IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received 26 February 2023, accepted 8 March 2023, date of publication 15 March 2023, date of current version 4 April 2023.

Digital Object Identifier 10.1109/ACCESS.2023.3257573

RESEARCH ARTICLE

Ontological Modeling for Contextual Data Describing Signals Obtained From Electrodermal Activity for Emotion Recognition and Analysis

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This work was supported in part by the Gdańsk University of Technology under the Technetium Talent Management Grants - ''Excellence Initiative-Research University'' under Grant DEC-2/2022/IDUB/III.4.1/Tc.

ABSTRACT Most of the research in the field of emotion recognition is based on datasets that contain data obtained during affective computing experiments. However, each dataset is described by different metadata, stored in various structures and formats. This research can be counted among those whose aim is to provide a structural and semantic pattern for affective computing datasets, which is an important step to solve the problem of data reuse and integration in this domain. In our previous work, the ROAD ontology was introduced. This ontology was designed as a skeleton for expressing contextual data describing time series obtained in various ways from various signals and was focused on common contextual data, independent of specific signals. The aim of the presented research is to provide a carefully curated vocabulary for describing signals obtained from electrodermal activity, a very important subdomain of emotion analysis. We decided to present it as an extension to the ROAD ontology in order to offer means of sharing metadata for datasets in a unified and precise way. To meet this aim, the research methodology was defined, mostly focusing on requirements specification and integration with other existing ontologies. Application of this methodology resulted firstly in sharing the requirements to allow a broader discussion and secondly development of the EDA extension of the ROAD ontology, validated against the MAHNOB-HCI dataset. Both these results are very important with respect to the vast context of the work, i.e. providing an extendable framework for describing affective computing experiments. Introducing the methodology also opens the way for providing new extensions systematically just by executing the steps defined in the methodology.

INDEX TERMS Affective computing, dataset, emotion, ontology, time series, ontology development, conceptualization, signal, EDA, electrodermal activity.

I. INTRODUCTION

The recognition of human emotions by computer systems is finding applications in a growing number of fields [32], such as distance learning [17], [73], healthcare [18], [38], [63], marketing [41], [50] and many others [7], [21]. Depending on the availability of particular channels, recognition methods can use different signals as a source of insight into human emotions. Among the most popular are face and speech recordings and biophysical signals such as EEG (electroencephalography), EDA (electrodermal activity) and ECG (electrocardiography) [74]. Emotions are complex psychophysiological processes that occur largely non-verbally, so multimodal approaches that rely on data from different channels are among the most effective [2].

The associate editor coordinating the review of this manuscript and approving it for publication was Yiming Tang.

Another popular trend in recent years is the use of deep learning methods. In combination with multimodal approaches, this makes it possible to achieve the most accurate results in emotion recognition [2], [4]. However, for deep learning methods to provide reliable results, it is necessary to train them on large amounts of data [47]. Therefore, numerous studies are conducted in the field of Affective Computing to provide datasets that contain signals from different channels. This has resulted in growth in the number of published datasets obtained from experiments related to emotion processing [42], [49], [57] and "in-the-wild" databases [33], [37].

An emerging problem, however, is that combining data from different datasets, developed during different studies, to train deep learning models is difficult, and sometimes impossible. In this respect, the field of Affective Computing suffers from the lack of a systematic approach to describing and storing data for emotion recognition. Applying the categorization of the National Science Board [58], data collections in Affective Computing can be classified to the category Resource of Community Data Collections,[1] i.e. collections of a single scientific community, often setting internal standards.

Still, the state of this category in Affective Computing is immature. Even while there are some standards such as emotional states models and reusable lexicons (e.g. EmotionML [52]) there are no unified formal representations [70] that can represent various aspects of data collections, i.e.: (1) obtained biosignals such as EEG, ECG, EDA and facial expressions; (2) annotated or recognized emotional states represented in various models; and (3) origin and meaning of biosignals and emotional states (further called contextual data).

Our long-term goal is to fill-in this gap and to provide a formal, expandable model for describing affective-related datasets, which allows:

- characterizing their origin and meaning,
- unifying terms in the field,
- creating extensions for defining various aspects of data obtained within the experiments.

In our previous work [75], we introduced the Recording Ontology for Affective-related Datasets (ROAD) which constitutes the foundation of such representation because the ROAD ontology is not application-oriented, unifies terms in the field and is expandable to allow the definition of various aspects of data obtained within the experiments. The ROAD ontology is multichannel and multimodal and, by default, it implements the origin aspects common to various types of signals. By design, the ability to represent metadata characteristic for specific signals (in other words mulitimodal and multichannel approach) is achieved via extensions.

