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Article

Modelling Adaptation through Social Allostasis: Modulating the Effects of Social Touch with Oxytocin in Embodied Agents

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Abstract: Social allostasis is a mechanism of adaptation that permits individuals to dynamically adapt their physiology to changing physical and social conditions. Oxytocin (OT) is widely considered to be one of the hormones that drives and adapts social behaviours. While its precise effects remain unclear, two areas where OT may promote adaptation are by affecting social salience, and affecting internal responses of performing social behaviours. Working towards a model of dynamic adaptation through social allostasis in simulated embodied agents, and extending our previous work studying OT-inspired modulation of social salience, we present a model and experiments that investigate the effects and adaptive value of allostatic processes based on hormonal (OT) modulation of affective elements of a social behaviour. In particular, we investigate and test the effects and adaptive value of modulating the degree of satisfaction of tactile contact in a social motivation context in a small simulated agent society across different environmental challenges (related to availability of food) and effects of OT modulation of social salience as a motivational incentive. Our results show that the effects of these modulatory mechanisms have different (positive or negative) adaptive value across different groups and under different environmental circumstance in a way that supports the context-dependent nature of OT, put forward by the interactionist approach to OT modulation in biological agents. In terms of simulation models, this means that OT modulation of the mechanisms that we have described should be context-dependent in order to maximise viability of our socially adaptive agents, illustrating the relevance of social allostasis mechanisms.

Keywords: embodied agents; embodied affect; embodied interaction; social allostasis; oxytocin; homeostasis; social salience; social adaptation; social simulation

1. Introduction

1.1. Background

For embodied agents to exist in the real world, adapting to changing conditions is a crucial skill in determining their long-term success. Animals—including humans—who exist in social groups have evolved by reacting and adapting their behaviours not only to their physical environment, but also to the changing dynamics of their society, developing skills for understanding social hierarchies, forming relationships and bonds with others, and learning how to react to threats and predators in order to maximise survival. How individuals adapt their (social) behaviours can be attributed to many mechanisms, one of which is affect [1]. The research presented in this paper is concerned with the dynamics of affect-based relationships in social groups of embodied agents, by identifying and modelling potential mechanisms that contribute to social adaptation. Building upon our previous work [2], this study investigates how dynamically adapting an agent's internal response to tactile contact with another agent affects their survival under several conditions implementing different social contexts.

Using only short-term regulatory mechanisms such as homeostasis, where individuals maintain their internal conditions within a set range of values, may not be sufficient when looking to adapt to complex changing conditions, as the set range of values might need to dynamically adapt to these changes. The additional mechanism of allostasis [3,4] allows for a more anticipatory, adaptive process that accounts for such complex (physiological, physical and social) changes, and permit a flexible, longer-term adaptation of the homeostatic mechanisms. Allostasis with respect to the social environment (the social milieu) is known as social allostasis [2,3].

Oxytocin (OT) is a hormone that has been consistently found to have effects on social behaviours and behavioural adaptation [5–8]. Its precise nature is still unclear, with divided opinions on its specific effects. One general agreement is that OT effects are context-dependent on internal and external contexts [5,9]. As our model concerns itself with dynamic adaptation with respect to social contexts, isolating and using such OT mechanisms provide a good framework on which to build this model. Our initial work [2] investigated the effects of two opposing hypotheses of OT mechanisms on social salience: that it should increase social salience [6], and that it should decrease social salience [10]. Initial results showed support for the former hypotheses in the modelled conditions, although it was noted that additional investigation was necessary. Inspired by work reported in [11], one way to extend our model of OT mechanisms for social adaptation is by further understanding the relationship between OT levels and satisfaction of social interaction.

Tactile contact between individuals is an example of social interaction, and is a powerful form of communication, particularly related to emotional states [12,13]. In social mammals, oxytocin has been reported to be endogenously released after tactile contact [14,15]. In the context of our current research—understanding and modelling the potential mechanisms that contribute towards socially adaptive behaviours—this finding provides an opportunity to explore the effects of endogenous OT mechanisms on tactile behaviours in our simulation. Taking inspiration from recent work that looked at the effects of OT on perceived pleasantness of touch [11], we investigate the effects of adapting the satisfaction of tactile contact behaviour between our simulated agents, across three world conditions (defined as "easy", "challenging" and "super challenging" in terms of availability of food in the environment) and two reported effects of OT on social salience (either increase it or decrease it), as posited by [6,10].

Our experiments have a twofold objective. Firstly, these experiments are part of our long-term objective to identify the potential mechanisms for dynamic, socially driven adaptation in embodied agents. Secondly, as mechanisms of OT are believed to be context-dependent [5,7,9,16], we aim to further isolate and investigate the nature of some of these specific effects under several different contexts in order to contribute to this divided field of research. We build on the work carried out by [14,15] and the findings of [11] to further investigate, in our social allostasis simulation model, the potential effects of endogenous hormone (OT) levels on this tactile behaviour response.

1.2. Related Work

1.2.1. Social Adaptation in Embodied Agents

To maximise the survival and wellbeing of embodied social agents, their decision-making and subsequent behaviours need to be adaptive and context-relevant, particularly in more realistic changing (internal and external) environments. For example, embodied physical robots that exist in the real world would need to adapt their behaviours to dynamic conditions if they are to be viable long-term solutions in tasks such as human assistants or companions. Adaptation can be seen as an individual's response to a change in these conditions—including physical, physiological and social changes. Affect is one of the mechanisms that permits such adaptation (see e.g., [1]). Much like humans and other social animals that have responded to the relationships and dynamics of their societies to adapt their behaviours accordingly [3], developing an adaptive model for social embodied agents must also consider the social dynamics of the world they exist in. Like in biological creatures, being able to understand and adapt to social dynamics (such as accounting for the amount of social support or friends, the response to the presence of a competitor, or noticing a stranger) would allow embodied artificial agents to maximise their chances of survival within their respective environments.

1.2.2. Social Adaptation with Allostasis

Homeostasis [17] is one of the mechanisms through which (biological) individuals adapt their behaviours to survive, notably by correcting internal deficits through internal processes or error-correcting behaviours. However, because homeostasis requires an agent to first experience a deficit, it becomes difficult to anticipate changes and adapt future behaviours by using only this method of behaviour regulation. For this reason, homeostasis allows for short-term regulation, but presents limitations regarding longer-term adaptation.

The work we report here is concerned with the more recent notion of allostasis, characterized by Sterling [4], with further work by Schulkin [3], as an anticipatory adaptive process that allows an agent to adjust its internal milieu in response, and in anticipation of, changes in the environment. Unlike homeostasis, in which agents keep their internal milieu within a fixed range of set values, mechanisms of allostasis allow this fixed range to adjust dynamically, as a result of changes in both the internal and external environment. Essentially, allostasis is the long-term adaptation of the short-term adaptive mechanism (homeostasis). In this way, allostasis permits more context-relevant responses to longer-term, and unforeseen, environmental changes.

The mechanisms of allostasis, when taking into account the social environment that an agent exists in, are called "social allostasis". Schulkin [3] argues that the evolution of social agents (including humans) through allostatic mechanisms was driven largely through social adaptation, and that all models that consider adaptability to an environment should also include social adaptation. With that in mind, social behaviours should be adapted through the allostasis mechanisms of individuals.

1.2.3. Social Behaviours and Oxytocin

Although Schulkin discusses a variety of hormones that influence social behaviours and social allostasis (including cortisol and vasopressin), it is oxytocin (OT) that has consistently been associated with social behaviours in the literature. In fact, its correlation with social behaviours has seen it historically dubbed as the "love hormone", and traditionally linked with prosocial behaviours such as trust [18], cooperation [8], generosity [19] and empathy [20]. However, OT has also been associated with defensiveness [21,22] and envy [23]. Additionally, exogenous OT has also been observed to have different effects on behaviours towards perceived "in-group" and "out-group" members [16,21,24–30].

These contradictory effects of OT have begun to shed light on the hypothesis that the mechanisms of OT are context-dependent [5,7,9], moving away from the traditional "one-size-fits-all" prosociality hypothesis of OT, towards an interactionist approach that accounts for contextual cues and individual differences [16]. Ultimately, the specific mechanisms of OT are incredibly complex and still not yet fully understood, with researchers still stopping short of attributing specific causality of behaviours to this hormone. This is largely due to the difficulty in being able to isolate its effects in humans and non-human animals, particularly because of the upstream and downstream interplay between OT and other hormones [3]. Although its precise effects may not be understood, the consensus that OT effects are physically and socially context-specific, provides an excellent framework on which to build a socially adaptable model for our embodied agents.

1.2.4. Our Previous Work: Oxytocin and the Social Salience Hypotheses

As a first step towards a model of social allostasis, our initial work investigated the proposed opposing hypotheses of OT on social salience: the "prosocial approach" postulating that OT should increase social salience [6], and the "interactionist approach" postulating that it should decrease social salience [10]. We tested both hypotheses using a simulated environment that posed different physical challenges related to food availability, modelling this single OT mechanism as an additional "hormone" within the homeostatic model in our agents [2]. Our initial results showed support for the hypothesis that OT mechanisms that increase social salience promote the viability of agents, particularly in conditions of food sparsity. Following the tradition of Ashby [31], we define viability as the maintenance of internal, survival-related physiological variables within a range of values in which survival is guaranteed

In the present paper, we build on this initial model and introduce a further social allostasis mechanism to adapt the internal milieu of the agent as a function of social contextual information: the dynamical modulation of the affective/physiological effects (degree of satisfaction produced) of a social behavior (social touch) as a function of the internal levels of simulated endogenous OT, released as a function of social interaction. Several conditions that vary the amount of satisfaction of social touch and test their adaptive value in worlds that pose different degrees of survival-related challenges (availability of food), are tested across the conditions investigated in our initial study [2]—one group of agents in which OT levels increase the perception of the social salience of other agents, and one group in which OT levels decrease the perception of social salience.

