VIRTUAL HUMAN-BUILDING INTERACTION EXPERIMENTATION ONTOLOGY (VHBIEO): A VHBIEO-BASED METADATA-DRIVEN EXPLORATION

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ABSTRACT: *Virtual reality (VR) offers promise as a tool for building performance simulations, especially when considering human-building interactions in buildings or spaces still under design. However, the absence of standardized data protocols impedes the consistent sharing of VR-related experiments and findings. This makes advancing VR experimentation as a reliable method for studying human-building dynamics challenging. The authors introduced the Virtual Human-Building Interaction Experimentation Ontology (VHBIEO) to address the challenge. VHBIEO seeks to standardize experimentation details as a domain-specific ontology, enhancing their interoperability. It includes essential experimentation concepts and employs semantic web technologies to ensure machine readability. Moreover, it integrates an application view (APV) to tailor details to specific experiments. Using VHBIEO-based metadata, this paper presents a case study aiming to standardize experiments that validate thermal sensations in immersive virtual environments (IVE), encompassing experimental protocol, variables, design, and data gathering. By exploring the main characteristics of VHBIEO-based metadata, the authors discuss its potential to improve the reliability of human-building interaction research.*

KEYWORDS: *Ontology, Metadata, Human-building interaction, Occupant behavior, Virtual reality, Building*

1. INTRODUCTION

Integrating virtual reality (VR) in studying human-building interactions has brought many novel opportunities to building design (Zhu et al., 2018). However, this integration is not devoid of inherent complexities. Foremost among these is the pressing requirement for rigorous standardization and systematic management of experimentation data. The present practice, characterized by non-standardized experimentation protocols, impedes researchers from optimally utilizing extant results and sharing their empirical findings efficiently. Therefore, advancing the reliability and validity of research within this domain necessitates the commitment to cultivating and adhering to the standardization of main experimentation data.

The Virtual Human-Building Interaction Experimentation Ontology (VHBIEO) was designed to standardize data pertaining to virtual human-building interaction experimentation (Chokwitthaya et al., 2023). It was developed by extending the ontology of scientific experiments (EXPO) at the domain level (Soldatova & King, 2006). The construction of VHBIEO employed the DOGMA methodology, ensuring a detailed and interconnected internal structure (Jarrar & Meersman, 2008). This ontology incorporates terms and concepts from pre-existing ontologies and semantic models and emphasizes terminologies intrinsic to virtual human-building interaction experimentation. Notably, VHBIEO possesses attributes of machine readability, accessibility, and processability. Additionally, its structure integrates Application Views (APVs), facilitating the accommodation of distinct information tailored to specific applications.

VHBIEO-based metadata thus contains the operational and application-specific information associated with VR-based experimentation. The metadata includes specific information about an experiment's components, such as the experimental protocol, design, setting, variables, and data collection procedures. The paper presents a case study showcasing the benefits of using VHBIEO-based metadata in retrieving virtual human-building interaction experimentation data. The case study specifically focuses on validating thermal sensation in an immersive virtual environment (IVE) and demonstrating how VHBIEO-based metadata can effectively capture and represent various elements of the experimental protocol, design, setting, variables, and data collection. The authors discuss how the metadata can improve the reliability of human-building interaction research by highlighting its main characteristics, including its use of the description logic, machine-readable, accessible, and processable, and inclusion of unique information through the application view (APV).

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2. VIRTUAL HUMAN-BUILDING INTERACTION EXPERIMENTATION ONTOLOGY (VHBIEO)

Virtual human-building interaction experimentation (VHBIEO) is an ontology developed specifically for the domain of virtual human-building interaction experimentation. It contributes to enhancing various aspects of the domain. First, it provides standardized information for VR-based experimentation, thus making information more consistent for researchers to share and reuse. Secondly, it allows for the production of machine-readable, accessible, and processable information. Finally, it aims at overcoming challenges caused by the diversity of experimental design and limitations of VR experiments. Therefore, VHBIEO can potentially accelerate the development of virtual human-building interaction experimentation as an emerging research approach. Furthermore, it can enhance collaboration between researchers, making it easier for them to share knowledge and build upon each other's work.