[1]The other two categories are Research Data Collections (data from one or more research projects, typically containing data that can only be processed to a limited extent) and Reference Data Collections (datasets used by numerous scientific community groups, introducing well-established, comprehensive standards).

The presented research is focused on creating a carefully curated vocabulary for describing signals (including their meaning and origin) obtained from electrodermal activity (EDA) as an extension of the ROAD ontology. The extension is needed because in the ROAD ontology there are no unified notions and structures related directly to specific signals.

While in the first version of ROAD ontology it is possible to describe EDA-specific information with extensions, we decided that proper description of that important sub-domain requires more in-depth ontology development. To illustrate the problem the following example is discussed. In the first version of the ROAD ontology there is the notion of *Measure* (name of class) allowing to define values capable of conveying information about emotions. It means that the user can define e.g. the measure *conductance* (instance of the *Measure* class) - however, still this measure is not unified. As a consequence, the other user can define semantically the same measure, but name it *electrical conductance*, which may lead to misunderstanding. The extension presented in the paper unifies notions and structures for EDA signals and e.g. solves the presented problem by defining the galvanic skin response electrical conductance measure in a unified way, allowing use of this measure by all the users of the ROAD ontology. To sum up, the presented extension unifies the notions and structures, characteristic for EDA signals as well as other notions and structures which are often used with EDA signals, and which were not defined or were not defined in sufficient detail in the first version of the ROAD ontology. By analogy we can treat ROAD as a general purpose dictionary (affective computing) and this extension as a domain specific dictionary (EDA). Now, to undoubtedly describe terms from the EDA scope, one should use the specific dictionary (with EDA specific terms) and not just the general one.

EDA refers to the variation of the electrical characteristics of the skin due to perspiration or sweat gland activity [68]. The EDA channel was chosen, as a first extension for ROAD because:

- there is a substantial increase in the usability and accessibility of devices that measure EDA [3], [65], [67], [68];
- wearable technologies provide more opportunities to measure EDA in real-world settings [16], [39], [43];
- it is one of the most commonly used methods to measure physiological arousal [18], [44], [51].

The main objectives of our work are to firstly identify the contextual data describing signals obtained from EDA devices and secondly to provide a formal model expanding the ROAD ontology with these data.

To achieve this goal, the research methodology described in Section II was applied. The subsequent sections (III-VI) of the paper correspond to the methodology steps (gathering requirements, analysis of existing ontologies, ROAD ontology extension, evaluation). Additionally, Section VII summarizes the paper.

It is worth noting that there is no Related Work section, which is commonly introduced in scientific papers. The reason is that to the best of our knowledge there was no such holistic attempt to create a vocabulary for metadata used to describe datasets coming from EDA-related experiments. However, naturally, there exists a large corpus of work providing knowledge about terms and methods used for acquiring EDA data in addition to existing ontologies (being also and de facto the related work for the presented research) and its analysis is a part of the methodology and an integral part of it.

II. METHODOLOGY

The main source of the requirements was a literature study. The coverage of the requirements governed within this study with practical solutions were also checked by analyzing existing datasets. In the last step, the requirements were validated and sometimes extended by experts.

The performed *literature study* allowed us to firstly identify the requirements for contextual data describing signals obtained from electrodermal activity and identify the set of ontologies possible to reuse using imports or by providing design clues. *Analysis of three existing datasets* (MAHNOB-HCI [59], DEAP [31] and the newer CASE dataset [54]) allowed us to verify and expand the requirements identified within the literature study. All of the research authors are actively involved in other Affective Computing projects, focusing mainly on emotion recognition and integration of emotional states obtained from various channels and algorithms. Moreover, additional knowledge was collected from other Affective Computing researchers in the form of unstructured interviews (*Background knowledge of the experts*).

A. ROAD ONTOLOGY

Ontologies are formal systems of concepts that can be used to describe numerous domains of interest [24], such as medicine and health care [45], [61]. They have become popular as tools for defining shared conceptualizations for complex problems. Logical languages, such as Web Ontology Language (OWL) [40], can be used to express ontologies and permit formulation of axioms that can define complex interrelationships between concepts. Domain ontologies describe vocabularies that are limited to a generic domain, such as medicine or automobiles [25], and are distinct from top-level and application ontologies. Top-level ontologies describe very general terms, and application ontologies depend not only on a particular domain but also a specific task.

