Towards Human Digital Twins for Public Health Simulations on the Metaverse

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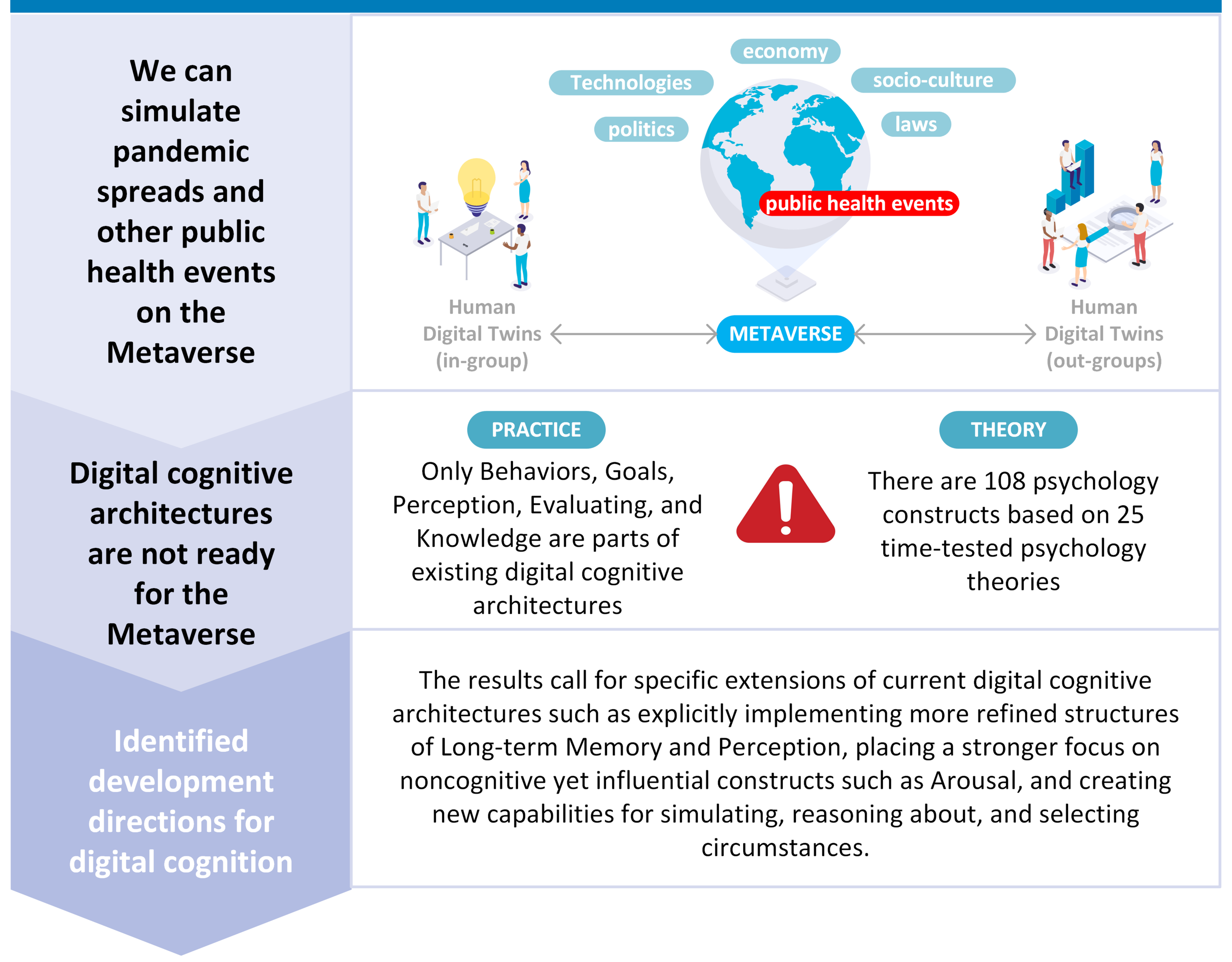
Visual Abstract



Highlights

This study aims to extend the current digital cognitive architectures such as SOAR and ACT-R as the first step toward more robust Human Digital Twins. 108 psychology constructs and thousands of related paths based on 25 time-tested behavioral cognitive theories were formally documented as Cybonto - a novel ontology. Then, 20 network science centrality algorithms were utilized in ranking of the Cybonto constructs by their influences.

