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Modeling of a Cognitive Hybrid Architecture for the Hygrothermal Regulation of a Room Manipulated by an Agent

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Abstract

This paper applies components of cognitive architectures to hygrothermal (humidity and temperature) control in a simulated room; an agent can affect the room hiygrothermal state. Hygrothermal control and its optimization is an important field of research due to constraints on fuel acquisition and the transition to renewable energies. The cognitive theory looks to model a mind's behavior as the joint work of multiple components. This first work implements two features of cognition related to hygrothermal regulation: procedural memory and attention. An agent uses these two modules to control the hygrothermal state of a room under environmental pressure.

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Keywords: Formal grammars; cognitive theory; Attention; Procedural memory

1. Introduction

Over the years, multiple models and architectures have surfaced with the intent of using cognitive theory to achieve a general intelligence [10]. These advances help us understand the inner workings of our minds, and we can apply these models to practical tasks that may benefit from such distributed approaches.

This paper presents a case study for the modeling and implementation of attention and procedural memory specific to the task of hygrothermal control of a room. Attention is a cognitive function that mediates while selecting information from sensory input [18]. Procedural memory stores information regarding actions; it activates when forming a plan. An agent uses modules based on cognitive theory for these two functions to control a room's humidity and temperature independently. Our objective is to model these two functions and connect them in an agent to achieve the task of hygrothermal control.

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Section 2 presents the case study and experimental setup in detail. Section 3 describes the elements of cognition implemented. Section 4 presents the results of simulations run for this case study. The document finalizes with sections for the discussion and conclusions garnered from the experiment.

1.1. Cognitive Architectures

Biologically inspired cognitive architectures help us understand our functioning as living and thinking beings [5]. They can also be applied to extract and model behaviors for specific tasks [17, 7]. Cognitive architecture research is decades old and spans multiple interests and viewpoints. The survey presented in [10] displays the wide range of architectures present in the literature, active today. We find elements of the following architectures helpful to this work's task:

ACT-R: This architecture started as a model of human memory. They modeled distributed memory and expanded on it with cognitive tasks [19]. ACT-R contains multiple distributed modules classified as perceptual-motor and memory. These modules interact through buffers and generate plans through pattern matching in procedural memory.

SOAR: This architecture was born from the same group as ACT-R; its initial focus was on tasks instead of memory. Their objective was a "General Problem Solver," [12]. It represents long-term memory as productions that contain sets of conditions and actions.

LIDA: The US Navy developed this architecture on a foundation of psychological theory to help human resource personnel using cognitive agents [4]. This architecture uses the Global Workspace Theory; elements in the workspace are fleeting and correspond to conscious processes broadcast to other unconscious processes. The architecture also presents attention codelets that copy their concerns to the global workspace.

Cuayollotl: This architecture uses neuroscience as its primary directive for development and includes a virtual human body to mimic the function of senses and actuators found in nature. It handles motivation as a set of internal (endocrine system), and external influences (sensory system) [27].

Each architecture uses its approach to reach the objective of an Artificial General Intelligence. For our purpose, we focus on specific elements of these architectures and cognitive theory for the task of hygrothermal control in a room.

In addition to these architectures, we find PRIMs [23] useful to our interests. PRIMs is a theory of cognition that defines cognitive skills as sequences of elements. It breaks cognitive tasks into sets of primitive information processing elements (PRIMs).

1.2. Hygrothermal Control

Climate control is an active field of research, more so currently due to energy constraints faced by most countries worldwide [20]. Climate control aims to generate a room environment habitable and comfortable for the room's residents with minimal energy consumption using multiple viewpoints.

The first approach that comes to mind when looking to save energy is to start from the room's design and manufacturing [13]; this way, hygrothermal control becomes a primarily passive process due to the interaction between the building and the outside.

For situations where room design is not an option, namely preexisting buildings or a restrictive budget, approaches vary from control strategies [3] to optimization in the schedule according to peak demand hours [28], to even updates to comfort standards and guidelines [1]. The review presented in [2] describes multiple control strategies already in use and other novel ones that use artificial intelligence as part of the control.

The novelty of the proposal comes from the hypothesis: The use of cognitive theory in conjunction with a formal specification grammar allows control of the hygrothermal state of a room.

2. Case Study

Our experiment focuses on the function of attention and procedural memory as described in multiple cognitive architectures. The evolution of the room's hygrothermal pressure shifts according to data gathered from the weather station located in Toluca, Mexico [21]. The data collected represents the average temperature and humidity reported by the weather station over February (see Fig. 1).