In OWL, ontologies subsist of objects (individuals), data type properties or roles (also called object properties and understood as binary relations between objects), and classes (concepts), wherein objects can be instances of classes. Domain ontologies tend to aim attention at the definition of properties, classes and the interrelationships among them delineated through axioms – this aspect of an ontology is known as a terminology or a TBox. Domain ontologies can be extended for specific applications via the introduction of objects and their properties – this aspect of an ontology is called an ABox.

According to the assumption of this research, the presented ontology is an EDA extension of the ROAD ontology. In ROAD, the *Experiment* concept denotes the set of experiments understood as a list of activities performed by the participants to gather various biosignals and emotional states for the purpose of emotion recognition. The list of activities performed by the participant is understood as an experiment scenario, i.e. the instances of *ActivityExecution* concepts arranged in a specific order. Execution of each activity can be recorded in various ways, which is modeled as an instance of *RegisteredData*. With each registered data, the set of instances of *RegisteredChannel*, representing the channels that are recorded for the specified registered data, are associated. The *Channel* is a medium for registration of a signal holding information on observable symptoms or recognized emotional states. There are two concepts – *Participant* and *ParticipantState* – describing a participant; one to model time-independent features and one for time-dependent features. The *Recording* concept is introduced to model the fact that the *Participation* of the participant within the activities is recorded in the specified channel of registered data. The *ActivityExecution* concept denotes activities performed by the participant or participants, and the *Activity* concept is introduced to allow activity patterns to be defined independent of the participants. The *TimeSeries* concept represents a single time series, which is obtained from one or more *ObservableInformation*.

B. ANALYSIS OF EXISTING ONTOLOGIES

The integral part of the methodology is to analyze the existing ontologies to identify concepts valid to reuse within the extension of the ROAD ontology. It was achieved by executing several tasks.

Requirements analysis – based on the definition of the requirements and expert knowledge of the researchers. In this step the decision about which requirements should be incorporated was made.

Requirements coverage by the ROAD ontology – was done by analyzing, which identified requirements are fulfilled by the current version of ROAD.

Identification of ontologies that meet the requirements not covered by the ROAD ontology – was done via a literature study and using the expert knowledge.

Requirements analysis versus identified ontologies – was done based on a requirements analysis for each identified ontology. This task was ended with a decision on if, and in what way to incorporate the identified ontologies into the ROAD extension.

C. ROAD ONTOLOGY EXTENSION

Development of the ROAD ontology extension is based mainly as an integration process. It is done by requirements implementation according to the adopted strategy of integration with the identified ontologies. First, the domain is defined, second, the domain is implemented and last the use of the ontology is facilitated.

D. EVALUATION

The evaluation of the ROAD ontology extension for contextual data describing EDA signals was done by implementing an excerpt of the MAHNOB-HCI dataset as instances of the EDA ROAD extension. The excerpt concerning the aspects identified within the requirements specification phase was developed.

III. GATHERING REQUIREMENTS

The process of gathering requirements consists of two steps. In the first step, the knowledge is captured (Section III-A), and in the second step, the requirements are formulated (Section III-B).

A. SPECIFYING REQUIREMENTS

The requirements were specified in three steps according to the defined methodology.

1) LITERATURE STUDY

A systematic literature review of the existing studies regarding EDA signal processing was conducted in order to collect a comprehensive list of metadata that must be included in the ontological models.

The literature study was performed on the Web of Science, IEEE Xplore and Scopus databases. The search was restricted to review papers written in English and published no earlier than in 2019. Additionally, snowballing was applied to key studies.

The search strings for the databases were constructed based on the two main areas of interest: EDA and emotion classification. The latter was expanded to include adjacent concepts such as emotion detection or recognition, resulting in the following search string: "emotion detection OR emotion classification OR emotion recognition." A second search string was constructed based on all known synonyms for electrodermal activity and the corresponding acronyms but excluding concepts such as energy decomposition analysis which shared a common acronym: "galvanic skin response OR gsr OR electrodermal activity OR (eda AND NOT energy decomposition analysis) OR electrodermal response OR edr OR psychogalvanic reflex OR pgr OR skin conductance response OR sympathetic skin response OR ssr OR skin conductance level OR scl." The two search string segments were combined using the AND boolean operator to form the search string used in the three identified databases. The restrictions regarding date of publication and type of study were applied during the search using tools provided by the three databases. The database search yielded 22 studies. Additionally, 18 studies were found as a result of snowballing, bringing the total to 40. The database search was limited to reviews, but snowballing also included individual studies. Eligibility was assessed based on the papers' subjects and reporting of methodology.