1.2.5. Affective Touch

Tactile contact is one of many behaviours through which biological agents interact socially. Social touch can be (and often is) emotionally coloured, in which case the term "affective touch" is commonly used. Affective touch can be defined as physical tactile contact which communicates, expresses, and/or evokes emotion [32–34]. In humans, touch can amplify the intensity of emotional displays from facial and auditory (e.g., vocal) cues [12] and can also communicate the positive or negative hedonic values of emotions [13]. In mammals, OT has been found to be endogenously released after social touch [14,15] (for a more in-depth review of social touch, see [35]). Work surrounding affective touch linked to emotional expression has been sparse in comparison to facial and vocal displays of affect [36], and is not understood as well as the other expressive modalities. As a result, work on affective touch in embodied agents and robots is affected by the limitations of this research, although there are notable examples such as The Huggable [37], Probo [38] and The Haptic Creature [34], which have used affective touch mechanisms in an attempt to communicate and understand emotional states in human-robot interaction.

Given the importance of touch in affective communication, in the work presented here we take inspiration from some of its underlying mechanisms. More specifically, we take into account the fact that social touch can be "satisfying" (although it can also be unpleasant) to different degrees [33,39], and we model the different amounts of perceived "satisfaction" provided by social touch through hormonal modulation of tactile contact satisfaction in our agents. Our model focuses initially on the "affective" effects (satisfaction of need for social interaction) of social touch on the emitter rather than on the recipient, although the latter is the aspect more widely explored in the literature. In our model, social touch provides physiological satisfaction of the internal variable $SocialNeed$. We define physiological satisfaction as the rate (a numerical value) by which an agent corrects the related internal homeostatic variable—in this case its $SocialNeed$—as explained in Section 2.3.1.

It could be argued that our model is in contradiction with findings such as [11] that oxytocin treatment does not increase the perceived pleasantness of touch. However, there are significant differences with respect to our model, as we are taking into account the satisfaction, rather than the pleasantness, of touch, and their study, involving real-life participants, included the evaluation of facial images, which may prime participants towards interpretation of emotional states and is therefore complementary to the effect of touch that they were studying. Additionally, their use of exogenous OT treatment is different from the internal mechanisms that have modelled in our agents. More recent research has shown differing effects between endogenous and exogenous OT treatment [40]. Isolating the effects of affective touch becomes difficult when facial and vocal cues are also involved, and so an opportunity is presented to use an artificial life approach with no additional affective cues to investigate these effects further.

2. Materials and Methods

2.1. Aim of Study

In this study, we aim to build on our previous work towards a model of social allostasis by investigating the effects of dynamically adapting the extent to which social agents are satisfied by one social behaviour—social touch. We study this through a simulated model that adapts the intensity of physiological satisfaction of a social behaviour, tactile contact, as a function of dynamic internal OT levels, and investigate its effects on the viability (see our previous definition) of the agent in a variety of food-related conditions that pose survival challenges. Using this approach, we look to further understand and identify potential adaptive mechanisms towards a model of social allostasis for embodied agents.

Currently, work on social allostasis in embodied agents is minimal, and work in modelling OT as a mechanism for social adaptation is, to our knowledge, non-existent at the time of writing. Given the correlation between OT and social behaviours in biological individuals and societies, it is interesting to note that these mechanisms have not yet been investigated further in the field of embodied or affective agents. Therefore, work in this area currently appears to be largely unexplored, although [41] modelled OT release in a robot in order to assess the impact on trust in human-robot interactions.

As OT is correlated with social support (such as the presence of a friendly/non-competitive conspecific) and attachments (such as parent-child or partner formation [42]), actual levels of OT can provide an embodied agent with contextual information about its society, and the level of OT can be used to adapt its behaviour. In this way, an agent's physiological response to social behaviours can become more context-relevant, and therefore adaptive to changing social conditions.

2.2. Hypothesis

We hypothesise that dynamic adaptation of the satisfaction of a social behaviour (social touch) through mechanisms akin to (some of the effects of) modulation by OT, will positively affect the viability of agents in our simulated environment.

2.3. Agent Model

2.3.1. Action Selection Architecture

In line with the long-standing model developed by Cañamero [43] and further explored in our group in different ways (e.g., [2,44,45]), our Action Selection Architecture (ASA) provides each agent with a real-time decision-making process grounded in the physiology of the agents. Agents have a number of (in our case, two) homeostatically controlled internal variables that need to be maintained within a range of values to ensure the agent's wellbeing and/or survival. The difference between the actual value and the "ideal" value of each variable produces an error signal that triggers motivational processes or "drives" that seek to correct those errors, e.g., by executing specific behaviours. The motivations to correct the different errors will have different intensities (reflecting their degree of urgency) calculated as a function of the magnitude of the error of the corresponding internal variable and the perception of external stimuli that are relevant to correct that error and therefore satisfy that need. In our architecture, to choose which need the agent should attend to at each point in time, we use a "winner-take-all" (WTA) behavior selection policy that will try to satisfy the motivation with the highest intensity.

Agents have two simulated variables: $Energy$ and $SocialNeed$, which must be homeostatically maintained to ensure the agent's wellbeing and survival. Both take values within the range [0, 1], where 0 is the lower limit and 1 the upper limit. The ideal value of both variables is 1. To maintain these variables, agents are motivated to execute one of two behaviours at any point:

- *Eat*, to satisfy their *Energy* deficiency,
- *Touch*, to satisfy their *SocialNeed*.

The errors of each internal variable feed into one of two motivations (*Hungry* and *Lonely*, respectively), which also compute the salience of external cues (*Food* and *Agent*, respectively), to calculate their intensity. After taking into account the intensity of the respective motivations, the ASA selects the motivation with highest intensity to be satisfied, and tries to execute the behaviour (either *Eat* or *Touch*) that could best satisfy it.

Figure 1 shows a visual representation of each of the steps of the ASA, as well as the effects on agent behaviour and the components of each experimental condition. The mathematical notation for each step of the ASA can be found in Appendix A.

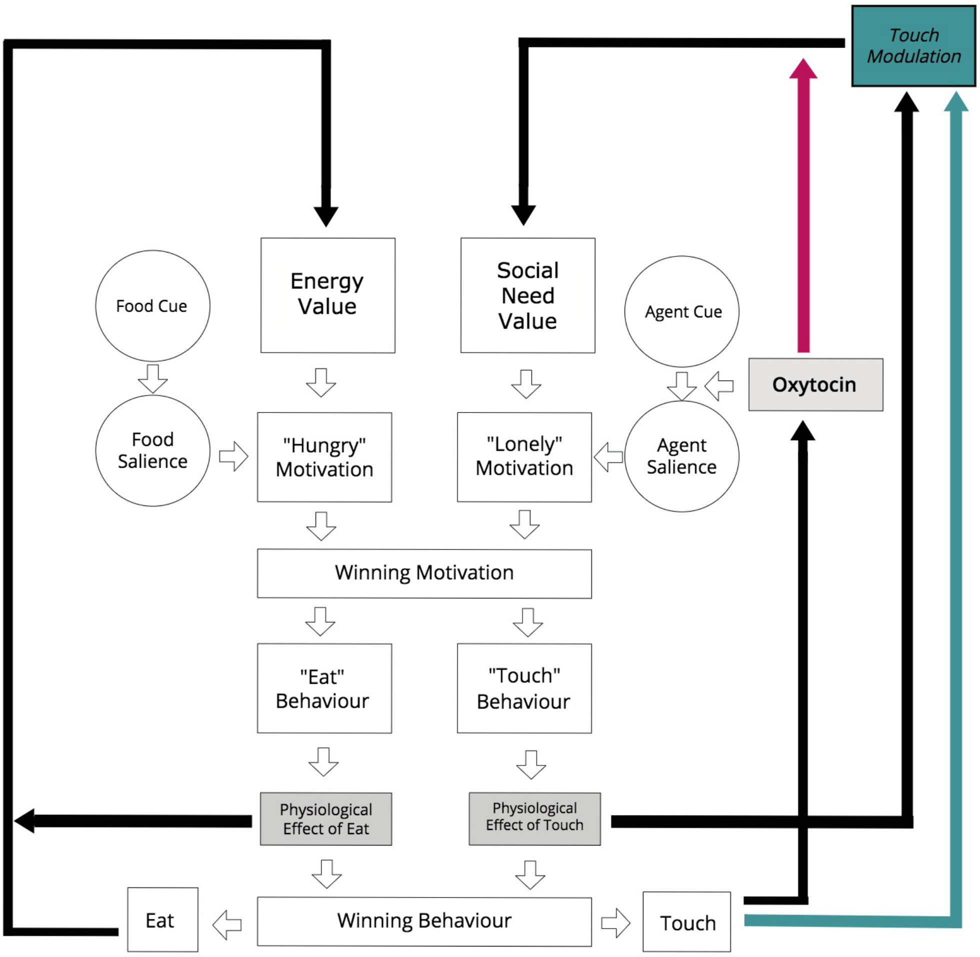

Figure 1. Visualisation of the internal ASA that each agent is equipped with. Calculations for both behavioural intensities are executed concurrently at each time step. *Oxytocin* exists outside of the main loop, modulating social salience and the satisfaction of the *Social Need* variable.