VHBIEO extended EXPO (Soldatova & King, 2006) and reused terms and concepts from spatial-temporal event-driven modeling (STED) (Saeidi et al., 2018), the ontology to represent energy-related occupant behavior in buildings (DNAs) (Hong et al., 2015), ifcOWL ontology (Pauwels & Terkaj, 2019), the semantic sensor network ontology (SSN) (Compton et al., 2012), the survey ontology (SUR) (Scandolari et al., 2021), and the units of measurement ontology (UO) (Gkoutos et al., 2012). The development of VHBIEO followed well-defined ontology development approaches, namely ONTOLOGIES (Uschold & Gruninger, 1996), METHONTOLOGY (Ferndndez et al., 1997), Ontology Development 101 (Noy & McGuinness, 2001), and NeOn (Suárez-Figueroa et al., 2012). It comprised three major steps: initiation, construction, and evaluation. Competency questions (CQs) were used to regulate the development process. A total of fourteen CQs represented four major requirements, which included VHBIEO must 1) provide terms describing aspects regarding virtual human-building interaction experimentation, 2) explicate its internal structure, 3) assist in the inclusion of unique information regarding particular experiments, and 4) promote machine-readable, accessible, and processable data files associated with virtual human-building interaction experimentation. VHBIEO used semantic web technologies to make it machine-readable, accessible, and processable. DOGMA methodology was applied to developing the internal structure of VHBIEO, which involves describing interconnectedness and commitment of terms, using Lexon and organizing groups of Lexons to support specific applications (Jarrar & Meersman, 2008). The commitment involves three groups, namely general, virtual, and in-situ commitments. The scheme of VHBIEO is illustrated in Fig. 1. APVs were established by adopting the concept of Model View Definition (MVD) implemented in Industry Foundation Classes (IFC) for allowing the inclusion of unique information for particular applications (Hietanen, 2006). The resources defined in VHBIEO are publicly available through a URL as https://w3id.org/vhbieo, and individual terms can be accessed using a unique URI as https://w3id.org/vhbieo#term. The ontology editor Protégé was used to support the development of VHBIEO (Musen, 2015).

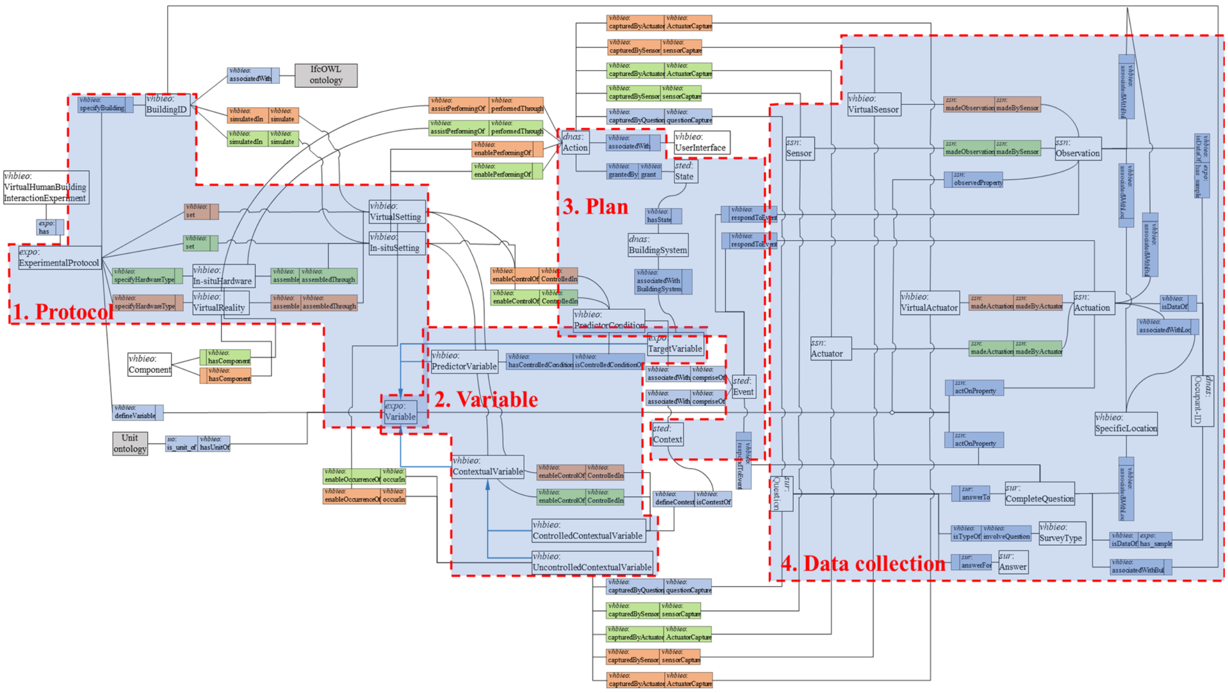

Fig. 1: Scheme of VHBIEO (Chokwitthaya et al., 2023).