The search identified three primary review papers, each focusing on a different aspect of the use of electrodermal activity – the extraction and selection of features for emotion recognition [56], the innovations in collection and processing of the signal [43] and the use of EDA signals in consumer research [11]. Additionally, a review of emotion detection methods with the use of EDA in learning contexts [29] was later identified as a result of a separate, non-systematic search. Despite the limited domain, it yielded significant insight into the commonly used EDA signal processing and features.

Several necessary preconditions for the ontological model were identified during the literature review. All laboratory tests relating to emotion recognition use stimuli as a means of eliciting specific emotional states in the observer. Said stimuli can be visual, aural, both, or involve performing specific tasks. Similarly, resting periods and baseline recordings can also involve specific activities such as breathing exercises [62]. Most of the studies separated the experiments into an initial resting period followed by a sequence of different stimuli [9], however, there was a not-insignificant amount of studies that conducted resting periods and stimuli interchangeably [31].

Additionally, studies related to emotions expressed in ambulatory settings such as learning contexts used interactive tasks to elicit a response, varying from programming tasks [5], [20], [55] to virtual reality scenarios [6], [12].

2) ANALYSIS OF EXISTING DATASETS

All three databases – MAHNOB-HCI, DEAP and CASE – contain signals obtained from EDA devices and the contextual data regarding the method of obtaining these signals.

MAHNOB-HCI [59] is a multimodal database recorded in an emotion elicitation experiment whose goal was emotion recognition and implicit tagging research. Thirty participants were observed within the sessions, which included playing a neutral clip, playing an emotional clip (taken from the Hollywood Human Actions Database), and performing a self-assessment. The participants were young, healthy, adult volunteers, 17 female and 13 male, and their ages varied between 19 and 40 years old. For each participant, gender, ethnicity, nationality and such features as having glasses, beard, or moustache were collected. During the sessions, the stimuli videos were shown to the participants. 20 videos were selected to be shown, which were between 34.9 and 117 seconds long. The emotions assigned to the videos were disgust, amusement, joy, fear, sadness and neutral. A Biosemi active II system was used for signal acquisition. The electrodes were active and positioned on the distal phalanges of the middle and index fingers. GSR (Galvanic Skin Response) was recorded at a 1,024 Hz sampling rate and later downsampled to 256 Hz to reduce the memory and processing costs. The obtained measure was resistance, which was expressed in Ohms.

DEAP [31] is a multimodal dataset whose goal was the analysis of human affective states. It contains the record of an experiment in which 32 healthy participants (50% female; 50% male) took part, aged between 19 and 37. Before the proper experiments, various information about the participants was collected, which were categorized into general information about the person (such as age, gender, handedness, etc.) and state-dependent information (e.g. hours of sleep last night). The experiment started with a baseline recording of physiological data. The participants were asked to relax during this period. Then 40 music videos were presented in 40 trials, each consisting of several steps, such as displaying the current trial number, the display of the music video itself, and self-assessment of the arousal, valence, liking and dominance. Each music video was assigned to one of the four quadrants of the valence-arousal space (LALV, HALV, LAHV, HAHV). The hardware and software configuration was comprised of a PC for presenting stimuli, a recording PC paired with a Biosemi ActiveTwo system, the presentation software by Neurobehavioral systems, the 17-inch screen (1280 CfB- 1024, 60 Hz) the music videos were presented on (at 800 CfB- 600 resolution, in order to minimize eye movements), and stereo Philips speakers. The subjects were seated approximately 1 meter from the screen. All of the physiological responses were recorded (among them GSR) at a 512 Hz sampling rate and later down-sampled to 256Hz to reduce the processing time. GSR provided a measure of the resistance of the skin through two electrodes positioned on the distal phalanges of the middle and index fingers.