2.3.2. Physiological Effects of Behaviour

Table 1 describes the effects that the successful execution of behaviours has on each internal variable of the agent. These effects are used during the calculation of behaviour intensity in the penultimate step of the action selection architecture described in the previous section. The decision to create asymmetrical physiological effects for both behaviours (*Eat* and *Touch*), along with the time variance of behaviour execution, was inspired partly by biological models, i.e., it takes time to eat, but tactile contact can be achieved immediately. The physiological effect of *Touch* on the variable *Social Need* was initially set to 0.05 (5% of its maximum value of 1) in our initial work [2]; values beyond 10% of its maximum value were not tested due to computational limitations. In the present experiment, however, all values between 5% and 100% are used (in increments of 5%), as we will see in Section 2.4, in order to create a more thorough control condition. In contrast, *Energy* is satisfied at a rate of 0.01 (1% of the maximum value of 1) per time step until the motivation is satisfied. The behaviour *Eat* does not affect internal OT levels, but social contact through *Touch* releases OT in the agents—again, inspired by biological literature—returning it to its maximum value of 1. All physiological variables undergo a decay at each time step, shown in Table 2.

Table 1. Effects on internal variables for both consummatory behaviours that an agent can execute. *tM* = *Touch Modulation* (the amount that the *Touch* behaviour satisfies agent physiology) within each condition and *OT* = the value of endogenous *Oxytocin* of the agent.

Behaviour b_i	Stimuli S_i	Energy	Social	Oxytocin OT	Time To Execute
Eat	Food	+0.01	0	0	Variable
Touch	Agent	0	$0.01 \times tM \times OT$	+1	Immediate

Table 2. Rate of change, per time step, of each internal variable for each agent. Please note that oxytocin (*OT*) is included in this table, but is defined as a modulating hormone, not as an internal variable that needs to be homeostatically maintained.

Internal Variable	Decay Rate	Motivation m_i	Behaviour b_i	Stimuli S_i	Physiological Effect f_i
Energy	-0.0003	Hungry	Eat	Food	+ Energy
Social	-0.0003	Lonely	Touch	Agent	+ Social, + Oxytocin
Oxytocin$*$	-0.0005	-	-	-	-

2.3.3. Roles of Oxytocin

In the context of our model, we use the term "oxytocin" to refer to a simulated hormone that plays some of the roles of biological OT. Namely, it acts as a modulating parameter with two roles or effects:

- On the one hand, it is applied to the function that calculates the social salience in our action selection architecture, and
- On the other hand, it modulates the rate of physiological satisfaction of social behaviours (social touch).

Only these two specific mechanism are included in our model of oxytocin, which does not intend to capture the vast and not always known effects of biological OT.

Unlike the studies on biological OT discussed previously, which have investigated OT through exogenous treatment, OT is endogenously released in our model, and used only to modulate the salience of social cues and of physiological satisfaction of *Touch*. Oxytocin is endogenously released by the agents at a fixed rate of $(+1)$, empirically determined for this study, when they successfully execute their social behaviour *Touch* with another agent. See Table 1 for more details.

Effect 1: Oxytocin and the Modulation of Social Salience

Noting the previously mentioned conflicting hypotheses regarding the effects of OT on social salience [6,10], and using the same approach as our previous work [2], OT affects the salience of social cues in our ASA by modulating them across one of three different options, which will constitute parameters in our experimental conditions:

- *None*, where oxytocin does not affect social salience.
- *Increase Social Salience*: Salience of social cues is increased, using:

$$S_{robot} = C_{robot} \times (1 + OT) \tag{1}$$

- *Decrease Social Salience*: Salience of social cues is decreased, using:

$$S_{robot} = C_{robot} \times (1 - OT) \tag{2}$$

Looking back at Figure 1, we can see that OT only modulates social cues (i.e., the salience of other agents), using the calculation shown in Appendix A. Direct modulation of the salience of food resources is not included in this model. This is also in line with the findings reported in [9] that exogenous treatment of oxytocin affects attention to social cues, but not to nonsocial cues.

Effect 2: Oxytocin and the Modulation of Social Satisfaction

In our model, we modulate the physiological satisfaction that tactile contact has on our social agents, proportional to the level of endogenous oxytocin of the agent. As already mentioned, unlike the studies related to affective touch reported in Section 1.2.5, this modulation does not directly produce external changes in behaviour or communication of internal states of other agents, but affects the agent's own internal physiology (satisfaction of *Social Need*).

The value of an agent's current *OT* level directly modulate the effect that *Touch* had on satisfying an agent's *Social Need* variable. Much like with the two social salience groups, we have modelled two opposing effects of modulation:

- *Direct Modulation*: where the intensity of physiological effect is directly correlated with the level of OT. This is calculated as:

$$SocialSatisfaction = touchingIntensity \times OT \tag{3}$$

- *Inverse Modulation*: where the intensity of physiological effect is inversely correlated with the level of OT This is calculated as:

$$SocialSatisfaction = touchingIntensity \times (1 - OT) \tag{4}$$

The parameter $touchingIntensity$ takes values within the range 5%–100% of its maximum value (a value of 1) in 5% increments in all our experimental conditions, as we describe in the next section. We also included a third (control) condition in which OT has no effect on physiological satisfaction.

2.4. Experimental Setup and Conditions

To test our hypothesis, we carried out two experiments to investigate the viability [31] of simulated social agents ($n = 6$) that adapt the degree of physiological satisfaction of their need for social interaction provided by tactile contact with another agent as a function of their internal OT levels. In other words, these experiments investigate the effects of adding dynamic modulation of physiological satisfaction after social contact, by modulating the intensity of physiological satisfaction that an agent experiences as a function of its current internal OT levels. Physiological satisfaction is defined as the value/rate by which an agent corrects the related internal homeostatic variable. In the first experiment, the degree of satisfaction is modulated by a range of fixed values, while in the second it is modulated dynamically as a function of endogenous oxytocin released following social interaction (tactile contact).

Experiments were performed in a simulated environment using the NetLogo platform [46], version 5.3.1. The use of a simulated environment reduces (although does not eliminate) potential extraneous variables, allows for more granular control of agents, their parameters and environments, and permits parallel experimental runs in order to accumulate a larger amount of data. As discussed previously, the specific effects of oxytocin remain difficult to study in complex biological agents, as outlined by the inconsistent and often-contradictory findings in the literature. Artificial life models permit to isolate specific mechanisms and to carry out systematic studies in a highly controlled environment.

The simulated world was set up as a bounded two-dimensional environment of size 99 × 99 patches. Blue patches are used to represent the outer limits of the world (the walls), and agents are unable to pass through walls. A society of six agents was created in this simulated world, visually represented as small bugs of 3 patches in size. All agents were initially homogenous—that is, they were all initialised with the same action selection architecture, behaviours and values of internal variables. Precise descriptions of the agent model are given in Section 2.3. Movement through the world is entirely random (via the *Wandering* behavior), unless agents are motivated to head in the direction of salient stimuli. Food resources are represented by yellow circles, the size and positioning of which are varied across the experimental conditions.

Our agents were tested under three different world conditions related to the availability of food resources, denoted as Easy (E), Challenging (C) and Super Challenging (S):

- *Easy* conditions are defined as a world with an abundance of food resources (18) distributed in small clusters throughout the world.
- *Challenging* conditions are defined as a world with scarce food resources (6) in two clusters, placed towards the corners of the world.
- *Super Challenging* conditions are exactly the same as Challenging conditions, but the food resources have half of the nutritional value.

Figure 2 shows screenshots of all three world conditions.

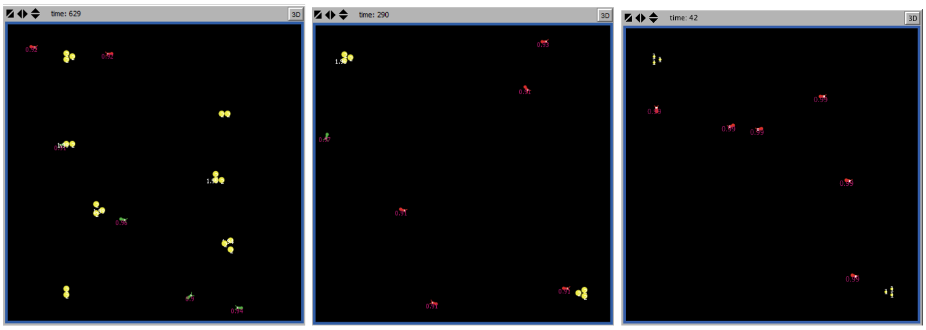

Figure 2. Screenshots for all three world conditions. Easy conditions (**left**) have an abundance of food resources, Challenging conditions (**middle**) have sparse resources on the outside of the world, and Super Challenging (**right**) conditions are the same as Challenging, but with less nutritional value.

The size of food items is dynamic, and determined by the nutritional value of the resource. For instance, a food resource with a nutritional value of 2 will have a size of 2 patches. When the nutritional availability of a food resource is reduced when an agent consumes it, the size of the food resource is also reduced by the same amount. Food resources regenerate over time at a rate of 1/1000th of their maximum nutrition value. As food resources regenerate their nutrition value, the size of that resource then increases as previously described.

Table 3 summarizes the setup of resources in each world.

Table 3. Availability of food resources in each of the three world conditions. For a visual representation of these worlds, see Figure 2.

World Name	# of Food Resources (Items)	# of Clusters	Nutritional Value/Item	Max. Nutrition In World
Easy	20	10	2	40
Challenging	6	2	2	12
Super Challenging	6	2	1	6

As in our previous study [2] and defined in Section 2.3.3, agents were allocated to one of three groups regarding the modulation of social salience by OT: increasing salience of social cues, decreasing salience of social cues, or no effect. Table 4 summarises these three groups and the notation used.

Table 4. Summary of the three groups to which agents were allocated regarding the modulation of social salience by OT, and of the notation used. E refers to Easy world conditions, C refers to Challenging world conditions, and S refers to Super Challenging world conditions; 0, + and − are used to denote conditions with no OT, Increased Social Salience through OT modulation, and Decreased Social Salience through OT modulation, respectively.