The top 10 most influential constructs are Behavior, Arousal, Goals, Perception, Self-efficacy, Circumstances, Evaluating, Behavior-Controllability, Knowledge, and Intentional Modality.

Background

The Metaverse is a massive unified digital realm simulating the real world and can be used for large-scale collaboration and knowledge mining. Within the Metaverse, Digital twins (DTs) are virtual models designed to accurately simulate real-world physical objects while human digital twins (HDTs) are a specialized form of DTs. HDTs are completely autonomous and can interact with other HDTs and DTs. Possible large-scale simulations for public health may involve modeling the spread of health-related fake news across communities, or potential impacts of certain events on people's health. The key is building realistic Human Digital Twins who can think and act like real humans within a defined scope.

The concept of HDTs previously appeared in human-computer interaction studies. In comparison with traditional models, HDTs for the Metaverse have broader scopes with emphasis on both behavioral and cognitive activities. Digital cognitive frameworks are essential for building HDTs' cognitive features. Ontologies are essential for HDTs' feedback loop communications, symbolic operations, the building of a knowledge base, and explainability. While massive DT projects are underway, digital cognitive twin development is pale in comparison, and HDT for public health is underdeveloped. For the main reason, digital cognitive frameworks and behavioral ontologies were not designed for the Metaverse use case. Then, the main research question is – **How should digital cognitive frameworks and behavioral ontologies be extended?**

Materials and Methods

- **Theory Selection.** In total, 50 candidate theories were investigated from the behavioral cognitive psychology body of knowledge with more than 70 theories. Each theory was ranked in accordance with its ability to generate research and consistency. The selected theories are: Protection Motivation Theory, Prospect Theory, General Theory of Crime, Self-Efficacy Theory, Social Norms Theory, Affective Events Theory, Differential Association Theory, Extended Parallel Processing Model, Focus Theory of Normative Conduct, Containment Theory, Theory of Planned Behavior, Social Identity Theory, Goal Setting Theory, Transtheoretical Model of Behaviour Change, Self-Determination Theory, Operant Learning Theory, Social Cognitive Theory, Change Theory, Precaution Adoption Process Approach, Diffusion of Innovations, Control Theory, Risk as Feelings Theory, Social Learning Theory, Norm Activation Theory, and the Technology Acceptance Model. These theories are then mapped into Cybonto (the ontology).

- **Ontology Designing.** Cybonto elected the BFO as its top-level ontology from more than 30 candidates. BFO is the only top-level ontology that adopts materialism, commits to actual-world possibilia, and has an intentional criterion of identity. The Cybonto Core is grounded further by employing Mental Functioning (MF) as its mid-level ontology. MF follows best practices outlined by the OBO Foundry and aligns with other projects in the Cognitive Atlas—a state-of-the-art collaborative knowledge-base in Cognitive Science.

Materialism is the key ontological commitment and what differentiates Cybonto from other behavioral cognitive ontologies. Recent breakthroughs in the brain-machine interface such as those of Neuralink enable measurements of brain activities that correspond to certain cognitive constructs. Therefore, it is now possible to ground behavioral or cognitive ontologies in materialism. Cybonto rejects conceptual objects, different linguistic descriptions of the same actual objects, process-based objects, and object labels that cannot be measured in real life.

- **Analyzing With Network Science.** The metrics are as follows. Top authority centrality constructs receive influence from constructs that have the most influence on others. Top Behavior Controllability (BC) constructs are the ones that sit in the shortest paths among other constructs. BC constructs can serve either as bridges or gatekeepers of other constructs and processes. Top Eigenvector centrality (EC) constructs are the leaders of their cliques. A clique is a group of constructs in which each member has relationships with the others. In the context of the cognitive digital twin, a clique may represent a strong cognitive or behavioral pattern. Not only the top EC constructs are well-connected with their clique members, but they also have relationships with other cliques.

Contribution centrality is EC on inverse-Jaccard weighted values of the input networks. A link between two constructs has the most contribution weight when the neighbors of one end are most different from the neighbors at the other end. Degree centrality has two sub measures—out-degree and in-degree. Top out-degree centrality constructs have the most out-links (influencing) to others while top incoming centrality constructs are influenced by the most important incoming neighbors. The top PageRank constructs have relationships with the most influential neighbors whether it is incoming or outgoing. The main results are in figure 1 and 2.

