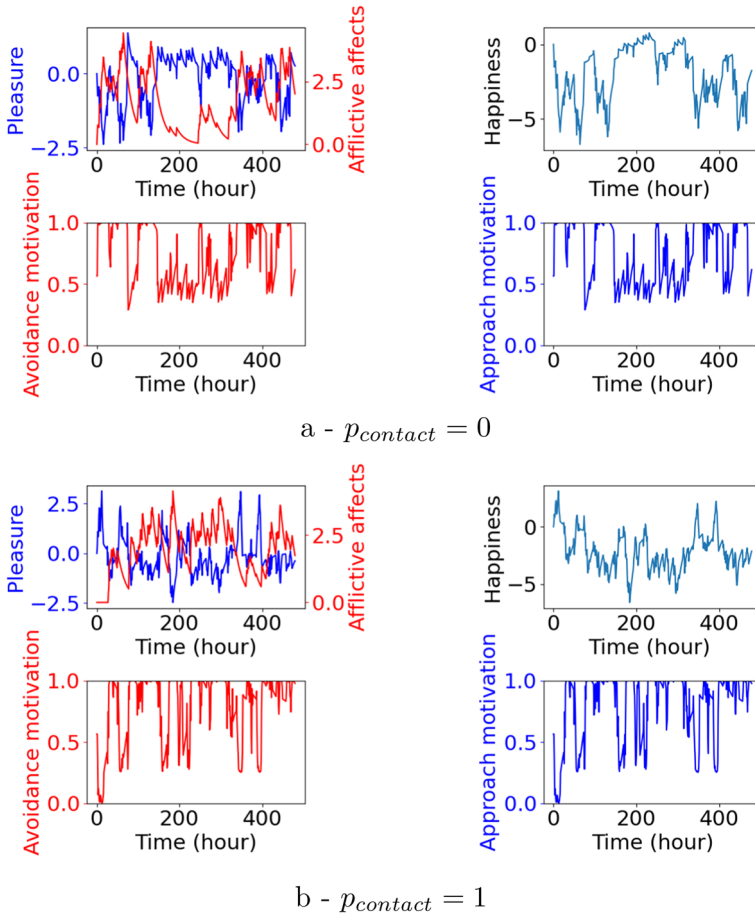


Fig. 21 Approach–avoidance dynamics in case of random success. In particular, $p_{success}=0.5$, for the cases when **a** the contact probability, $p_{contact} = 0$, if a behaviour is not activated and **b** there is always contact with the stimuli if the behavior is not activated, i.e., $p_{contact} = 1$

their interactions may help understanding not only happiness dynamics as a whole but also the specific roles played by these dimensions in the dynamics of happiness.

It is known that the selflessness processes of happiness contribute to long-term happiness; while this is not the case for self-centeredness processes (Dambrun, 2017). In particular, it has been shown that self-centeredness is positively related to fluctuating happiness, whereas selflessness is positively related to enduring happiness (Dambrun, 2017). Also, the experience of selflessness increases the likelihood of experiencing stable happiness the next moment and the next day (Pellerin et al., 2022).

Figure 21 reveals that the approach–avoidance process promotes fluctuating happiness via transient pleasures and affective affects, consistent with the SSHM. This figure also reveals that, on average, the level of happiness is below zero, which seems inconsistent with existing data. For example, in a recent study using the experience sampling method, Pellerin et al. (2022) found that, on average, individuals experience positive happiness (i.e., 67.71 on a 0–100 scale). Work on happiness and life satisfaction also indicates that most people report happiness

levels above the neutral point (Veenhoven, 2012). We believe this reflects a limitation of the present model, which focuses exclusively on the process of approach–avoidance and does not take into account more related selflessness processes such as connection to others, pro-social behaviors, and benevolent emotions such as empathy and compassion, which are known to increase happiness (Dambrun and Ricard, 2011; Dambrun, 2017). The psychology literature on the evaluative side of well-being, shows, for example, that life satisfaction can encompass various aspects such as the meaning given to life, or the success obtained in achieving life goals. Other elaborations, such as the Mental Health Continuum, combine aspects of subjective (Diener et al., 2002) and psychological (Ryff and Singer, 2008) well-being, and even add a “social well-being” component (Keyes, 2002). In line with empirical findings of what constitutes well-being for lay people over the planet (Delle Fave et al., 2011, 2016), more recent approaches also consider harmony, either in the form of a “principle of harmony” (Dambrun and Ricard, 2011), or “harmony in life” (Kjell et al., 2016; Kjell and Diener, 2020). Thus, it would be important to complement this mathematical model with the “selflessness” branch of the SSHM to obtain a more realistic picture of an individual’s experience of happiness.