World Name	No OT Modulation	OT Increases Social Salience	OT Decreases Social Salience
Easy	E0	E+	E−
Challenging	C0	C+	C−
Super Challenging	S0	S+	S−

Finally, as explained in Section 2.3.3, the modulation by OT of the degree of satisfaction of social touch can be either direct (OT positively modulates the physiological satisfaction provided by *Touch*) or inverse (OT negatively modulates the physiological satisfaction provided by *Touch*).

In our initial study [2], several values of the physiological effect of social contact (called the *touchingIntensity*) were tested −2%, 5% and 10%. These percentage values describe the physiological effects as a percentage of the maximum value of the internal variable (set to 1). As values beyond 10% were not initially tested due to computational limitations, the present experiments consider all values of *touchingIntensity* from 5% to 100% in 5% increments, observing the effects of different levels of physiological satisfaction across all social salience groups (Experiment 1), and using them as the control variant once the mechanisms of OT are used to dynamically adapt these values (Experiment 2).

Table 5 summarises all our experimental conditions and the notation used.

Table 5. Summary of our experimental conditions for experiments where *touchingIntensity* is modulated by oxytocin, and of the notation used. D refers to conditions where *touchingIntensity* is directly modulated, I refers to conditions where *touchingIntensity* is inversely modulated, and 0 refers to no modulation. World conditions (E, C, S) and social salience conditions (0, +, −) are denoted as previously.

Social Salience Direction/*touchingIntensity* Direction	Easy	Challenging	Super Challenging
None/Direct	E0D	C0D	S0D
None/Indirect	E0I	C0I	S0I
Increase/Direct	E+D	C+D	S+D
Increase/Inverse	E+I	C+I	S+I
Decrease/Direct	E−D	C−D	S−D
Decrease/Inverse	E−I	C−I	S−I

Each experimental condition was run for 20 simulation runs, with a cut-off at 30,000 time steps. The decision to have a pre-determined run time for each experimental run was made based on previous experience and several trial runs of the model. A time step is defined as a single iteration of the code, which translates as a single frame update within the GUI. The different combination of parameters across all experimental conditions resulted in a total of 7200 experimental runs, which equated to roughly 122–125 h of real time.

2.5. Metrics Definition

In line with the approach adopted in our group that postulates that viability should be investigated as a multi-faceted notion (see e.g., [44,45,47,48]), each simulation run considered two main metrics: survival (length of life) and average comfort (that the above-mentioned previous work in our group defined as one of the various possible ways of measuring the maintenance of viability), defined as follows (see Appendix B for the corresponding mathematical definitions):

(i) *Life Length*: The simulation time steps that an agent survived, i.e., remained viable by keeping its $Energy > 0$, given as a percentage of the maximum simulation length (30,000 time steps).
(ii) *Average Comfort*: The average level of satisfaction of internal variables throughout an agent's lifetime.

Each result was reported using the mean figure for all agents across all 20 experimental runs. For instance, life length was reported as the mean life length of all the agents across all simulation runs.

2.6. Statistical Significance Testing

Statistical significance testing was performed on the two key viability indicators—length of life and overall comfort—across all experimental conditions using one-way ANOVA testing, reporting significance at $p = 0.05$.

3. Experiments and Results

3.1. Experiment 1: Varying the Intensity of the Effect of Touch

Prior to adding the OT modulatory mechanism to dynamically modulate the degree of physiological satisfaction of the social behavior *Touch*, in a first experiment we investigated the effects of increasing and decreasing social salience using different static values, in a more thorough way than we had done in previous work [2], taken from the range 5%–100% of the maximum value that the parameter $touchingIntensity$ can take (as a reminder, our previous experiments in [2] reported results only using a value of 5%).

The results of this experiment are shown in Figure 3 and Table 6. In the sections below we summarise the results for the different conditions.

3.1.1. Easy World Conditions

Results for agent groups in the Easy (E) world were as expected. In terms of life length, agents survived for the entirety of the simulation length (100% survival rate) across all the different social salience effects (Figure 3a). This is also in line with our previous experimental results in [2]. Comfort levels remained steady across all the $touchingIntensity$ values tested (Figure 3b), with only conditions of E$-$ experiencing the lowest initial comfort level of 0.81. Overall, agents in easy conditions lived a very comfortable life for all the simulation runs, regardless of the social salience effects.

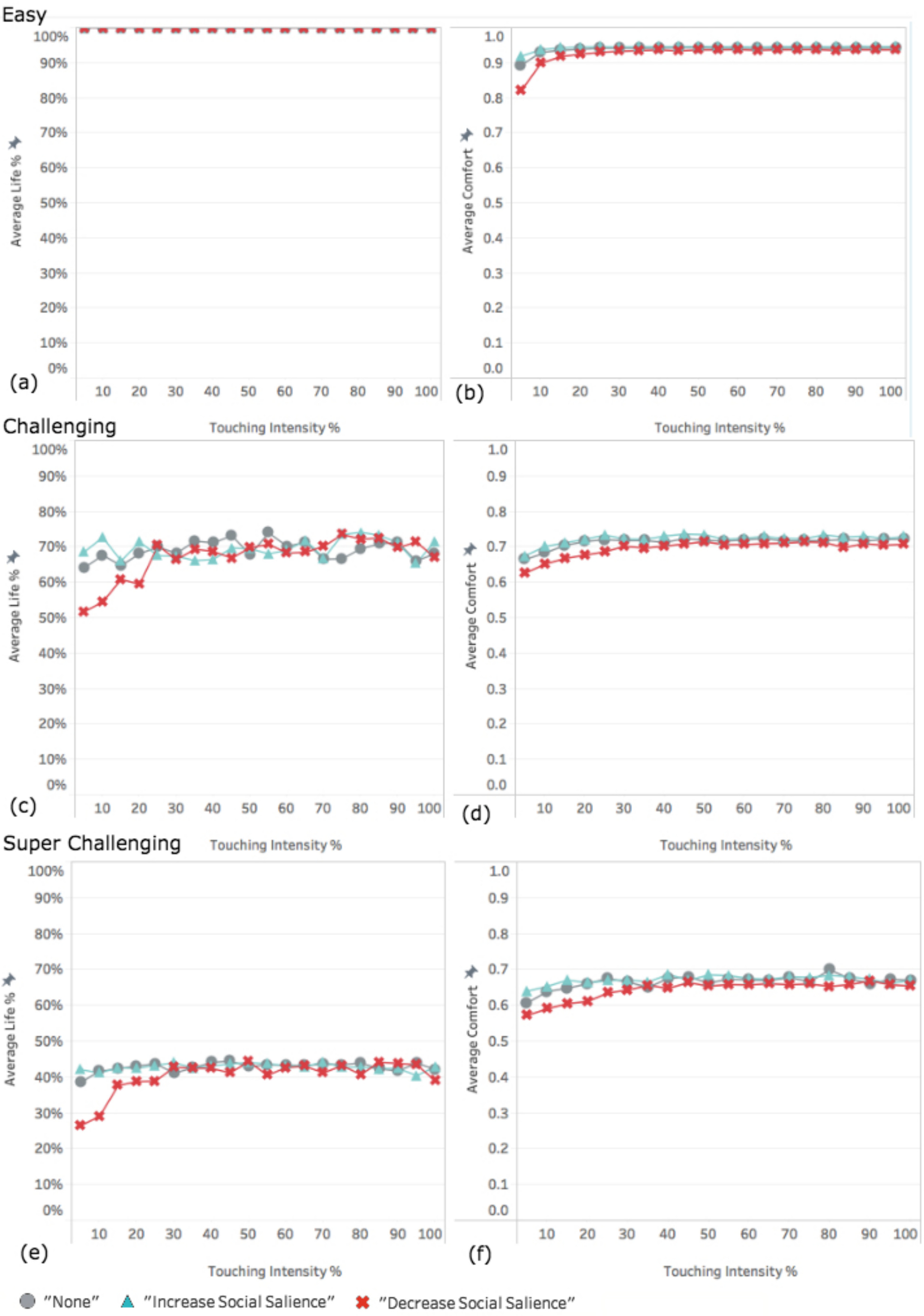

Figure 3. Results of experiment 1, showing the Average Life Length and Comfort Levels across all initial values of *touchingIntensity*. This experiment did not involve dynamic modulation by *OT*, only modulation of Social Salience using fixed, static values. Groups with no social salience (E0, C0, S0) are represented by a grey line, groups with increased social salience (E+, C+, S+) are represented by a blue line, and groups with decreased social salience (E−, C−, S−) are represented by a red line. (**a**) Average life length across Easy (E) conditions. (**b**) Average comfort levels across Easy (E) conditions. (**c**) Average life length across Challenging (C) conditions. (**d**) Average comfort levels across Challenging (C) conditions. (**e**) Average life length across Super Challenging (S) conditions. (**f**) Average comfort levels across Super Challenging (S) conditions.

Table 6. Summary of results for Experiment 1, including p-values for all conditions. The p-values are for all results in bucketed $touchingIntensity$ values; * indicates statistical significance, 0 indicates control group with no OT effects, + are Increased Social Salience groups, and − are Decreased Social Salience groups.