- **Validity and Reliability Control.** The ontology was reviewed by five reviewers from The Chicago School of Professional Psychology and the Journal of Medical Internet Research. The current Cybonto version should be treated as the "alpha release". The next version of Cybonto will have refined constructs with evidence from the neuroscience domain.

More at https://xmed.jmir.org/2022/2/e33502/#ref53

Results

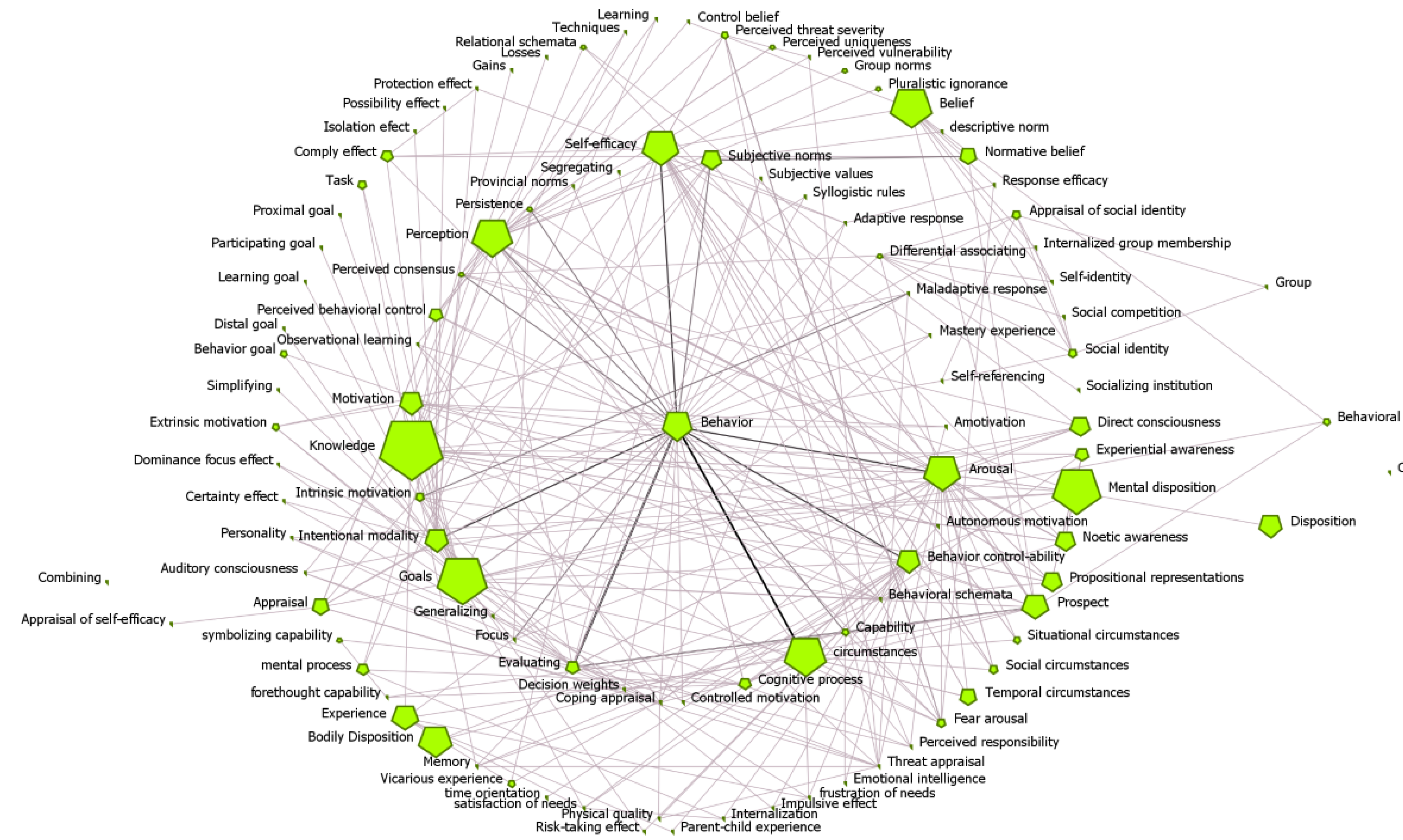


Figure 1. Behavioral Cognitive constructs and their relationships visualized. Constructs are nodes and the relationships are the edges. Each node's size equals the log scale of the node's page rank. A darker edge color indicates a higher relationship counts mentioned among the chosen theories. Nodes were automatically arranged in a multi-circle layout with higher betweenness centrality nodes closer to the center.