Another potential following work is the validation of the proposed model through surveys or specific experiments. For instance, the dynamics of the proposed dynamical model presented not only overall fluctuations in the levels of happiness but also specific fluctuation regimes determined by afflictive affects (see Figs. 12 or 20 for instance), which may provide insights for the design of new experiments to test the model. For instance, we may use the experience sampling method (ESM; e.g. (Pellerin et al., 2020; Pellerin et al., 2022)) on mobile devices for following hedonic cycle (pleasure measurement) as well as afflictive affects. Then, the purpose is to see if hedonic cycles are shorter when individuals experience afflictive affects until two days before this given shorter hedonic cycle. It will require to develop ESM measurement with a short time step (1 h in order to be consistent with our results). Another perspective may rely on the characterization of hedonic adaptation for pleasure and afflictive affects dynamics by identifying hedonic adaptations γ_P and γ_A from Eqs. 6 and 7. For this purpose, we may also use ESM on mobile devices and extracting pleasure and afflictive affects curve. The main challenge is to have this curve with a time step of 1 (or 2) hours in order to identify this parameter. Having a large sampling of people may give us not only the distribution of hedonic adaptation within a population but also potential predictors (to be determined) of high and low hedonic adaptation.

The proposed mathematical model and its dynamics offers new perspectives for decision-makers to understand the impact of policies on individuals’ well-being. For instance, economic policies influence people’s level of happiness (Frey and Stutzer, 2002), and physical stimuli caused by urban design for citizens may impact their happiness in daily life (Samavati and Ranjbar, 2017). These stimuli, which may be imposed (depending on where people live), might influence happiness dynamics much more than the individual psychological characteristics. In this regard, we showed that having a high probability of contact with positive stimuli may decrease the approach motivation, while having a frequent contact with negative stimuli may result in the appearance of afflictive affects and displeasure regardless of the avoidance motivation levels of the individual. In practice, the physical aspects of urban environments (buildings, public parks) can be considered in city policies in terms of imposed stimuli that affect happiness (Samavati and Ranjbar, 2017). Therefore, the next step is to evaluate the influence of urban component on hedonic motivation in order to evaluate its contribution, not only on happiness as done before but on the mechanisms highlighted by our study, i.e. imposed stimuli may increase hedonic motivation, yielding higher expectations and therefore potential displeasure and afflictive affects. A specific survey—inspired by (Samavati and Ranjbar, 2017)—can be considered for this purpose.

In summary, the mathematical modelling approach to happiness offers an alternative way for better understanding the dynamics of happiness that emerge from complex interacting and non-linear psychological processes.

Appendix A Proof of Eqs. (4) and (5)

We start by rewriting Eqs. (2) and (3),

$$P(t) = \sum_{\tau=0}^t P_s(\tau) e^{-\gamma_P(t-\tau)},$$

$$A(t) = \sum_{\tau=0}^t A_s(\tau) e^{-\gamma_A(t-\tau)},$$

and noticing that isolating the last term of these sums leads to the following equations

$$P(t) = \sum_{\tau=0}^{t-1} P_s(\tau) e^{-\gamma_P(t-\tau)} + P_s(t), \quad (\text{A1})$$

$$A(t) = \sum_{\tau=0}^{t-1} A_s(\tau) e^{-\gamma_A(t-\tau)} + A_s(t). \quad (\text{A2})$$

Taking out $e^{-\gamma_P}$ and $e^{-\gamma_A}$ as common factors of the summation terms in Eqs. (A1) and (A2), respectively, we obtain

$$P(t) = e^{-\gamma_P} \sum_{\tau=0}^{t-1} P_s(\tau) e^{-\gamma_P(t-1-\tau)} + P_s(t), \quad (\text{A3})$$

$$A(t) = e^{-\gamma_A} \sum_{\tau=0}^{t-1} A_s(\tau) e^{-\gamma_A(t-1-\tau)} + A_s(t). \quad (\text{A4})$$

Note that the factorization required to add e^{γ_P} and e^{γ_A} in the summation terms, which correspond, respectively, to $P(t-1)$ and $A(t-1)$. Thus, we can rewrite Eqs. (A3) and (A4) as

$$P(t) = e^{-\gamma_P} P(t-1) + P_s(t),$$

$$A(t) = e^{-\gamma_A} A(t-1) + A_s(t),$$

which are precisely Eqs. (4) and (5).

Appendix B: List of Variables and Parameters of the Model

The list and description of variables and parameters of the model is reported in Table 2. Note that the third column contains both variables and parameters, and the fourth column contains their value ranges and/or the values used for the numerical simulations.