CASE [54] is a dataset of continuous affect annotations and physiological signals for emotion analysis. Thirty volunteers (15 males and 15 females, aged 22–37 years) took part in the data collection experiment, and their cultural backgrounds varied. The goal of the experiment was to elicit amusing, boring, relaxing and scary emotional states through video stimulation. A set of videos was selected for presentation, each participant was presented a sequence of them with the order different for every participant. After each video, a two-minute-long blue screen was presented (to isolate the emotional response). The configuration of the experiment was comprised of a 42'' flat-panel monitor (open-source VLC media player was used for video-playback) before which the participants were seated, and one SA9309M GSR sensor (Thought Technology) placed on the index and ring fingers of the non-dominant hand measuring the electrical conductance in microsiemens.

3) BACKGROUND KNOWLEDGE OF THE EXPERTS

The gathered knowledge was extended by expert knowledge mainly with respect to the authors' experience while conducting affect-related experiments and experience with datasets other than those chosen for this analysis.

B. REQUIREMENTS DEFINITION

The requirements were categorized according to the types of identified metadata:

- **Participant definition** – requirements connected with features of the participants,
- **Course of the session** – requirements that make it possible to define the activities carried out during the session and their sequence,
- **Source of the signal** – requirements for device setup,
- **Type of the signal** – requirements for measurements obtained from devices,
- **Stimulus** – requirements that make it possible to define the stimulus and the method of achieving the baseline.

A detailed description of the requirements and their sources is also included in Tables 1 - 3.

IV. ANALYSIS OF EXISTING ONTOLOGIES

The analysis of the existing ontologies was divided into four stages, corresponding to the following sections.

A. REQUIREMENTS ANALYSIS

In the case of our modified approach, requirements specification was a separate task, to a certain extent independent from the rest of the process of extending the ROAD ontology. We wanted the list of requirements to be an artifact presenting its own value. Consequently, the search for requirements was relatively broad, as we did not want to artificially narrow the list.

Nothing precludes the list from being adapted to specific needs, however, and this was also the case for the ROAD expansion. As a preliminary step to the proper ontology engineering tasks, we performed an analysis of the requirements, consisting primarily in their selection and adjustments to the scope assumed for the extended version of ROAD, and motivated by time and resource constraints.

Three requirements were limited in some way. Firstly, only commonly used participant features were chosen for unification (PART_1 and PART_2). The list of state-independent features was limited to date of birth, sex, ethnicity, nationality and handedness, as the others are defined only in one dataset, often only in DEAP, which is the multimodal dataset – the richest in this type of metadata. The list of state-independent features was limited to age, appearance and personality for the same reason. Also, designing a new personality model (OCEAN) was abandoned to not widen the range of the ROAD extensions not directly connected with EDA signals. The next limited requirement embraces the methods of modeling a specific kind of stimuli, which was intended to distract or distress participants of experiments. In this research, only continuous stimulus was designed i.e. the stimulus which lasts for the whole activity and is not treated as a sequence of events appearing at specific points in time while carrying out the activity. This decision was made as, to the best of our knowledge, most of the available affective datasets incorporate just this kind of stimulus.

As mentioned in the description of the methodology, we wanted the process of expanding ROAD to be based on adapting existing specifications of related domains to the

TABLE 1. Requirements for the participant definition and the course of the session.

ID	Name	Description	Source
Participant definition			
PART_1	State-independent participant features	Participants have features that do not change over time. These features are called state-independent, are constant for each experiment in which the participant took part and are constant for each session within the same experiment. The list of identified state-independent features is as follows: date of birth, sex, ethnicity, nationality, handedness, mother tongue, Nasion-Inion distance, head circumference and left-right jaw hinge distance	[59], [31], [54], [64], [46]
PART_2	State-dependant participant features	Participants have features that can change over time. These features are called state-dependant and may vary across experiments in which the participant took part, and may even vary between sessions within the same experiment. The list of used state-dependent features is as follows: age, appearance, personality (in PANAS and OCEAN models), attention/neurological/psychiatric syndromes, hours of sleep last night, vision, vision aid, education, alcohol consumption, coffee consumption, black/green tea consumption, tobacco consumption, other drug/medication consumption and level of alertness.	[31], [14], [64]
Course of the session			
SESS_1	Activity definition	It is possible to define the activity and its performance understood as a performance of this activity at a specific point in time (e.g. watching a specific movie is an activity but a particular person watching it at a particular point in time is understood as its performance).	[14], [59]
SESS_2	Sequence of activities	The activities can be performed in a particular order that is common for all participants or different for each of them.	[14], [59]
SESS_3	Subactivities	An activity can be defined as part of another activity. The typical situation is that the activity consists of the action itself and the tagging process.	[59]

TABLE 2. Requirements for the source and type of the signal.