Experiment Condition	Touch Intensity %	World Condition	Social Salience Direction	Viability Indicator	Result	p-Value vs. Control	p-Value vs. + Condition	p-Value vs. − Condition
E0 (Control)	All	Easy	None	Life Length	100%	-	n/a	n/a
E+	All	Easy	Increase	Life Length	100%	n/a	-	n/a
E−	All	Easy	Decrease	Life Length	100%	n/a	n/a	-
C0 (Control)	⩽20%	Challenging	None	Life Length	66%	-	0.006528 *	0.00001 *
C+	⩽20%	Challenging	Increase	Life Length	70%	0.006528 *	-	0.00001 *
C−	⩽20%	Challenging	Decrease	Life Length	57%	0.00001 *	0.00001 *	-
C0 (Control)	>20%	Challenging	None	Life Length	69%	-	0.692435	0.740763
C+	>20%	Challenging	Increase	Life Length	67%	0.692435	-	0.73957
C−	>20%	Challenging	Decrease	Life Length	70%	0.740763	0.73957	-
SC0 (Control)	⩽20%	Super Challenging	None	Life Length	42%	-	0.098236	0.00001 *
SC+	⩽20%	Super Challenging	Increase	Life Length	42%	0.098236	-	0.00001 *
SC−	⩽20%	Super Challenging	Decrease	Life Length	33%	0.00001 *	0.00001 *	-
SC0 (Control)	>20%	Super Challenging	None	Life Length	43%	-	0.801502	0.012161 *
SC+	>20%	Super Challenging	Increase	Life Length	43%	0.801502	-	0.021922 *
SC−	>20%	Super Challenging	Decrease	Life Length	42%	0.012161 *	0.021922 *	-
E0 (Control)	All	Easy	None	Comfort	0.93	-	0.00001 *	0.00001 *
E+	All	Easy	Increase	Comfort	0.94	0.00001 *	-	0.00001 *
E−	All	Easy	Decrease	Comfort	0.8	0.00001 *	0.00001 *	-
C0 (Control)	⩽20%	Challenging	None	Comfort	0.67	-	0.000977 *	0.00001 *
C+	⩽20%	Challenging	Increase	Comfort	0.7	0.000977 *	-	0.00001 *
C−	⩽20%	Challenging	Decrease	Comfort	0.65	0.00001 *	0.00001 *	-
C0 (Control)	>20%	Challenging	None	Comfort	0.72	-	0.00001 *	0.00001 *
C+	>20%	Challenging	Increase	Comfort	0.73	0.00001 *	-	0.00001 *
C−	>20%	Challenging	Decrease	Comfort	0.71	0.00001 *	0.00001 *	-
SC0 (Control)	⩽20%	Super Challenging	None	Comfort	0.64	-	0.007487 *	0.00001 *
SC+	⩽20%	Super Challenging	Increase	Comfort	0.66	0.007487 *	-	.00001.
SC−	⩽20%	Super Challenging	Decrease	Comfort	0.59	0.00001 *	0.00001 *	-
SC0 (Control)	>20%	Super Challenging	None	Comfort	0.67	-	0.118938	0.00001 *
SC+	>20%	Super Challenging	Increase	Comfort	0.67	0.118938	-	0.00001 *
SC−	>20%	Super Challenging	Decrease	Comfort	0.65	0.00001 *	0.00001 *	-

3.1.2. Challenging World Conditions

In line with the findings from our initial experiments, it can be seen that, in challenging conditions (C), the group of agents with increased social salience (C+) had longer lives (70% vs. 66%, $p = 0.006528$) and average comfort (0.69 vs. 0.67, $p = 0.000977$) when compared to the control group in the same conditions (C0) (Figure 3c). The group with decreased social salience (C−) initially had a shorter overall life length (57% vs. 66%, $p < 0.00001$) and a more uncomfortable life overall (0.65 vs. 0.67, $p < 0.00001$) vs. control. These are the aggregated results across experiments where $touchingIntensity < 20\%$.

However, as the value of $touchingIntensity$ increased $> 20\%$, so too did the viability of agents in C− conditions, from an average of 57% to 70% ($p < 0.00001$) (Figure 3c). At the same time, the life length of agents in C+ decreased from an aggregated 70% to 67% ($p < 0.00001$). Notably, it is conditions of C− that experienced a more significant increase in life length as the physiological satisfaction of *Touch* increased (from a low of 52% to a high of 73%) than both C0 and C+, the latter of which saw life length peak with lower values of $touchingIntensity$. In levels of higher intensities (where $touchingIntensity \geqslant 75\%$), average life lengths were comparable between C+ and C−, with both conditions outperforming the control group in terms of agent life length.

Average comfort levels improved across all challenging conditions, although it was the agents within the C− group that experienced the highest rate of improvement as intensity increased (Figure 3d). When $touchingIntensity < 30\%$, agents in the C− group were slightly less comfortable in their comparatively shorter lives, with an average comfort level of 0.66, vs. 0.69 in the control group ($p = 0.000127$) and 0.7 in C+ ($p < 0.00001$). Please note that, despite the small difference between C0 and C+ comfort levels (0.1), change was statistically significant ($p = 0.003945$) between those two groups. In conditions where $touchingIntensity$ was $\geqslant$30%, there was no statistically significant difference in comfort levels among all three conditions of OT. Despite a lack of significance, a clear trend emerged, with agents in C+ being more comfortable than in the other two conditions as $touchingIntensity$ increased. Those in C− appeared to be the least uncomfortable overall, regardless of the values of $touchingIntensity$.

3.1.3. Super Challenging World Conditions

Unlike in the Challenging world, increased social salience does not appear to be advantageous for life length in the Super Challenging (S) world, even at lower levels of $touchingIntensity$ (Figure 3e). Increasing this $touchingIntensity$ did not benefit agent life length in either the S+ or S0 groups. At lower levels of $touchingIntensity$, life length for S− was hindered compared to the other two groups. Following a similar trend to the Challenging groups, agents in S− saw comparative life lengths to both S0 and S+ as $touchingIntensity$ increased beyond 30%. Comfort levels in the Super Challenging world conditions still appear to be slightly in favour of S0 and S+ across all values of $touchingIntensity$, despite a comparable life length across these conditions.

3.2. Experiment 2: Adapting Touch Intensity with Oxytocin

In the second experiment, we added a modulatory mechanism to dynamically modulate the degree of physiological satisfaction of the social behavior *Touch* as a function of the level of endogenous OT of the agents. Direct and inverse modulation conditions were tested across the conditions used in Experiment 1.

The results of this experiment are shown in Figures 4 and 5 and Table 7. In the sections below we summarise the results for the different conditions.

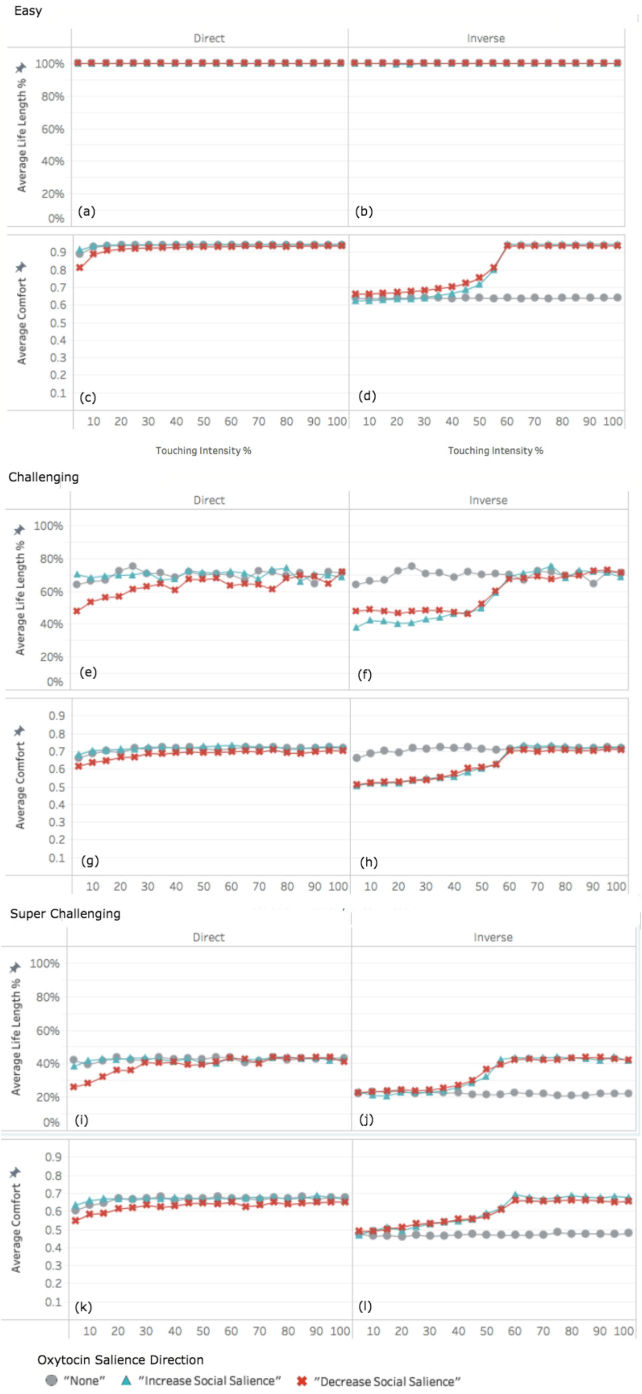

Figure 4. Summary of results for Experiment 2. Average Life Length and Comfort Levels across all *touchingIntensity* values with modulation of internal *Oxytocin* levels. Direct modulation of *touchingIntensity* are all graphs to the left, Inverse modulation of *touchingIntensity* are all graphs to the right. (**a**) Average life length across Easy (E) worlds + Direct (D) modulation. (**b**) Average life length across Easy (E) worlds + Inverse (I) modulation. (**c**) Average comfort levels across Easy (E) worlds + Direct (D) modulation. (**d**) Average comfort levels across Easy (E) worlds + Inverse (I) modulation. (**e**–**h**) As (**a**–**d**), for Challenging world conditions. (**i**–**l**) As (**a**–**d**), for Super Challenging world conditions.