Table 2 State variables and parameters of the mathematical model

Name	Description	Sym- bol	Value
Time	Discrete time with a time step of one hour	t	0, 1, 2, ...
Valence	Valence of stimuli	$V(t)$	$[-1, 1]$
Approach motivation	Sum of the contributions from the pleasure-based and afflictive affects-based motivations to the approach motivation.	$M_{ap}(t)$	$[0, 1]$
Pleasure-based motivation of the approach motivation	Part of the approach motivation that depends only on the level of pleasure.	$M_{ap}^P(t)$	$[0, 1]$
Afflictive affects-based motivation of the approach motivation	Part of the approach motivation that depends only on the level of afflictive affects.	$M_{ap}^A(t)$	$[0, 1]$
Pleasure weight in the approach motivation	Fraction contribution of the pleasure-based motivation in the approach motivation	α_{ap}	$[0, 1]$
Avoidance motivation	Sum of the contributions from the pleasure-based and afflictive affects-based motivations to the avoidance motivation	$M_{av}(t)$	$[0, 1]$
Pleasure-based motivation of the avoidance motivation	Part of the avoidance motivation that depends only on the level of pleasure.	$M_{av}^P(t)$	$[0, 1]$
Afflictive affects-based motivation of the avoidance motivation	Part of the avoidance motivation that depends only on the level of afflictive affects.	$M_{av}^A(t)$	$[0, 1]$
Pleasure weight in the avoidance motivation	Fraction contribution of the pleasure-based motivation in the avoidance motivation	α_{av}	$[0, 1]$
Pleasure threshold	Level of pleasure for which the pleasure-based approach or avoidance motivation equals 0.5. The pleasure-based motivation increases significantly below this value	θ_p	$[0, +\infty[;$ $\theta_p = 0.25$
Afflictive affects threshold	Level of afflictive affects for which the afflictive affects-based approach or avoidance motivation equals 0.5. The afflictive affects-based motivation increases significantly above this value	θ_A	$[0, +\infty[;$ $\theta_A = 0.05$
Approach motivation tuning parameter	It tunes how the approach motivation increases or decreases around the pleasure and afflictive affects thresholds	q^{ap}	$[1, +\infty[;$ $q^{ap} = 5$
Avoidance motivation tuning parameter	It tunes how the avoidance motivation increases or decreases around the pleasure and afflictive affects thresholds	q^{av}	$[1, +\infty[;$ $q^{av} = 5$
Activation threshold	Motivation level above which the approach or avoidance behavior is activated	θ_B	$[0, 1]; \theta_B = 0.5$
Expectations in the approach behavior	Expected levels of pleasure from a positive stimuli	$E_{ap}(t)$	$[0, 1]$
Expectation coefficient for the approach behavior	The coefficient allows for the possibility of having levels of expectation higher or lower than those of the valence of the stimulus	μ_{ap}	$[0, 1];$ $\mu_{ap} = 0.5$
Expectations in the avoidance behavior	Expected levels of displeasure (negative pleasure) from a negative stimuli	$E_{av}(t)$	$[-1, 0]$
Expectation coefficient for the avoidance behavior	The coefficient allows for the possibility of having levels of expectation higher or lower than those of the valence of the stimulus	μ_{av}	$[0, 1];$ $\mu_{av} = 0.5$

Table 2 (continued)

Name	Description	Sym- bol	Value
Fraction proportionality constant of expectations for the approach strategy	The displeasure experienced after failure of an approach strategy is assumed to be a fraction of the expectations	β_{ap}	$[0, 1]; \beta_{ap} = 0.5$
Fraction proportionality constant of expectations for the avoidance strategy	The pleasure experienced after a successful avoidance behavior is assumed to be a fraction of the expectations	β_{av}	$[0, 1]; \beta_{av} = 0.5$
Probability of success	The probability of having a successful approach to/avoidance from the stimuli depends on the context, the environment, and individual skills	$P_{success}$	$[0, 1]$
Probability of contact	Probability of having contact with the stimuli when the approach/avoidance behavior is not activated	$P_{contact}$	$[0, 1]$
Stimulus pleasure	Pleasure (displeasure) experienced due to the success (failure) in approaching or avoiding the stimulus at time t	$P_s(t)$	$[-1, 1]$
Stimulus affective affects	Affective affects experienced due to failure in approaching or avoiding the stimulus at time t	$A_s(t)$	$[0, 1]$
Hedonic adaptation of pleasure	It reduces the impact of stimuli pleasure over time	γ_P	$[0, +\infty[; \gamma_P = 0.1$
Hedonic adaptation of affective affects	It reduces the impact of stimuli affective affects over time	γ_A	$[0, +\infty[; \gamma_A = 0.05$
Accumulated pleasure	Accumulated pleasure at time t caused by all past stimuli pleasure subjected to hedonic adaptation	$P_m(t)$	$] -\infty, +\infty[$
Accumulated affective affects	Accumulated affective affects at time t caused by all past stimuli affective affects subjected to hedonic adaptation	$A_m(t)$	$[0, +\infty[$
Total pleasure	Total pleasure at time t caused by all past stimuli pleasure subjected to hedonic adaptation and the current stimulus pleasure	$P(t)$	$] -\infty, +\infty[; P(0) = 0$
Total affective affects	Total affective affects at time t caused by all past stimuli affective affects subjected to hedonicadaptation and the current stimulus affective affect	$A(t)$	$[0, +\infty[; A(0) = 0$
Happiness	Happiness is defined as the total pleasure minus the total affective affects	$H(t)$	$] -\infty, +\infty[$

Funding The study was funded by the French National Research Agency (project VIRGO, ANR-16-CE03-0003-01 grant) and the Athabasca University AVPR-SRO fund

Data Availability The code for generating the simulations can be downloaded at <https://github.com/jdmatias/happiness>.

Declarations

Conflict of interest The authors certify that there is no Conflict of interest with any individual/organization for the present work. The authors have no Conflict of interest to declare that are relevant to the content of this article.

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Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

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