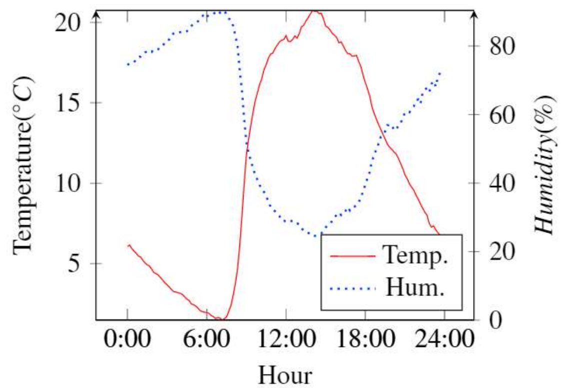

Fig. 1. Average environmental temperature and humidity over a day gathered for February in Toluca, México.

The following variables pertain to the hygrothermal configurations and pressures present in the simulation: The room's hygrothermal state is defined by the tuple (T_R, H_R), the room's temperature and humidity. The agent has a pre-established need for a hygrothermal configuration called goal configuration (T_G, H_G). The environment exerts pressure according to the dataset at any given time (t) in the simulation $(T_E, H_E)_t$. The agent also exerts pressure according to its goal configuration (T_A, H_A), similar to activating an HVAC unit.

The room is susceptible to environmental pressure by conduction heat transfer with the following characteristics: The room is modeled as a closed $2m \times 2m \times 2m$ space. The area of contact with the environment (A) is thus $24m^2$. The room's walls are modeled using aerated concrete blocks, so the thermal conductivity is $k = 0.16\frac{W}{mC}$ [8]. Additionally, the thickness of the walls is $d = 0.2m$.

The heat transfer between the room and the environment is dependent on their temperature difference and the agent's action (T_A). We use a time step of 10 minutes for the case study. The International Civil Aviation Organization (ICAO) standard atmosphere [9] gives us the density of air $\rho_0 = 1.225\frac{kg}{m^3}$ and allows us to calculate the mass of air in the room $m = 9.8kg$. The heat capacity of the air in the atmosphere is $1.012\frac{J}{gK}$; this helps us convert the energy into temperature changes.

With this data, we calculate the temperature change in the room at every step of the simulation (see Eq. 1). Its parameters are the agent's actions T_A and the differential between T_R and T_E.

$$
\begin{aligned}
Q &= \frac{kA(T_{hot} - T_{cold})t}{d} \\
\Delta T_R &= \frac{600 * Q}{9800g * 1.012\frac{J}{gK}} \\
\Delta T_R &= 1.161 * (T_{hot} - T_{cold}) + \frac{T_A}{16.529\frac{J}{K}}
\end{aligned}
\tag{1}
$$

Regarding humidity, relative humidity is the amount of water vapor in percentage according to the environment's saturation vapor density (measured in $\frac{g}{m^3}$). A value of 100% means the moisture content is saturating the air, and further cooling will cause condensation. Water's saturated vapor density depends on the environmental temperature, and multiple fits exist. We use [16] (see Eq. 2) since it reflects a fit of empirical data up to 40°C, a valid range for our case study.

$$V_D = 5.018 + 0.32321T_C + 8.1847 \times 10^{-3}T_C^2 + 3.1243 \times 10^{-4}T_C^3 \quad (2)$$

We extract the saturation densities for moisture from this fit in our range of operations (see Table 1).

Table 1. Saturation densities for each temperature point.

$^\circ C$	Saturation density	$^\circ C$	Saturation density	$^\circ C$	Saturation density	$^\circ C$	Saturation density
0	5.018	7	7.7886	14	12.0044	21	18.3082
1	5.3497	8	8.2874	15	12.7621	22	19.4167
2	5.6996	9	8.8176	16	13.5643	23	20.5828
3	6.0697	10	9.381	17	14.4129	24	21.8084
4	6.4917	11	9.9795	18	15.3097	25	23.095
5	6.8777	12	10.6149	19	16.2566	26	24.4455
6	7.3193	13	11.2793	20	17.2555	27	25.8608

The saturation densities shown in Table 1 dictate the limit of humidity for the room, also known as dewpoint. This limit makes the room's humidity H_R dependent only on T_R and H_A since our case study does not model an inflow or outflow of air. Humidity has a lower limit of 0 and an upper limit given by the saturation density of moisture at a given temperature $S(temp) : \mathbb{R} \longrightarrow \mathbb{R}$ and is dependent on T_R and H_A:

$$\begin{aligned} H &= H_R * S(T_R) \\ new_H &= max(H + H_A, 0) \\ H_R &= \frac{min(new_H, S(T_R))}{S(T_R)} \end{aligned} \quad (3)$$