The evaluation of VHBIEO was performed, consisting of two parts: taxonomy evaluation and application evaluation. The taxonomy evaluation assessed the logical sequence, the completeness of the ontology, and the redundancy of terms. It ensured that VHBIEO provided a comprehensive and coherent representation of the domain of virtual human-building interaction experimentation. The application evaluation tested the ability of VHBIEO to describe and integrate information from real-world experiments. It also showed that VHBIEO promoted machine readability, accessibility, and processibility by providing several examples of querying information in the data files. VHBIEO was able to incorporate unique information (e.g., 7-point Likert scales) using APV. The evaluation revealed the efficacy of VHBIEO in providing standardized information and enabling machine-readability, accessibility, and processability, which is crucial for promoting consistency and accelerating the maturity of the virtual human-building interaction experimentation approach.

3. CASE STUDY

The case study aims to illustrate data described in VHBIEO-based metadata and prove that the metadata was machine-readable, accessible, and processable through query using a standardized query language (SPARQL). This objective is significant because it ensures the effective utilization and interoperability of the data marked in the metadata. When metadata is machine-readable, accessible, and processable, it can be leveraged to develop sophisticated analyses and applications. The accessibility and processability of the metadata mean that it can be dynamically engaged, enabling researchers and developers to manipulate and interpret the data efficiently, enhancing the comprehensibility and utilization of the information contained within the experimentation.

The case study involves retrieving and analyzing information related to a VR-based experiment performed in an existing study (Rentala et al., 2021). The experiment primarily focused on evaluating the influence of outdoor temperature variations on participants' thermal states within IVE. It was grounded in detailed and methodical experimentation aimed at dissecting the intricacies of thermal states in varying conditions, utilizing various events to simulate diverse environmental settings. The structure of the experimental data reflected the comprehensive nature of the research and the diversity of the variables considered. The variables range from environmental conditions (e.g., indoor and outdoor temperatures and humidity) to participants' physiological (e.g., skin temperatures at various body locations and heart rate) and perceptual responses (e.g., thermal perceptions at different body locations), providing a multidimensional perspective on the impact of outdoor temperature variations on thermal states in IVE experiments. These variables provide a robust and comprehensive dataset that allows for a thorough exploration and understanding of the thermal states of participants under different environmental conditions within IVE. The comprehensive dataset allowed the creation of the VHBIEO-based metadata, exploring all commitments and the majority of Lexons and rules defined in VHBIEO. In addition, the dataset enabled the exploration of APV since the experiment included the use of 7-point Likert scales, which needed customization in VHBIEO.

The metadata was formatted in the Resource Description Framework (RDF) format, which is a standard format for representing ontologies and linked data. It was deployed on the Dataverse, a data repository platform, for testing. It was uploaded as a tabular data file that provided context and description of the data. It included information such as the experiment title, authors, funding sources, and descriptions of the data structure, variables, and observations.

3.1 VHBIEO-based metadata

The structure of VHBIEO-based metadata revolved around four core components of VHBIEO: experimental protocol, variable, plan, and data collection. This section discusses such components and their associated data pieces. The discussion aims to elucidate these components by exemplifying the key data elements pertinent to the experiment, thereby underlining the efficacy of VHBIEO in developing the metadata.

3.1.1 Experimental protocol

The experimental protocol, referred to as the backbone of the experiment, laid down the research's overarching strategy. This information was essential for understanding the core of the experiment. Fig. 2 delves into data intricately associated with the experimental protocol, illustrating several instrumental components, namely the protocol itself, experimental setting, hardware, and building, each playing a role in steering the experiment toward its intended objectives.

Within the detailed protocol (*expo*:ExperimentalProtocol), a holistic introduction and thorough description covering experimental statements, background, hypothesis, and methods sections - including inclusion and exclusion criteria - are encapsulated. Notably, the procedural roadmap for conducting the experiment, study timelines, visits, potential risks, and confidentiality assurances are also placed within this component.

The settings utilized during the experiment are distinctly described using *vhbieo*:VirtualSetting and *vhbieo*:In-situSetting, denoting the use of a fully immersive virtual environment and a climate chamber setting, respectively.

The hardware associated with these settings, integral to the execution of the experiment, is detailed through *vhbieo*:VirtualReality and *vhbieo*:In-situHardware. The critical element of a building, significantly tied to the protocol, is narrated via *vhbieo*:BuildingID. The building elements, representing architectural or design specifics, were meticulously described using the IfcOWL ontology.