ID	Name	Description	Source
Source of the signal			
SOUR_1	Used device	It is possible to indicate the device from the most frequently used devices used in recent research, and to define a new one. The alphabetical list of recently used devices is as follows: BioNomadix, Biopac, BioSemi Active 2, BodyMedia Core, Empatica 4, Empatica E3, Empatica E4, MIT sensor, ProComp Infiniti, Q-Sensors 2.0, and Shimmer3 GSR+ Moreover, it is also possible to define a device as custom-made.	[29]
SOUR_2	Sampling rate	It is possible to express the sampling rate in Hertz.	[29]
SOUR_3	Exosomatic or endosomatic measurement method	It is possible to define two types of measurement methods *exosomatic* and *endosomatic*. In the exosomatic method, a constant, external current or voltage source is applied via electrodes on the skin. Exosomatic devices measure the modulated current or voltage, depending on whether the constant source is the voltage (most typical) or current, to compute the skin conductance using Ohm's law. The endosomatic measurement method makes it possible to obtain a voltage without an external source of electricity. The voltage between an active site and a reference electrode at a relatively inactive site is collected. Different measurement methods result in different types of signals that fall under the umbrella of electrodermal activity. For the exosomatic method, these are Skin Resistance Response (SRR), Galvanic Skin Response (GSR) and Skin Conductance Response (SCR). For the endosomatic method, these are Skin Potential Response (SPR), Galvanic Skin Potential (GSP) and Skin Potential Level (SPL).	[1], [10], [29]
SOUR_4	Direct/alternating current for exosomatic measurement method	Direct or alternating current can be applied for the exosomatic methods. Although AC-source devices are highly recommended over DC-source devices, both types of EDA devices are widely used and must be possible to define.	[43], [36]
SOUR_5	Material from which the electrodes are made	Electrodes can be made of silver-silver chloride (Ag/AgCl), stainless steel or carbon.	[10]
SOUR_6	Dry/wet electrodes	Wet electrodes, in contrast to the dry ones, are placed using a gel or paste with a chloride salt. The other name for a wet electrode is a hydrogel electrode.	
SOUR_7	Placement of the electrodes	It is possible to define the placement of each electrode used (including the reference electrode). The possible values are the wrists, soles, hands and fingers. Other placement locations should also be possible to define. It should be possible to define on which wrist, hand, sole or finger the electrode is placed as well as in some cases in which part of the specific body part (e.g. where on the hand).	[29]
Type of the signal			
SIGN_1	Name of the measure	The five measures *electrical conductance*, *resistance*, *impedance*, *admittance*, and *potential* should be possible to define. [23] Electrical conductance shows how easily electricity flows through electrical components for a given voltage difference [13]. Resistance is a measure of the opposition to current flow in an electrical circuit [13]. Potential is the voltage between an active site and an electrode at a relatively inactive site. Impedance is the analogous measure of resistance to an alternating current measuring the total opposition to current flow. Similarly, admittance is the analogous measure to conductance and the reciprocal of impedance [66].	[1].
SIGN_2	Unit measure of the signal	It is possible to define in what unit the measure is given. For electrical conductance, these can be siemens with any possible prefixes and mho [13]. For resistance, it can be Ohms also with any possible prefixes [13]. For potential, these are volts with prefixes [13].	[23]

TABLE 3. Requirements for stimulus.

ID	Name	Description	Source
Stimulus			
STIM_1	Definition	It is possible to define a stimulus, both as multimedia and as other factors e.g. triggering the malicious behavior of IDE [72]	[72]
STIM_2	Assignment to the emotional state	It is possible to assign the specific emotional state to the stimulus. The emotional state may express more than one emotion and moreover it can be expressed in various models. In particular, it must be possible to assign the stimulus to one of Ekman's emotions and to the specific quadrant in the valence-arousal model.	[59], [31], [54], [14]
STIM_3	Method of presentation	A stimulus that is defined as multimedia must be presented using a specific device or devices.	[31, 14]
STIM_4	Baseline activity	It is possible to define the activity done to achieve baseline (the natural emotional state). The typical activities to achieve baseline are watching video, learning session, different tasks, resting time and breathing exercises. Also, it is possible to express no specific activities.	[29]
STIM_5	Baseline length	It is possible to define the length of the baseline.	[29]
STIM_6	Stimulus and baseline sequence	It is possible to define various sequences consisting of stimulus and baseline in a specific order.	[59, 31, 14]
STIM_7	Stimulus metadata	The basic metadata describing the stimulus can be expressed and it is possible to define user-metadata not previously defined. The list of base metadata is identified in Table 4.	[14, 31, 59, 54]

TABLE 4. Basic stimulus metadata.