Moving on to the agent, it can influence the temperature and humidity trends according to its needs. For this case study, the agent's objective temperature and humidity are within a range described by international standards:

- Temperature (T_G) must be between 18°C and 24°C according to the World Health Organization [26]. This range prevents health risks associated with low or high temperatures (e.g., respiratory, cardiovascular, or heat stroke).
- Humidity (H_G) must be between 40% and 60% since dry air impairs the respiratory elements of the immune system [11] while too much humidity leads to dampness and mold generation [26].

The agent affects the room through the tuple (T_A, H_A). This tuple's possible values are constrained to products available in the market.

Room humidifiers' output ranges between 200 and 300 mL every hour [15]. Small room dehumidifiers range in operation between 450 and 700 mL per day [25]. We translate these to three levels of effect for humidification and dehumidification each. Finally, we convert these actions to their corresponding change in vapor density in the room.

Regarding temperature, according to Energy Star [6], a basic 5000 BTU air conditioner is more than sufficient. We convert this specification into energy transfer for Eq. 1 using the correspondence $1BTU = 0.293W$ and divide the transfer into ten minutes instead of one hour. Finally, we divide it into five levels for heating and cooling each.

In summary, the possible actions of the agent regarding the tuple (T_A, H_A) appear in Eq. 4.

$$\begin{aligned} T_A &\in \{-244.15, -195.32, -146.5, -97.66, -48.83, 0, 48.83, 97.66, 146.5, 195.32, 244.15\} \\ H_A &\in \{-0.062, -0.05, -0.037, 0, 0.375, 0.5, 0.625\} \end{aligned} \quad (4)$$

The environment and agent interactions are the following: The agent can query (T_R, H_R) and its current (T_A, H_A). The agent can change (T_A, H_A) once each simulation step. Changes in (T_R, H_R) happen according to the T_E and (T_A, H_A) pressures.

For the agent to achieve this task, we have decided to implement elements of cognitive theory. Our objective is to identify the applicability of modules based on cognitive theory to the task of hygrothermal control. This case study omits functions modeled by cognitive architectures other than the following two components:

Attention. This cognitive function is a mediator when selecting information from sensory data [18].

Procedural memory. It is a subset of long-term memory that stores information regarding actions [22].

Attention will allow the agent to select data from its input to engage procedural memory. Meanwhile, procedural memory will generate the agent's plan for the current simulation step. These components grant the agent awareness of its environment decision-making capabilities. The flow of information and activation we propose appears in Fig. 2.

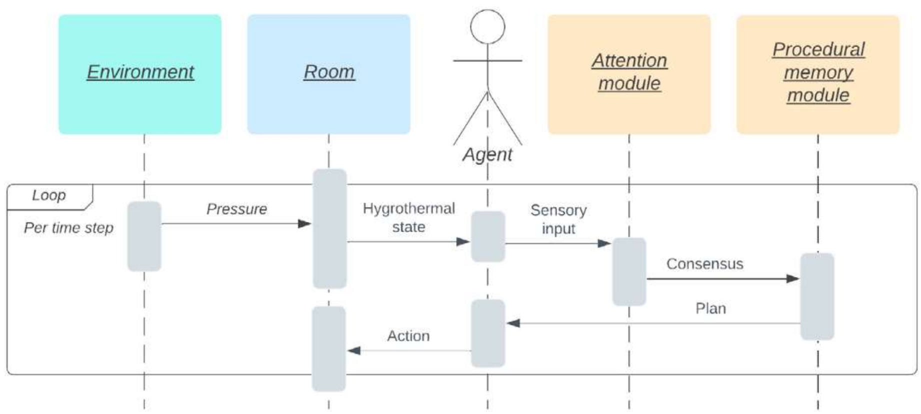

Fig. 2. Sequence diagram of the agent's interaction with the room and the interconnection between its modules.

3. Proposed Models

The cognitive capacity of the agent comprises two components: an attention component that keeps the agent aware of the environment and a procedural memory component that takes this information as input and processes it using production rules to obtain an action in the form of changes to (T_A, H_A).