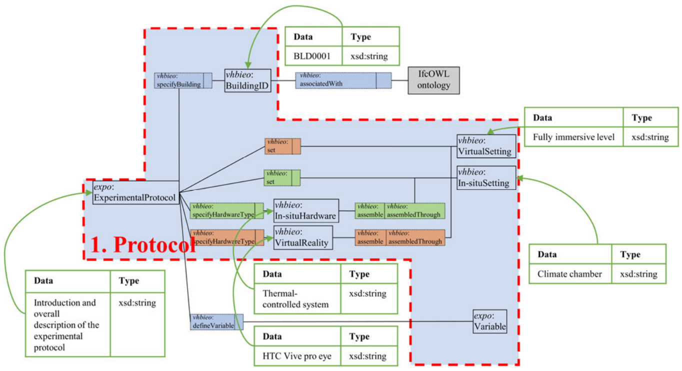

Fig. 2: Example of data associated with protocol.

3.1.2 Variable, plan, and data collection

While the concepts of variable, plan, and data collection are distinct, it is vital to recognize their interconnected nature. Variables define what data is collected, the plan dictates how to navigate and observe through the variables, and data collection strategies depict the methodology for gathering insights on these variables and aligning with the plan. Fig. 3, 4, and 5 exemplify this integrative relationship, offering a consolidated perspective through discrete examples and thereby facilitating a coherent understanding of the experiment's structure and methodology. Noteworthy is that the components spotlighted in each figure represent selective excerpts from the experiment, highlighting particular elements that significantly contribute to the focus of each example. To streamline and succinctly encapsulate the discussion, components not directly pertinent have been judiciously omitted.

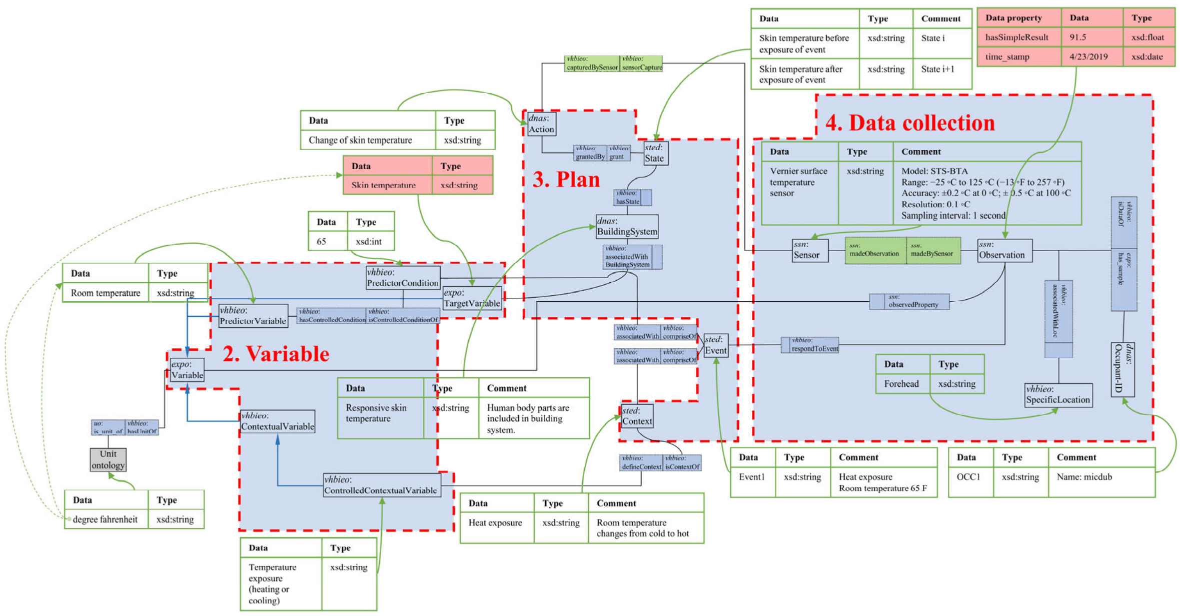

Fig. 3: Example of data associated with skin temperature.

Fig. 3 narrates variable, plan, and data collection components, specifically focusing on the human-skin temperature, particularly at the forehead. This temperature was identified as the target, or the dependent variable (*expo*:TargetVariable), for the experiment. Its measurements were taken in degrees Fahrenheit, referencing the Unit ontology. The predictor or independent variable was set as the room temperature, with a controlled setting fixed at 65 degrees Fahrenheit. This was described under *vhbieo*:PredictorVariable and *vhbieo*:PredictorCondition, respectively. The controlled contextual factor was temperature exposure (*vhbieo*:ControlledContextualVariable).