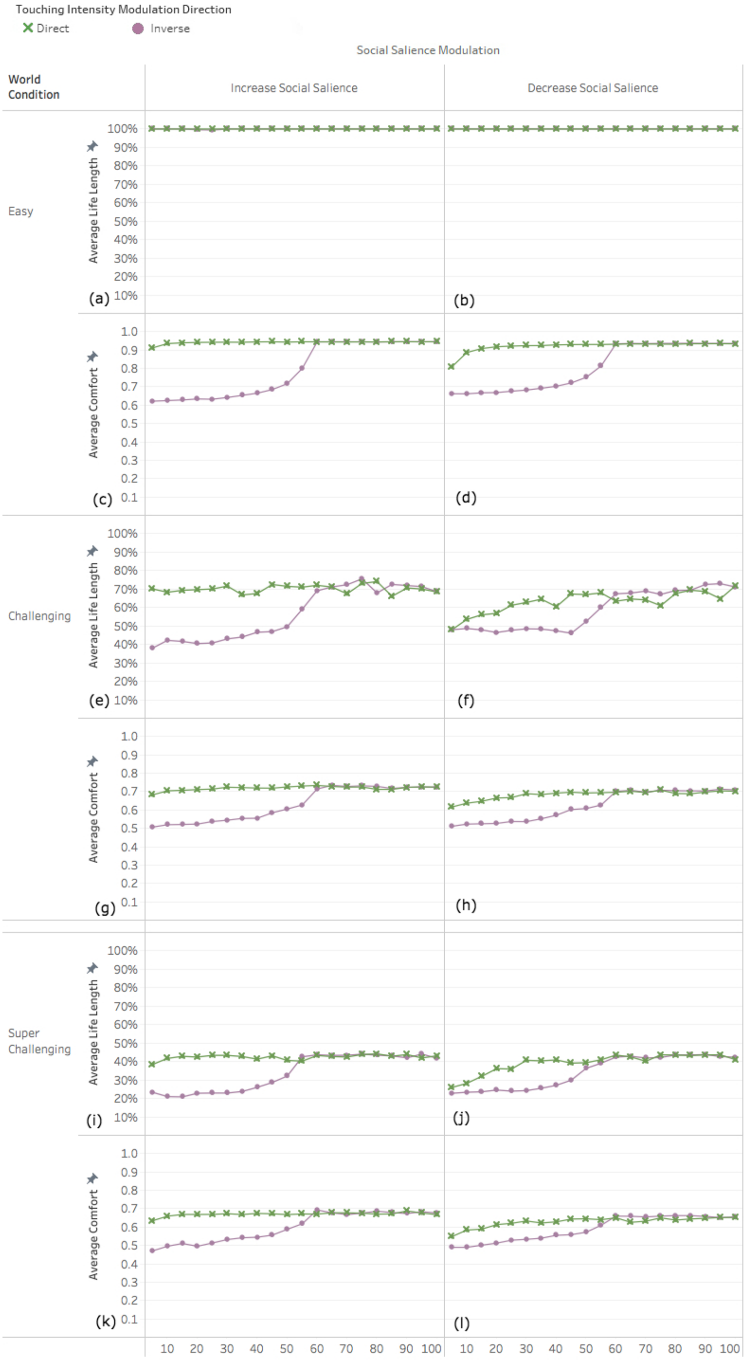

Figure 5. Summary of results for Experiment 2, showing a comparison of Average Life Length and Comfort Levels across all *touchingIntensity* values, split by social salience and *touchingIntensity* modulation direction. Increased Social Salience groups are all graphs to the left, Decreased Social Salience groups are all graphs to the right. (**a**) Average life length across Easy (E) worlds and Increased Social Salience (+). (**b**) Average life length across Easy (E) worlds and Decreased Social Salience (−). (**c**) Average comfort levels across Easy (E) worlds and Increased Social Salience (+). (**d**) Average comfort levels across Easy (E) worlds and Decreased Social Salience (−). (**e**–**h**) As (**a**–**d**), for Challenging world conditions. (**i**–**l**) As (**a**–**d**), for Super Challenging world conditions.

Table 7. Summary of results for Experiment 2, including p-values for all conditions. The p-values reported are for aggregated results across all $touchingIntensity$ values. * indicates statistical significance. 0 denotes Control group with no oxytocin effects, $+$ are Increased Social Salience groups, and $-$ are Decreased Social Salience groups. D denotes Direct modulation of $touchingIntensity$, and I indicates Inverse modulation of $touchingIntensity$.

Experiment Condition	Oxytocin Touch Modulation Direction	World Condition	Social Salience Direction	Viability Indicator	Result	p-Value vs. Control	p-Value vs. + Condition	p-Value vs. − Condition
E0D (Control)	Direct	Easy	None	Life Length	100%	-	n/a	n/a
E+D	Direct	Easy	Increase	Life Length	100%	n/a	-	n/a
E−D	Direct	Easy	Decrease	Life Length	100%	n/a	n/a	-
C0D (Control)	Direct	Challenging	None	Life Length	70%	-	0.648132	0.00001 *
C+D	Direct	Challenging	Increase	Life Length	70%	0.648132	-	0.00001 *
C−D	Direct	Challenging	Decrease	Life Length	63%	0.00001 *	0.00001 *	-
S0D (Control)	Direct	Super Challenging	None	Life Length	43%	-	0.701904	0.00001 *
S+D	Direct	Super Challenging	Increase	Life Length	42%	0.701904	-	0.00001 *
S−D	Direct	Super Challenging	Decrease	Life Length	39%	0.00001 *	0.00001 *	-
E0D (Control)	Direct	Easy	None	Comfort	0.937	-	0.00001 *	0.00001 *
E+D	Direct	Easy	Increase	Comfort	0.941	0.00001 *	-	0.00001 *
E−D	Direct	Easy	Decrease	Comfort	0.92	0.00001 *	0.00001 *	-
C0D (Control)	Direct	Challenging	None	Comfort	0.71	-	0.001468 *	0.00001 *
C+D	Direct	Challenging	Increase	Comfort	0.72	0.001468 *	-	0.00001 *
C−D	Direct	Challenging	Decrease	Comfort	0.68	0.00001 *	0.00001 *	-
S0D (Control)	Direct	Super Challenging	None	Comfort	0.665	-	0.028883 *	0.00001 *
S+D	Direct	Super Challenging	Increase	Comfort	0.671	0.028883 *	-	0.00001 *
S−D	Direct	Super Challenging	Decrease	Comfort	0.628	0.00001 *	0.00001 *	-
E0I (Control)	Inverse	Easy	None	Life Length	100%	-	n/a	n/a
E+I	Inverse	Easy	Increase	Life Length	100%	n/a	-	n/a
E−I	Inverse	Easy	Decrease	Life Length	100%	n/a	n/a	-
C0I (Control)	Inverse	Challenging	None	Life Length	70%	-	0.00001 *	0.00001 *
C+I	Inverse	Challenging	Increase	Life Length	57%	0.00001 *	-	0.197257
C−I	Inverse	Challenging	Decrease	Life Length	58%	0.00001 *	0.197257	-
S0I (Control)	Inverse	Super Challenging	None	Life Length	22%	-	0.00001 *	0.00001 *
S+I	Inverse	Super Challenging	Increase	Life Length	34%	0.00001 *	-	0.598223
S−I	Inverse	Super Challenging	Decrease	Life Length	34%	0.00001 *	0.598223	-
E0I (Control)	Inverse	Easy	None	Comfort	0.64	-	0.00001 *	0.00001 *
E+I	Inverse	Easy	Increase	Comfort	0.79	0.00001 *	-	0.249459
E−I	Inverse	Easy	Decrease	Comfort	0.8	0.00001 *	0.249459	-
C0I (Control)	Inverse	Challenging	None	Comfort	0.71	-	0.00001 *	0.00001 *
C+I	Inverse	Challenging	Increase	Comfort	0.63	0.00001 *	-	0.411145
C−I	Inverse	Challenging	Decrease	Comfort	0.62	0.00001 *	0.411145	-
S0I (Control)	Inverse	Super Challenging	None	Comfort	0.47	-	0.00001 *	0.00001 *
S+I	Inverse	Super Challenging	Increase	Comfort	0.6	0.00001 *	-	0.259483
S−I	Inverse	Super Challenging	Decrease	Comfort	0.59	0.00001 *	0.259483	-

3.2.1. Easy World Conditions

Figure 4 shows the results with dynamic modulation by internal OT of the value of $touchingIntensity$ in each group. In conditions of both direct and inverse physiological modulation by OT in Easy world conditions, all agents survived the entirety of the simulation runs. In conditions with direct modulation of $touchingIntensity$, average comfort levels throughout each of these runs remained above 0.90 across all variants of social salience modulation, with the only exception being agents in the Decreased Social Salience group who saw an average comfort level of 0.8 when smaller values of $touchingIntensity$ were used. However, when $touchingIntensity$ was inversely modulated by OT levels, the trend of average comfort levels changed significantly. At lower levels of $touchingIntensity$, there was some small variance between comfort levels across the different groups. In contrast to the Direct Modulation conditions, these comfort levels were in favour of Decreased Social Salience groups (E−I), with an average comfort of 0.68 when $touchingIntensity < 50\%$, compared to 0.64 and 0.65 for E+I and E0I respectively. As $touchingIntensity$ increased to values beyond 50%, the comfort level of E0I remained relatively unchanged. However, the comfort of both E+I and E−I groups increased significantly, to 0.94 ($p < 0.00001$) for both groups.