3.1. Attention Model

Attention is a broadly researched topic. We will extract characteristics from different proposals to implement a basic attention module. According to [24], attention is a set of mechanisms within the categories of suppression, selection, and restriction. We have extracted the following list from this review:

- Alerting: Process, identify, and move attention to priority signals.
- Disengage attention: Release focus and prepare shift of attention.
- Endogenous influences: Direct attention using domain knowledge or instructions.
- Engage attention: Fixate a stimulus.
- Executive control: Generate a response by coordinating elements into a coherent unit.
- Exogenous influence: The external stimulus influences attention.
- Inhibition of return: Bias against returning attention to previously attended element.
- Post-attention: Create a representation of the attended item.

- Selection: Choose one element over the remainder.
- Shift attention: Move to a new point of fixation.
- Update fixation history: Keep track of what has been processed.

By reducing the list found in [24] we identify the main elements to implement for a minimal attention module. For the specific case study, the features are: engaging and disengaging attention, awareness of the room's state and the agent's latest actions, and identifying the more critical factors to address. From these, we identify four tasks:

- *Engage attention:* To fixate the agent on one of its inputs.
- *Disengage attention:* To dissuade the agent from fixating on an input.
- *Handle external/internal factors:* To address additional knowledge about the problem and the agent's previous actions when deciding on which input to address.
- *Select a target of attention:* To handle the agent's fixation or focus shift.

These four tasks are the basis for our attention module to handle fixation and shift of focus between its inputs to address at any given moment. Table 2 shows our sort of the mechanisms for each of the four tasks.

Table 2. Classification of the mechanisms according to their utility to each task.

Engage attention	Disengage attention	Handle external/internal factors	Select target of attention
Alerting	Disengage attention	Endogenous influences	Selection
Engage attention	Inhibition of return	Exogenous influences	Shift attention
	Update fixated history	Executive control	
		Post-attention	

The attention module has the following variables: The module receives (T_R, H_R) as input; the module knows (T_G, H_G); The module retains (T_R, H_R) from the previous step; the module keeps a variable $prev \in \{none, temp, hum, both\}$ representing which input the agent fixated on during the previous iteration.

The attention module works as consensus from multiple mechanisms to each of T_R and H_R:

To engage

- Alerting: R out of G's range.
- Post-attention: R farther from G than previous.
- Shift attention: R farther from G than the opposite objective.
- Executive control: T_R trends down and H_R not below H_G or T_R trends up and H_R not above H_G.

To disengage

- Disengage attention: current R in G's range.
- Inhibition of return: R in history.
- Shift attention: current R closer to G than the opposite objective.
- Executive control: T_R trends down and H_R below H_G or T_R trends up and H_R above H_G.

Each mechanism has a vote in the final consensus regarding temperature and humidity. Votes to engage have a positive value, whereas votes to disengage have a negative value. The sum of all the votes is the module's consensus.

The sum of all the votes dictates the module's consensus to engage (positive value) or disengage (negative value) a task and thus whether to feed the procedural memory module. After reaching the consensus of both tasks, the module updates its fixed history $prev$.

3.2. Grammar Model

A formal grammar based on parametric L-systems [14] represents the procedural memory of the agent. For our proposal, the grammar produces plans to change the room's hygrothermal configuration via T_A and H_A. The grammar receives the hygrothermal values of the room and the agent's goal and applies its stored production rules to generate a word that determines the levels of T_A and H_A that the agent will apply during the current time. Each production rule stores a response to a given input.

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Running the complete production process for the grammar generates the agent's current plan. The grammar's definition is as follows:

$$G = (V, P, \Sigma, S) \tag{5}$$

where:

- V is the grammar's alphabet, a set of the terminal and non-terminal elements. The non-terminals are the initial determiners of which production rules are applicable and turn into a sequence of other elements in V. Meanwhile, the terminals represent the actions that the agent will perform.
- P is the set of production rules representing the agent's procedural memory. A production rule converts a non-terminal into a sequence of elements in V if the rule's requirements for the input are met. A production rule can generate terminals as part of the agent's current plan and non-terminals and alter the production process flow.
- $\Sigma = \{t, h\}$ is the set of parameters. The parameters are the input the agent gathers from its environment and represent the distance between the room's state and the agent's goal state regarding temperature and humidity, respectively. Σ is dependent on the attention module; if attention fixates on an input, the module feeds it to procedural memory; on the other hand, if attention ignores the input, it does not reach procedural memory and is not accounted for by the grammar at the time.
- S is the initial non-terminal in the production process. It starts the production of the agent's current plan.