The temperature exposure outlined the context (*sted*:Context) of heat exposure as a trajectory from a cold to a hot environment. Drawing upon this setting, the predictor condition and context conjoined to devise an event (*sted*:Event) introduced to a participant in the IVE. The human body was conceptually integrated as part of the building. Consequently, the responsive skin temperature was described in the *dnas*:BuildingSystem, linking it directly to the target variable of skin temperature. Invoking the concept of "state" from STED (as elaborated by Saeidi et al., 2018), a state embodies the dynamic status of the building system. It is susceptible to variations stemming from occupants' interactions and responses to the events they are subjected to. As a result, the skin temperature responses manifested in multiple states, including the temperature recordings before and after event exposure (*sted*:State). These recordings translated into the very act of skin temperature alterations encapsulated under *dnas*:Action.

To hone in on data collection specifics, Fig. 3 illustrates using the Vernier surface temperature sensor under *ssn*:Sensor. This sensor was strategically positioned on the forehead described under *vhbieo*:SpecificLocation of the participant, uniquely identified by *dnas*:Occupant-ID. The resulting data was systematically chronicled in *ssn*:Observation. It showed a recorded forehead skin temperature of 91.5 degrees Fahrenheit, timestamped precisely to mark the experiment's execution on 23rd April 2019.

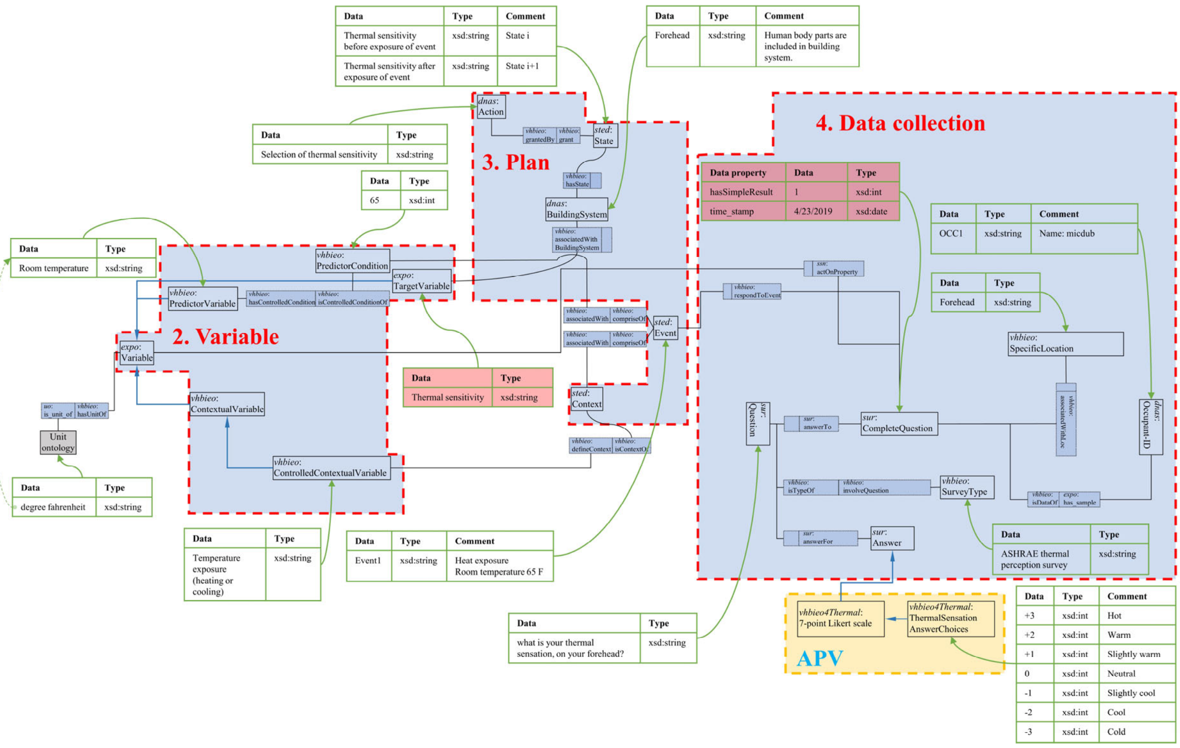

Fig. 4: Example of data associated with thermal sensation.

Fig. 4 provides a detailed examination of the variable, plan, and data collection components with a concentration on thermal sensation—another distinct target variable within the experiment. The structures of the variable and plan components mirrored those elaborated upon in Fig. 3. However, the method of data collection exhibited notable differences.