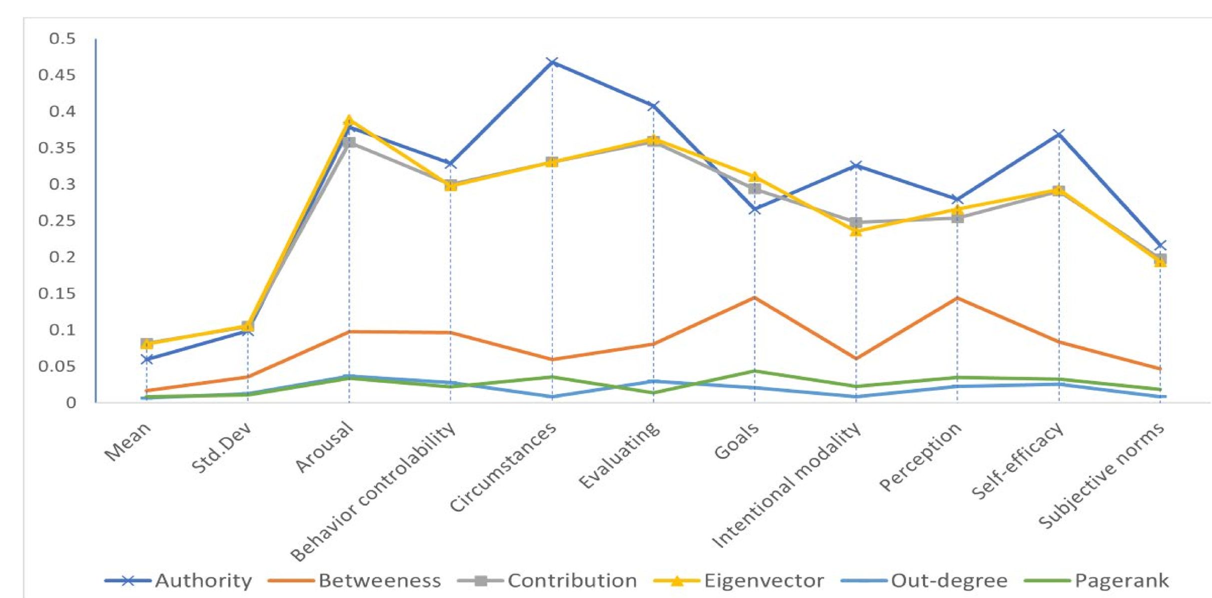


Figure 2. The most influential constructs.

Within cognitive architectures, we may consider implementing Goals, Knowledge, Perception, and Evaluating explicitly with finer granularity. For example, Perception is more than short-lived sensory perception. Alice perceives Bob as a nice guy, and such perception may persist even when Bob is no longer there with Alice. Finer structures mean more nodes in the knowledge graph and may lead to cognitive engine improvements such as more diverse rule firing mechanisms and more explainable information decay. Additionally, influential noncognitive constructs such as Arousal, Intentional Modality, and Circumstance should also be added. Finally, the author recommends a new component—Imagining—to enable HDTs to run their own situational simulations and reason about possible circumstances.

Conclusion

Once massive noncognitive digital twin systems mature, adding human cognitive digital twins will be the only logical next step. A good body of agent-based simulations for public health exists. However, autonomous agents have been designed in specific ways for solving specific problems and are more limited than HDTs. Within the Metaverse, HDTs and DTs can automatically act and interact in much wider sets of situations.

The vision of letting human digital twins "run free" in connected digital twin worlds (the Metaverse) and observing them offers a new paradigm in knowledge mining. For example, HDTs, internet-enabled cars DTs, retail point DTs, socio-political DTs, hospital DTs, and economic DTs that were developed by various organizations can be collectively leveraged within the Metaverse to simulate different possible scenarios relating to certain public health events for making decisions of regional/national impacts. In smaller scales, HDTs can be used for simulating health-related fake-news spreads or creating virtual chat bots for applied psychology training.

While massive DT projects are underway, digital cognitive twin development is pale in comparison, and HDT for public health is underdeveloped. To help with that problem, this work proposes the Cybonto ontology that serves as the foundation for answering the question of how current cognitive systems should be extended for use in HDTs.