Name of stimulus metadata	Description	Source
Source	Source of the selected stimuli material, such as the original full feature film in the case of movie snippets as stimuli material	[14, 31, 59, 54]
Source dataset	Information about the source dataset in the case that the stimuli material was sourced from an existing dataset	[14]
Filename	Name of the file used as stimuli material	[14, 59]
Resolution	Used only for visual stimuli. Width and height in pixels.	[59]
Frame rate	Used only for video stimuli. Frame rate of the displayed material.	[59]
Link	Link to stimuli material available in an online repository	[31, 54]
Source link	Link to additional information about the source of the stimuli material	[54]
Clip start timestamp	Starting timestamp of the clip used as stimuli when it is a fragment of the original source material.	[31, 54, 59]
Clip end timestamp	Ending timestamp of the clip used as stimuli when it is a fragment of the original source material.	[54, 59]
Duration	Duration of stimuli.	[14, 54]

particulars of describing affective computing experiments. This was the reason why we put much more stress on integration with existing ontologies, and from the step of requirements analysis proceeded directly to identifying the areas not covered by the original ROAD and then to searching for specifications that could fill these gaps, while assessing their potential usefulness for the task.

B. REQUIREMENTS COVERAGE BY THE ROAD ONTOLOGY

Coverage of the requirements by the ROAD ontology was performed by analyzing the requirements one-by-one with respect to the ROAD ontology. The results of this analysis are shown in Table 5.

This analyses led to the following observations:

- new, unified state-independent features of participants should be introduced,
- a method of building a hierarchy of activities is necessary,
- there is a need for a solution to provide a unified method of expressing the source of the signal,
- stimulus and its features should be introduced,
- the measures expressing quantities for EDA signals are to be unified.

C. IDENTIFICATION OF ONTOLOGIES THAT MEET THE REQUIREMENTS NOT COVERED BY THE ROAD ONTOLOGY

The identification of ontologies took the form of an unstructured search across specific areas of interest not covered by ROAD – stimuli description as well as the sources and types of signals.

In regard to stimuli description, the initial search was aimed at all ontologies for event notation and later narrowed to focus on stimuli notation specifically. As a result of this search, the STIMONT upper core ontology was identified. STIMONT is an extension of the W3C EmotionML format, meant to describe and integrate the emotion and context of a multimedia stimulus. STIMONT facilitates the storage of stimuli in emotionally-annotated databases, and does so in a machine and human-processable way. It allows for differentiation of stimuli with similar emotion content based on high-level semantics – the contents of the multimedia stimulus in question. Stimulus is defined here as any combination of emotion, semantics, physiological response and contextual

TABLE 5. Requirements coverage by the ROAD ontology.

ID	Coverage by ROAD
Participant definition	
PART_1	In the ROAD ontology, there is a *Participant* concept, for which the datatype properties make it possible to define the date of birth and disorder. Additionally, using an object property it is possible to define the sex of the participant. The Participant concept is a subclass of *PropertyConcept*. This construction makes it possible to define additional state-independent features. However, this solution does not allow for the unification of these features. The list of commonly used state-independent participant features includes nationality, race and handedness which are not unified in the current version of ROAD thus the list of datatype and object properties for the Participant concept should be expanded by these commonly used features.
PART_2	In the ROAD ontology, there is a *ParticipantState* concept. More than one instance of the *ParticipantState* concept can be defined for the same instance of the *Participant* concept. Additionally, for an instance of the *ParticipantState* concept, the appearance (expressed as an instance of the *Appearance* concept) and personality (expressed as an instance of the *Personality* concept) can be defined. Analogically as for the *Participant* concept, the *ParticipantState* concept is a subclass of *PropertyConcept*, which makes it possible to define additional state-dependent features. No new state-dependent features were identified which should be unified in the ROAD ontology. The list of datatype and object properties for the *ParticipantState* concept may be expanded by other commonly used state-dependent features of participants.
Course of the session	
SESS_1	In the ROAD ontology, there are two concepts: *Activity*, which makes it possible to define the pattern of the activity, and *ActivityExecution* which is a specific execution of an activity by specific participant(s) at a specific point in time.
SESS_2	The sequence of activities in the ROAD ontology is defined as a sequence of activity executions. It is connected with the semantics of the *Activity* and *ActivityExecution* concepts. There is no possibility, in the current version of ROAD, to define the sequence of activities understood as a pattern of a scenario.
SESS_3	There is no possibility to define an activity in the ROAD ontology as a part of another activity.
Source of the signal	
SOUR_1 SOUR_2 SOUR_3 SOUR_4 SOUR_5 SOUR_6 SOUR_7	The ROAD ontology does not unify any of these metadata. Optionally, all of these metadata can be defined as not unified properties of a *Recording*
Type of the signal	
SIGN_1 SIGN_2	The ROAD ontology provides the solution to introduce measures i.e. measure name extension point. There is no measure name extension that can express quantities generated by EDA signals.
Stimulus	
STIM_1	There is no possibility to define the stimulus in the ROAD ontology.
STIM_2	There is no possibility to assign stimulus to the specific emotional state. There is a solution that makes it possible to express various emotional states, especially the neutral state, basic Ekman's emotions and emotions represented in the PAD model. However, the current version of the PAD model cannot express quadrants.
STIM_3 STIM_4 STIM_5 STIM_6 STIM_7	The ROAD ontology does not unify any of these metadata. Still, there is a possibility to define such features in the form of key-value pairs for the activity. It is achieved by inheritance from *PropertyConcept*.