In the context of thermal sensation, data was accumulated through a survey mechanism, described in *sur*:Question. Significantly, the application view (APV) was utilized to annotate and clarify the 7-point Likert scale, which constituted the unique response choices in the experiment. This scale was referenced as (*vhbieo4Thermal*:ThermalSensationAnswerChoices). The nature of this question aligned with a thermal perception survey, a standard defined and endorsed by ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) and cataloged under (*vhbieo*:SurveyType). The culmination of this survey's execution was preserved under *sur*:CompleteQuestion, which depicted the participant's thermal sensation as being "slightly warm". It was anchored with a timestamp, noting the date of conducting the experiment.

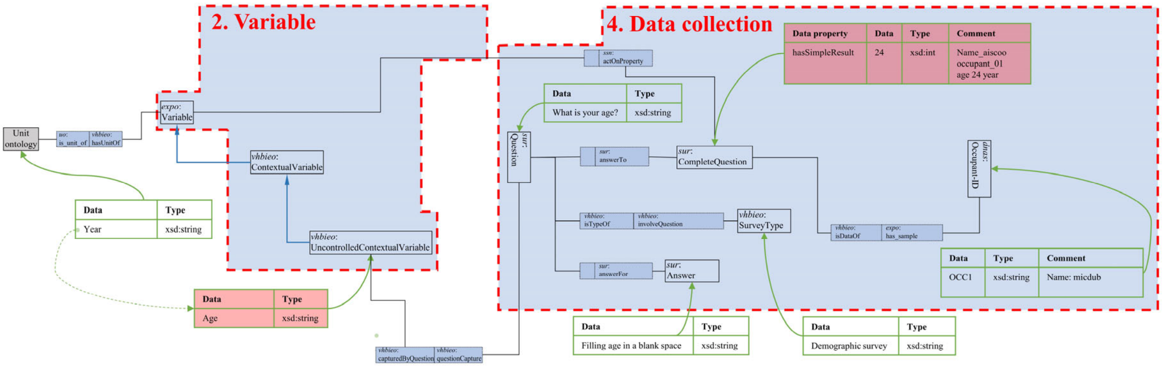

Fig. 5: Example of data associated with age.

Fig. 5 shifts its focus from target variables and delves into an uncontrolled contextual variable encountered in the experiment—specifically, the age (*vhbieo*:UncontrolledContextualVariable) of a participant. The unit used to measure age was "year", which draws reference from the Unit ontology. For data collection pertaining to age, a demographic survey (*vhbieo*:SurveyType) was employed. Participants were prompted with a straightforward question, "What is your age?", which was recorded under *sur*:Question. Responding to this question required participants to fill in a blank space, indicating their age, and this form of response was described in *sur*:Answer. In a manner akin to the thermal sensation data collection, the resultant age data was encapsulated under *sur*:CompleteQuestion. This documented an instance of a participant's age being 24 years old.

3.2 Querying VHBIEO-Based Metadata

The executed data query was instrumental in validating the machine-readability, accessibility, and processability of the metadata. To resonate with the provided examples, the query was formulated to extract specific data points corresponding to variables such as the skin temperature at the forehead, thermal sensation, and age. In conjunction, the computation of averages for each variable within the query further attested to the metadata's machine-processable nature. This ability to programmatically access, read, and compute values from the metadata substantiates its utility and robustness in supporting research and data-driven applications.

Fig. 6 presents the specific queries crafted to extract data pertaining to the skin temperature (Fig. 6a), thermal sensation (Fig. 6b), and age (Fig. 6c) of all participants. These queries are structured to target the data points within the dataset precisely. It also conveys the outcome of the queries. Notably, the result encapsulated the computed averages of the obtained data, underlining the machine-processable nature of the metadata.

For Fig. 6a, the query primarily focuses on obtaining data related to the forehead skin temperature of participants. Such data held significant relevance, as skin temperature could provide insights into a participant's thermoregulation response in a given environment. By furnishing both individual temperature data points and an overall average, the query aided researchers in discerning patterns and anomalies within the data.

The emphasis in Fig. 6b shifts from physiological responses to perceptual experiences. Querying the thermal sensation looked into how participants subjectively felt about the thermal environment they were placed in. The provision of an average sensation value offered a summarised perspective. Such data could be vital in studies aiming to align objective environmental parameters with subjective human comfort levels.

The query in Fig. 6c acknowledges the demographic diversity of the participants. Age is a potential confounding variable in many human studies, as age might influence a person's physiological or perceptual response to environmental factors. Researchers could factor in age-related nuances in their analysis by procuring both individual age data and its average.