The following function defines production rules for this grammar:

$$p \in P : (n \in V, t \in \mathbb{R}, h \in \mathbb{R}) \mapsto (w \in V^*, t \in \mathbb{R}, h \in \mathbb{R}) \tag{6}$$

A production rule has the form $n \in V \rightarrow v \in V^* | Bool_t(t), Bool_h(h)$ where n is a non-terminal, and the boolean functions *Bool* determine if the rule is applicable with the parameters t and h the procedural memory module receives form the attention module.

The grammar's input is a conversion from the tuples(T_R, H_R) and (T_G, H_G) into the the parameters $\Sigma = \{t, h\}$ where:

- $t \in \mathbb{R} = d(T_R, T_G)$ is the distance from the necessary temperature.
- $h \in \mathbb{R} = d(H_R, H_G)$ is the distance form the necessary humidity.

The terminal elements of the grammar represent the agent's response as dictated by procedural memory. The agent's response is a change in (T_A, H_A) dictated by the tokens $\{a, b, c, d\} \subset V$ where:

- a and b dictate an increase/decrease of one level in T_A.
- c and d dictate an increase/decrease of one level in H_A.

Once the grammar's processing completes, parsing the resulting word for these tokens and counting them determines the change in the agent's response.

For the definition of non-terminals, we adapt the PRIMs theory's vision of cognitive tasks. PRIMs [23] is a theory of cognitive skills that models them as an amalgamation of primitive information processing elements. We adapt this principle into our grammar model by breaking down the handling of specific inputs into groups of non-terminals and their respective production rules. This approach facilitates the definition of production rules for flow control within the grammar and the generation of the agent's plan.

The non-terminal elements of the alphabet help encode the procedural memory into production rules. The proposed set of non-terminals is $\{S, T, H, A, B, C, D\} \subset V$.

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By joining terminals and non-terminals, we obtain the grammar's alphabet $V = \{S, T, H, A, B, C, D, a, b, c, d\}$.

For ease of understanding, the non-terminals are classified into four groups according to their use during information processing:

1. This group is temperature-oriented. These non-terminals only manage the parameters t: $\{T, A, B\}$.
2. This group is humidity-oriented. These non-terminals only manage the parameters h: $\{H, C, D\}$.
3. This group can handle all four parameters, be it to generate a response or to control the flow of information: $\{S\}$.
4. This group handles information flow and leads to the appropriate production rules according to the parameter values: $\{S, T, H\}$.

This classification helps us establish the agent's information flow when retrieving responses from procedural memory. Fig. 3 presents this flow using the grammar's non-terminals.

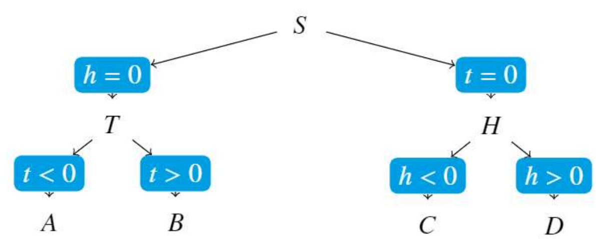

Fig. 3. Flow of information for procedural memory in the proposed grammar.

This separation of non-terminals into different functions reduces the complexity of the production rules in exchange for additional non-terminals focused only on flow control. In this model, rules for S handle both t and h, rules for $\{T, H\}$ handle their respective parameters, and rules for $\{A, B, C, D\}$ only handle their parameter's distance from the goal in a single direction.

4. Implementation results

In this section, we present the implementation of our model. We show a simulation of our model running without agent intervention; then, we display the agent's effect on the room. For our simulations, we make the following assumptions:

- The simulation's time step is 10 minutes.
- A full simulation consists of 24 hours.
- The room's temperature depends only on the environmental pressure and the agent's actions.
- The room's humidity is isolated from the environment.
- The saturation density is restricted to unit changes in temperature. Intermediate values are truncated.

The initial run of simulations occurs without agent input. This run presents how the room's temperature behaves solely under environmental pressure (see Fig. 4). The green line shows the environmental pressure on temperature, the red line shows the room's temperature, and the dotted line shows the room's humidity.

The room's temperature follows the environment's temperature closely. This phenomenon can be surmised from Eq. 1 by removing the agent's actions T_A. The room's humidity appears to move in steps because the saturation density in the simulation changes per unit change in temperature according to Table 1.

We also present an agent with simple procedural memory and an attention module acting on the room (see Fig. 5). This figure's plots use the same nomenclature as Fig. 4. For Fig. 5, the dotted areas show the agent's goal for temperature and humidity (the red and blue areas, respectively). The agent's attempts to remain within this area are noticeable.