3.2.2. Challenging World Conditions

In challenging conditions, the results are more varied. At lower values of $touchingIntensity$, the life length of agents in the Decreased Social Salience group is significantly hindered (56%) when compared to agents in the other two groups, with an average life length of 70%. As $touchingIntensity$ increases, there is little variance in the life length in either the control group or the Increased Social Salience group. As $touchingIntensity$ exceeds 35%, agents in the Decreased Social Salience group have an increased life length (69%). Despite their increased life length, this group is still outperformed in terms of life length by both the Increased Social Salience group and the control group. Average comfort across all these groups follows similar trends, with agents in the C0D and C+D groups maintaining a steady comfort level of 0.71 and 0.72 ($p < 0.014774$) respectively. C−D groups experienced a slightly more uncomfortable life, at 0.68 across all conditions. While this variance may look small, when compared to C+D, it was a statistically significant result ($p < 0.00001$).

When OT inversely modulated $touchingIntensity$, a different picture appeared. At low values of $touchingIntensity$, agents in the Decreased Social Salience group survived longer (48%) than agents in the C+I group (43%) (Figure 4b). Despite that, average comfort level remained the same between the two groups (0.55). This is in contrast to what was observed in experiments when OT did not modulate $touchingIntensity$ (Figure 3c), when conditions of Decreased Social Salience and low values of $touchingIntensity$ became detrimental to agent viability. Conversely, as $touchingIntensity$ increased beyond 50%, viability in both C+I and C−I increased by 19% pts (from 43% to 62%) and 15% pts (from 48% to 63%) respectively. As $touchingIntensity$ exceeds 50%, conditions of Increased Social Salience appear to benefit agent viability more than the other two conditions. Again, this is in contrast to what has been seen in previous experiments, where the Increased Social Salience group experienced little benefit at higher values of $touchingIntensity$. Importantly, however, the control condition, where oxytocin was not present, outperformed the other conditions (70% vs. 48% for C−D at lower $touchingIntensity$ values (<50%). Therefore, although the C−I group outperformed the C+I group in terms of life length, it still remained more beneficial to have no modulation if the initial intensity was not high enough.

3.2.3. Super Challenging World Conditions

In the Super Challenging world conditions where OT directly modulated $touchingIntensity$, average life length of agents was hindered in Decreased Social Salience groups (S−D, 39%) when compared to both the control group S0D (43%, $p < 0.00001$), and the Increased Social Salience group S+D (42%, $p < 0.00001$). There was no statistical difference between the life length of S0D and S+D, with a very small increase in comfort level (0.671 vs. 0.665, $p = 0.028883$), suggesting no advantage to viability for Increased Social Salience groups when OT directly modulates $touchingIntensity$. When OT inversely modulated OT, a significant increase was seen for the Increased Social Salience group (S+I) for both life length (34%) and comfort level (0.6) when compared to the control condition (S0I) with a life length of 22% and comfort level of 0.47. Decreased Social Salience groups in the inversely modulated conditions (S−I) were also observed to have a similar life length (59%) and comfort level (0.59) to the S+I group. In super challenging conditions, both directions of social salience modulation similarly outperformed the control group S0I. However, no statistical significance was found between the performances of S+I and S−I, suggesting that in conditions where food availability was significantly challenged, the presence of a hormonal modulation function was sufficient to promote viability.

4. Discussion

4.1. Decreased Social Salience Is Detrimental When Touch Intensity Is Low

In our previous experiments [2], we reported an overall increase in viability of agents when levels of OT increased social salience, supporting the initial prosocial hypothesis proposed by [6]. Let us recall that, in those experiments, a fixed $touchingIntensity$ of 5% was used across all social salience groups. The new experiments using fixed values of $touchingIntensity$ reported in this paper corroborate the same results as our previous experiments—increased viability for Increased Social Salience groups—for low values of $touchingIntensity$ (between 5% and 20%).

However, as the values of $touchingIntensity$ increase beyond 20%, the picture changes and Decreased Social Salience groups become comparable to Increased Social Salience groups in terms of viability, whereas for lower levels of $touchingIntensity$, Decreased Social Salience is detrimental to the viability of agents, both in terms of absolute life length and overall comfort.

The decrement in viability for Decreased Social Salience groups and the increment of viability for Increased Social Salience groups are not symmetrical. The difference between the Decreased Social Salience group and the control group (57% vs. 67% for $touchingIntensity \geqslant 20\%$) is greater than that of the Increased Social Salience group (70% vs. 67% for $touchingIntensity \geqslant 20\%$), suggesting that, with no additional (dynamic) modulation of $touchingIntensity$, decreasing social salience with (fixed values of) endogenous OT does not benefit the viability of agents. As seen in Figure 3c, however, their life length does increase as the value of $touchingIntensity$ increases.

The reason for this is as follows. When the behaviour $Touch$ is executed, agents satisfy their internal need by the value of $touchingIntensity$ (for example, $SocialNeed$ is satisfied by +5% when $touchingIntensity = 5\%$). Once this need is satisfied, agents then divert their efforts towards looking for food, as the new winning motivation would be $Hungry$. As agents find food resources, they consume food until the internal motivation $Lonely$ becomes more intense than $Hungry$, at which point agents start looking for other agents. As the action selection architecture is run at every time step and agents will always look to execute the behaviour that satisfies the highest (most intense) motivation, the current value of the $SocialNeed$ variable becomes effectively an approximate upper limit for which the $Energy$ variable can be successfully satisfied to. When the physiological satisfaction for the $SocialNeed$ is low, the value of this "upper limit" is also low. Conversely, when the value of $touchingIntensity$ is higher, it creates a higher upper limit. This means that it takes longer for the agents to have a motivation for social contact, as social contact satisfies their physiological need to a larger extent, and they can spend more time searching for and consuming food. Indirectly, the creation of an "upper limit" for energetic satisfaction is akin to a social allostasis mechanism, adapting the range of values in which an agent can remain viable. Agents appear to adapt their maximum satisfaction of $Energy$ to the approximate upper limits defined by their $SocialNeed$ variable. The internal plots of this can be seen in Figure 6. This then results in comparable life lengths across all conditions of social salience modulation as physiological satisfaction of tactile contact ($touchingIntensity$) increases, since the rate of satisfaction of the $SocialNeed$ is so large that it becomes irrelevant whether an agent has social contact frequently (in Increased Social Salience groups and, to a lesser extent, the control group), or more infrequently (in the Decreased Social Salience group). Infrequent social contact does create a more uncomfortable life in the latter conditions, and as viability includes both life length and comfort levels, it would still remain detrimental to viability to decrease social salience through OT modulation.

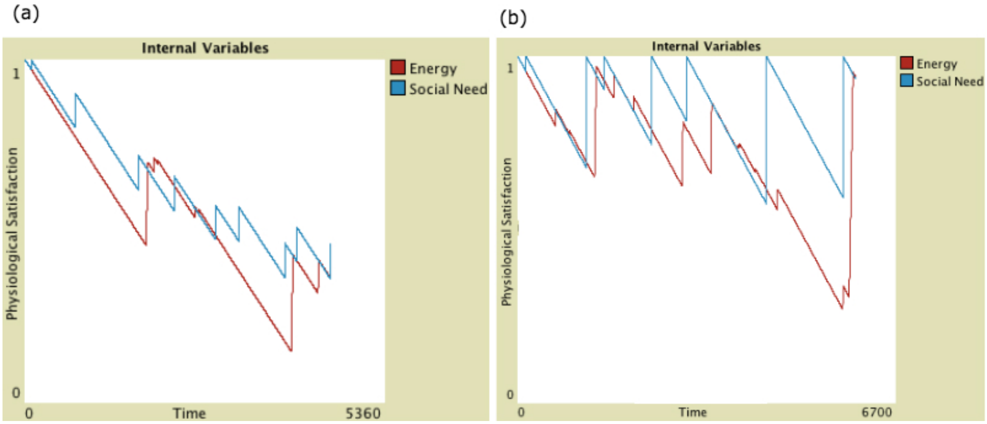

Figure 6. Comparison of the physiological satisfaction of the $Energy$ (red) and $SocialNeed$ (blue) within an agent. (**a**) A simulation run when $touchingIntensity = 10\%$. (**b**) A simulation run when $touchingIntensity = 60\%$. Please note that the higher the rate of physiological satisfaction for *Social Need*, the more an agent can satisfy its $Energy$ value through the *Eat* behaviour.

4.2. Interplay among Parameters

Looking at the results from these experiments, we observe an interplay among the different parameters: the degree of physiological satisfaction, the direction of the modulation of the physiological satisfaction (direct or inverse) and the direction of OT modulation of social salience (increase or decrease). In our current model, the combination of the effects of oxytocin decreasing social salience and having a direct modulatory effect on the physiological satisfaction provided by the *Touch* behaviour, is detrimental to the overall viability, but only when the initial $touchingIntensity$ is low. In conditions of direct modulation, both control and agents that have increased social salience consistently outlive those who have decreased social salience. However, when looking at the two modulating conditions in both the Increased and Decreased Social Salience groups (Figure 5e,f), a very clear trend is observed. At lower intensities, agents in Decreased Social Salience conditions are significantly hindered by inverse OT modulation. However, as intensity increases, it then appears beneficial to inversely modulate physiological satisfaction of *Touch* in this group, as they begin to outlive agents in the Increased Social Salience group, with comparable comfort levels. This provides further support for the interactionist approach of oxytocin in that its effects are context-dependent and should have different behavioural expression depending on the situation.

4.3. Infrequent Social Contact Intensifies the Effects of Tactile Contact

One potential reason for the increased viability of the Decreased Social Salience group in inversely modulated conditions may be, perhaps counter-intuitively, their lack of consistent social contact. As oxytocin is endogenously released as an agent executes the *Touch* behaviour, less OT is present in an agent who socialises infrequently, as is the case in Decreased Social Salience groups. This fact intensifies the inverse modulation of *Touch* when agents do eventually find an opportunity for social contact. From an adaptive point of view, it would appear that agents become indirectly adapted to their lack of social satisfaction: the less social contact an agent has, the less endogenous OT is present and the more the agent maximises its opportunity to satisfy its physiological need (increased physiological satisfaction). Oxytocin is then released in the system, meaning that any further social contact in the short term would have substantially smaller effects on physiological satisfaction. Therefore, there appears to be a considerable benefit to an agent's viability from both decreasing social salience and inversely modulating satisfaction of its social needs in order to maximise its life length in a challenging environment, provided the baseline intensity of physiological satisfaction is high enough.