In essence, these queries demonstrate the versatility and depth of VHBIEO-based metadata. Furthermore, the structure of each query, particularly the incorporation of averages, emphasizes granularity and summarization, ensuring that the metadata is machine-readable, accessible, and processible.

```
PREFIX expo: <http://www.hozo.jp/owl/EXPOApr19/>
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-systax-ns#>
PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>
PREFIX sosa: <http://www.w3.org/ns/sosa/>
PREFIX vhbieo: <https://w3id.org/vhbieo#>
SELECT ?occupantID ?property ?temperature ?location ?Average_forehead_temperature
    WHERE {
    {
        SELECT (AVG(?Result) AS ?Average_forehead_temperature) ("" AS ?occupantID)
        ("" AS ?property) ("" AS ?temperature) ("" AS ?location) ("" AS ?Result)
        WHERE {
            ?individual a sosa:Observation .
            ?individual ?property_ ?value_ .
            FILTER (?value  = vhbieo:HBL000002)
            ?individual sosa:hasSimpleResult ?Result .
        }
    }
    UNION
    {
        ?occupantID a sosa:Observation .
        ?occupantID ?property_ ?value_ .
        FILTER (?value_ = vhbieo:HBL000002)

        OPTIONAL {?value_ rdfs:comment ?location }
        ?occupantID ?property ?temperature .
        FILTER (?property = sosa:hasSimpleResult)
        BIND("" AS ?Average_forehead_temperature)
    }}
    ORDER BY ASC(?Average_forehead_temperature)
```

OccupantID	Property	Temperature	Location	Average forehead temperature
				91.22
OCC0001	hasSimpleResult	91.57	forehead	
OCC0002	hasSimpleResult	93.00	forehead	
OCC0003	hasSimpleResult	94.38	forehead	
OCC0004	hasSimpleResult	92.80	forehead	
OCC0005	hasSimpleResult	95.84	forehead	
OCC0006	hasSimpleResult	97.11	forehead	
…	…	…	…	

(a) Skin temperature at forehead.

```
PREFIX expo: <http://www.hozo.jp/owl/EXPOApr19/>
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-systax-ns#>
PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>
PREFIX sosa: <http://www.w3.org/ns/sosa/>
PREFIX vhbieo: <https://w3id.org/vhbieo#>
SELECT ?occupantID ?property ?temperature ?location ?Average_forehead_sensation
    WHERE {
    {
        SELECT (AVG(?Result) AS ?Average_forehead_sensation) ("" AS ?occupantID)
        ("" AS ?property) ("" AS ?sensation) ("" AS ?location) ("" AS ?Result)
        WHERE {
            ?individual a sur:CompleteQuestion .
            ?individual ?property_ ?value_ .
            FILTER (?value_ = vhbieo:TAV000006)
            ?individual sosa:hasSimpleResult ?Result .
        }
    }
    UNION
    {
        ?occupantID a sur:CompleteQuestion .
        ?occupantID ?property_ ?value_ .
        FILTER (?value_ = vhbieo:TAV000006)

        OPTIONAL {?value_ rdfs:comment ?location }
        ?occupantID ?property ?sensation .
        FILTER (?property = sosa:hasSimpleResult)
        BIND("" AS ?Average_forehead_sensation)
    }}
    ORDER BY ASC(?Average_forehead_sensation)
```

OccupantID	Property	Thermal sensation	Location	Average forehead thermal sensation
				0.62
OCC0001	hasSimpleResult	-2	forehead	
OCC0002	hasSimpleResult	1	forehead	
OCC0003	hasSimpleResult	0	forehead	
OCC0004	hasSimpleResult	0	forehead	
OCC0005	hasSimpleResult	-1	forehead	
OCC0006	hasSimpleResult	-1	forehead	
…	…	…	…	

(b) Thermal sensation at forehead.

```
PREFIX expo: <http://www.hozo.jp/owl/EXPOApr19/>
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-systax-ns#>
PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>
PREFIX sosa: <http://www.w3.org/ns/sosa/>
PREFIX vhbieo: <https://w3id.org/vhbieo#>
SELECT ?occupantID ?property ?age ?Average_age
    WHERE {
    {
        SELECT (AVG(?Result) AS ?Average_age) ("" AS ?occupantID)
        ("" AS ?property) ("" AS ?age) ("" AS ?Result)
        WHERE {
            ?individual a sur:CompleteQuestion .
            ?individual ?property_ ?value_ .
            FILTER (?value_ = vhbieo:UCV000003)
            ?individual sosa:hasSimpleResult ?Result .
        }
    }
    UNION
    {
        ?occupantID a sur:CompleteQuestion .
        ?occupantID ?property_ ?value_ .
        FILTER (?value_ = vhbieo:UCV000003)
       ?occupantID ?property ?age .
        FILTER (?property = sosa:hasSimpleResult)
        BIND("" AS ?Average_age)
    }}
    ORDER BY ASC(?Average_age)
```

OccupantID	Property	Age	Location	Average age
				25.71
OCC0001	hasSimpleResult	24	forehead	
OCC0002	hasSimpleResult	26	forehead	
OCC0003	hasSimpleResult	21	forehead	
OCC0004	hasSimpleResult	35	forehead	
OCC0005	hasSimpleResult	42	forehead	
OCC0006	hasSimpleResult	32	forehead	
…	…	…	…	

(c) Age of participants.