Regarding humidity, it is noteworthy that our model for the agent's actions has differing strengths. The humidifying action is an order of magnitude more potent than the dehumidifying action. This difference is apparent in the

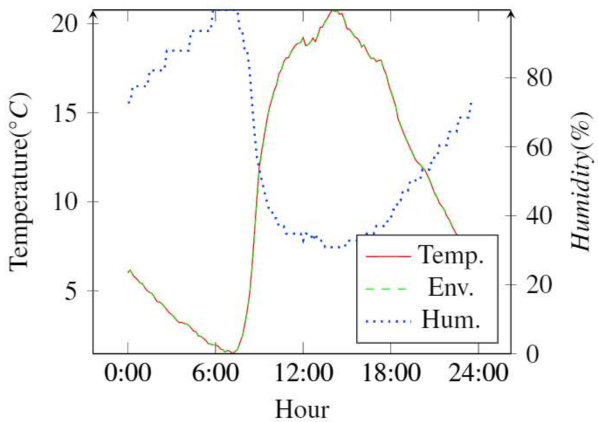

Fig. 4. Environment effect on the room's hygrothermal configuration. With our model's characteristics, T_R follows T_E closely.

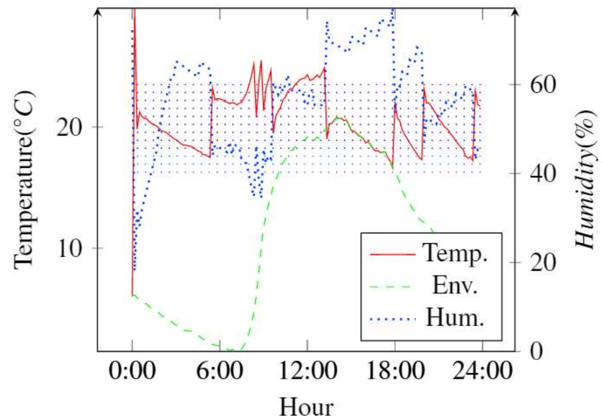

Fig. 5. State of the room after a simple agent's actions. The agent attempts to keep temperature and humidity within its goal ranges.

simulation; the curve's ascending slope is steeper than when descending. Ultimately, significant impacts on relative humidity come from temperature changes; every degree added or subtracted from T_R changes the room's saturation density. This effect strengthens as the temperature rises, causing the jumps in relative humidity. It is noteworthy that H_R never reaches the dewpoint (100%) where temperature reduction would cause condensation.

For temperature, the effect of the environment is substantial and requires strong action from the agent. The initial distance from T_R to T_G causes the agent to react with a high level of heating, which it quickly dials down to remain within its goal range. There are segments throughout the simulation where the agent leaves T_A stationary or deactivated and only reacts when T_E pushes T_R out of the goal range.

5. Discussion

For this case study, a simple agent with modules based on cognitive theory proved valuable and capable of reacting to changes in its environment to maintain its goal state. The agent can change the room's hygrothermal state despite environmental pressure.

The cognitive modules implemented into the agent allow it to attempt to reach its goals; further refinement for actions when the agent is within its goal range can increase the agent's effectiveness. Likewise, reducing the time step will help reduce the magnitude of the jumps in temperature caused by T_A. Improvement may be achievable following the PRIMs theory's approach to skill transfer. This theory sees tasks as an amalgamation of primitive elements. We defined the agent's procedural memory as a set of rules focusing on a specific input for our proposal. Complexification for this task may be possible by mixing production rules capable of handling both inputs.

Lastly, this case study established a specific objective for the cognitive theory implemented. It shows the theory's effectiveness when applied to particular tasks.

6. Conclusions

This paper presents a case study to implement elements of cognitive theory, particularly attention and procedural memory, into an agent of hygrothermal control of a room under environmental pressure.

The room's model considers continuous environmental pressure and an agent's actions in the same room. Due to the lack of insulation in the room, its temperature is highly dependent on the environment. The room's humidity directly depends on its temperature since it dictates the saturation density of moisture in the air. The agent directly affects the room's hygrothermal state at a rate according to HVAC models for room use found on the market. The agent uses two modules based on cognitive theory for awareness and action: attention and procedural memory.

The attention module allows the agent to address the room's temperature and humidity according to its needs, previous actions, and knowledge of the relationship between temperature and humidity. The procedural memory module allows the agent to decide on its actions on the environment and their magnitude. The design for procedural memory simplifies the production rules in exchange for additional non-terminal variables for flow control.

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