When endogenous OT did not modulate the physiological satisfaction of *Touch* (see Figure 3), there was a negligible difference in life length between the control group and those affected by modulation of social salience in both the Challenging and Super Challenging conditions (Figure 3c,e), across the majority of $touchingIntensity$ values. The same was seen for the average comfort levels (Figure 3d,f). When OT inversely affected the physiological satisfaction in those same world conditions, OT modulation had a notable effect (Figure 4). In challenging conditions and inverse modulation of $touchingIntensity$ (Figure 4f,h, both C+I and C−I were unable to outperform the control group (C0I, where no endogenous OT was present), across both viability metrics. In Super Challenging conditions, with less food available than in Challenging world conditions, both S+I and S−I outperform the control group across both life length and comfort levels. This again provides further support to the context-dependence nature of OT modulation dynamics.

4.4. Modelling Approach

A last point we would like to discuss here concerns our model. As already mentioned (Section 2.3.3), we do no aim to model the behavior of oxytocin per se, but rather the dynamics of two specific modulatory roles and their effects as a mechanism for social allostasis. Attempting to model a biological hormone is a complex task, particularly when the precise physiological effects of the hormone remains a divisive issue, as is currently the case with OT. The real-world physiological and behavioural effects of OT are far more complex than the mathematical models that have been included in our agent architecture. The methodology that we have adopted takes inspiration from a few of its specific hypothesised behavioural effects and dynamics, in order to model social adaptation in our simulated embodied agents.

While comparatively simpler than its biological counterpart, our model of OT can nevertheless provide some limited, correlative support for the theories that have inspired us (see Section 1.2). As mentioned previously, one key advantage of using an Artificial Life simulation is the granularity of control, limiting potential noise or extraneous variables that may exist in observations of real-world individuals and societies, and allows us to better correlate behaviours to specific internal mechanisms.

It must also be noted that the decision to model simple tactile behaviours to implement social touch was a deliberate choice as part of our experimental design. By initially reducing unnecessary complexities of behaviour execution, the focus of the model can instead remain on the physiological adaptation through hormonally inspired mechanisms, the results of which can be used to extrapolate to other types of embodied agents.

It is important to mention that this model is only one potential approach to social adaptation, using previously hypothesised mechanisms of one biological hormone. Even in Schulkin's approach to allostasis [3], social adaptation of natural world agents is driven by several different hormones—also including (but not limited to) vasopressin, cortisol and dopamine. Attempting to implement all these mechanisms from the outset in an agent architecture would create an overly complex initial model; however, following an incremental design approach, we envisage the (step-by-step) addition of other mechanisms in the future to widen our study of social adaptation through social allostasis.

5. Conclusions and Future Work

In this paper, we have presented a model of social adaptation using mechanisms of social allostasis that investigate how adapting the physiological response of simulated embodied social agents ($n = 6$) to a social behaviour (tactile contact) using hormonal modulation affects their survival and viability. We have developed and tested an Action Selection Architecture driving the behavior of the agents that includes a model of two specific modulatory effects the hormone oxytocin (OT): firstly, modulating the salience of social stimuli (by either increasing or decreasing social salience), and secondly, modulating the physiological satisfaction of a social behavior (tactile contact) in one of two directions (directly or inversely). We have presented and discussed the experiments that we have carried out, using the NetLogo simulation environment, to test our model under three different environmental conditions that pose varying degrees of challenges related to food availability (Easy, Challenging and Super Challenging). Results have been reported across two performance metrics (viability indicators): agent life length and comfort.

The main conclusion that we can draw from our results is the fact that adaptive OT modulation is context-dependent. The results of our experiments highlight that OT modulation of the mechanisms that we have described should be context-dependent in order to maximise viability of our socially adaptive agents. Specifically, we provide support for the interactionist approach to OT modulation [10], suggesting that there is no "one-size-fits-all" effect of the hormone, but that its effects should instead be adapted to an agent's "understanding" or perception of its internal and social environment. In our experiments, the model of the prosocial approach [6] (which proposes that OT increases social salience) significantly increased agent viability in conditions where internal satisfaction of social touch was small, whereas decreasing social salience using OT caused a significant disadvantage in those same conditions. As the intensity of social touch increases, agent viability is maximised when OT decreases social salience. Depending on the degree of physical challenge that the environment presents, we observe that agent viability can also be promoted by no modulation of either social salience or the intensity of social touch. In particular, viability in conditions of extreme food sparsity (the Super Challenging worlds) is improved across both social salience effects (increase and decrease), but only when OT inversely modulates the internal satisfaction of social touch. When food availability is slightly higher (in our Challenging worlds), inversely modulating satisfaction of social touch is significantly detrimental to both social salience groups. Through these mechanisms of dynamic satisfaction, agents are undergoing an element of social adaptation—by adapting the rate at which they satisfy their physiology relative to the social "support" that they experience. This is, in essence, a key element of social allostasis—the adaptation of physiology relative to the dynamics of the (social) conditions, and we will continue to iteratively build upon this model in the future.

The findings described in this paper highlight that the combination of modulatory effects of OT that best promote viability of our social agents is dependent upon the degree of challenge that the environment poses. As a result, we propose that socially adaptive agents should adapt the effects of the modulatory mechanisms as an adaptive response to their perception of different types of (challenges posed by) physical and social environments. As we continue to build towards a model of social allostasis for our embodied agents, future work will consider adapting the modulatory mechanisms in this way. We hypothesise that the adaptation of these modulatory mechanisms will promote the long-term viability of our agents across a wider range of environmental and social conditions.

Importantly, no social challenge exists in the worlds that we have modelled in the present experiments and, despite the limited availability of food, agents are physically safe from a predator or competitor species. The findings and support for the hypothesis should take this into account, and our future work will address those challenges. We further hypothesise that, as competition is introduced to the world, perceived satisfaction of social touch will play a more integral role in agent viability. In particular, the satisfaction of social touch might better contextualise the level of social support available to an agent in a competitive environment, allowing agents to adapt their physiology and behaviours in those environments.

Future work will also look at introducing dynamic OT modulation as a function of affiliative relationships among agents, notably of familiarity, as discussed in Section 1.2. The literature supports the idea that oxytocin has different effects depending on agent familiarity (including perceived in-group and out-group agents), and this provides an opportunity to further explore contextually relevant modulatory mechanisms for adaptation through social allostasis in our model.

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Abbreviations

The following abbreviations are used in this manuscript:

ASA	Action Selection Architecture
OT	Oxytocin

Appendix A. Mathematical Notation of the Action Selection Architecture

(i) Calculate the drive/error for each internal variable. Errors are calculated as the difference between the current values of the variables from their ideal value:

$$e_v = p_v - j_v \tag{A1}$$

where e_v is the error value, p_v is the ideal value for that internal variable, and j_v is the current value of that internal variable.

(ii) Calculate the cues, i.e., the value of each external stimulus. The value of food cues is calculated as:

$$C_{food} = \sum nutritionValue \tag{A2}$$

where $\sum nutritionValue$ is the total nutritional amount of food resources seen in an agent's vision. The value of agent cues is calculated as:

$$C_{agent} = \sum agents \tag{A3}$$

where $\sum agents$ is the total count of agents in an agent's vision.

(iii) Calculate the salience of each stimulus. The value of food salience is the same as food cues, therefore:

$$S_{food} = C_{food} \tag{A4}$$

The value of social salience is calculated as:

$$S_{agent} = C_{agent} \times \alpha \tag{A5}$$

where α is the effect of oxytocin defined in the next section.

(iv) Calculate the intensity of each motivation, *Hungry* and *Lonely*, as follows:

$$m_i = e_v + (e_v + S_i) \tag{A6}$$

where e_v is the error of internal variable v and S_i is the stimuli linked to that motivation. The motivation with the highest intensity is selected as the winning motivation:

$$m_{winner} = max[m_{hungry}, m_{lonely}] \tag{A7}$$

(v) Calculate the intensity of both behaviours by multiplying the winning motivation by the physiological effect of each of the behaviours:

$$b_i = m_{winner} \times f_{winner} \tag{A8}$$

where m_{winner} is the winning motivation and f_{winner} is the physiological effect that m_{winner} has on behaviour b_i

(vi) The behaviour with the highest intensity is the winning behaviour, and the one that is executed:

$$b_{winner} = max[b_{eat}, b_{touch}] \tag{A9}$$

Appendix B. Mathematical Definitions of Our Metrics

Our performance (viability) metrics are calculated as follows:

(i) *Life Length*: The simulation time steps that an agent survived—remained viable by keeping its $Energy > 0$—as a percentage of the maximum simulation length (30,000 time steps). Calculated using:

$$R_{life} = t_{life} / t_{simulation} \tag{A10}$$

where t_{life} is the total time steps that the agent remained viable (alive) and $t_{simulation}$ is the maximum length of the simulation (30,000 time steps).

(ii) *Average Comfort*: The average level of satisfaction of internal variables throughout an agent's lifetime. At each time step, comfort levels are calculated by

$$q_t = 1 - (\frac{\sum Err}{max_{Err}}) \tag{A11}$$

where $\sum Err$ is the sum of errors of the agent's two internal variables at time t, and max_{Err} as the sum of the maximum errors of all the internal variables. The average comfort level per experimental run is then given by:

$$Comfort = \frac{\sum q_t}{t_{life}} \tag{A12}$$

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