Fig. 6: Queries and their results.

4. DISCUSSION

The primary objective of this work was to demonstrate the efficacy of the Virtual Human-Building Interaction Experimentation Ontology (VHBIEO) in supporting the development of VHBIEO-based metadata. This metadata aims to create a structured representation of experimental data, promoting machine-readability, accessibility, and processability. Reflecting upon the objective, development of VHBIEO-based metadata, and query results, this section broke down the accomplishments, implications, and broader impact on the research horizon.

Systematic Representation: At its core, VHBIEO is an ontology that aims to systematically represent knowledge in the domain of human-building interaction experiments. The VHBIEO-based metadata took advantage of this structured knowledge representation, ensuring that every aspect of an experiment was adequately documented, from the broader experimental protocol to the minutiae of data collection methodologies.

Data Accessibility and Processability: The design of VHBIEO ensures that data is machine-readable, accessible, and processible. This was evident in the queries we discussed (e.g., Fig. 6), which retrieved data efficiently and could also compute statistics such as averages, showcasing the power and flexibility of this ontology-based metadata.

Facilitating Advanced Analyses: The granularity offered by the VHBIEO-based metadata, segmenting data into categories like skin temperature, thermal sensation, and age, paved the way for more complex and nuanced analyses. Discerning patterns or influences among these variables became relatively straightforward when they were clearly organized.

Overall, VHBIEO provides standardization for virtual human-building interaction experimentation as a robust mechanism for associated experimental data. Such standardization diminishes the scope of ambiguities, ensuring the data remains consistent across different stages and platforms of its utilization. Furthermore, data exchange across diverse platforms and researchers is inevitable. VHBIEO potentially enables researchers to transfer, match, and integrate data from varied sources without the nuances of interpretation. This is akin to creating a seamless bridge where data flows without errors.

5. LIMITATION

Despite the evident advantages and the transformative potential of VHBIEO, certain limitations need to be considered.

Continuous Maintenance and Refinement: A pressing challenge associated with ontologies, VHBIEO being no exception, is their continuous upkeep. Changes in domain knowledge or enhancements in ontology capabilities require periodic revisions. This process demands not just a technological revamp but also the infusion of domain-specific expertise to ensure the ontology stays relevant and accurate.

Potential Overlaps with Existing Ontologies: It is conceivable that some terms introduced in VHBIEO might overlap with those in existing ontologies or semantic models. The authors, in their initial sweep, might not have identified these overlaps. Should such duplications be spotted in the future, VHBIEO will be updated to reflect a more harmonized structure.

Scalability with Evolving VR Technology: Virtual Reality (VR) technologies are in a state of flux, constantly evolving. As VR matures, simulating intricate simulations over prolonged durations might become feasible. In such scenarios, the foundational structure of VHBIEO, anchored on STED, might demand reevaluation and fine-tuning.

Potential Limitations in Collaborative Experiments: As research becomes increasingly collaborative, the experiments often span multiple geographies and phases. This dynamic nature of collaboration, marked by continuous data exchanges and iterative updates, could pose challenges for VHBIEO in its current form. Future iterations of VHBIEO will need to address this aspect to stay relevant in an interconnected research ecosystem.

Lack of Advanced Features in APV: Although the current APV supports unique terminology descriptions tailored for specific experiments, it falls short in several other features. Features such as internal structure customization, automation capabilities, and bridging with other ontologies are crucial for enriching VHBIEO's utility. The integration of these features could significantly expand its scope and application.

6. CONCLUSION

The study showcased the advantages of using VHBIEO in human-building interaction research. By providing a structured approach to document experimental protocol, design, settings, variables, and data collection, VHBIEO-based metadata paves the way for better experiment reusability, comparability, and reproducibility. This is especially crucial for experiments relying on IVE-based experimental information and results. Yet, it is crucial to acknowledge the limitations inherent in this preliminary implementation. Specifically, the research's scope was constrained mainly due to the limited number of validation cases. As the field progresses, it is essential to continually refine VHBIEO by addressing these limitations and validating its utility across a broader array of experimental contexts.

7. ACKNOWLEDGEMENT

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