data – at least one of these components must be specified to consider the stimulus annotated.

The knowledge base of STIMONT consists of two main components – the terminological component and the assertional component. The terminological component is defined by the foundation ontology and contains the representation of the knowledge in stimuli content. The assertional component constitutes the information extracted from analysis of the stimuli as a formal set of assertions describing specific semantics or emotion in terms of the terminological knowledge. The process of extracting the semantic knowledge from the audio-visual stimuli is itself considered as a black box from the point of view of STIMONT.

While STIMONT provides for a good definition of stimuli, it does not by itself allow for annotation of sequences of stimuli. An extension of STIMONT exists that addresses specifically this problem – StimSeqOnt [27]. However, annotation of stimuli as event sequences has been excluded from the requirement definition so StimSeqOnt was not used. Nonetheless, it should be acknowledged as a possible extension of the ontology.

For the area concerning sources and types of signals, we decided to rely on the experts' knowledge, who directed us to the *SSN/SOSA* ontology [53]. The ontology has the status of a W3C recommendation, which places it very high in the hierarchy of adaptability, as many W3C recommendations are treated as *de facto* standards in their respective domains. The scope of the ontology covers devices, sensors, their stimulation and actuations, which is very well suited for the area covered by our requirements.

To additionally verify if the ontology is in fact being adapted by practitioners, we performed an additional research experiment. For the research, we used the LOV ontology repository [69]. The repository collects ontologies prepared for various goals and gives its users the ability to perform a structured search based on the ontologies' metadata (through SPARQL [60] queries).

In our search, we constrained ourselves to ontologies registered in 2018 and later. From among those, we selected the ones referring to sensors or other types of devices. The results strongly supported the opinion of the experts, as among those finally selected, a large majority (75%) imported one of the *SSN/SOSA* ontologies, with only one importing SAREF [15] (a prominent ontology of devices and sensors, also mentioned by our experts as a potential second choice), and a single one not importing anything. The results of the experiments ultimately convinced us to choose SOSA/SSN for further processing.

SSN/SOSA are in fact a pair of ontologies that provide means of describing sensors and their observations in a way that is aligned with W3C Semantic Web technologies. The names of the ontologies are decoded as Semantic Sensor Network (SSN) and Sensor, Observation, Sample, and Actuator (SOSA).

Sensor, Observation, Sample, and Actuator (SOSA) is the lightweight core of the pair. It implements a design pattern of the same name (being, in turn, an extension of the more primal Stimulus-Sensor-Observation pattern), in which the main concepts are represented by subsequent letters of the acronym. *Sensors* are devices, agents, or pieces of software that respond to stimuli and make *Observations* on *Samples*. Devices can also influence the state of the world, and those capable of doing that are called *Actuators*. SSN augments this pattern by more advanced descriptions of stimuli, hardware platforms and systems.

D. REQUIREMENTS ANALYSIS VERSUS IDENTIFIED ONTOLOGIES

The STIMONT ontology is designed as a tool for describing affective-related stimuli. Their usefulness is presented in a document retrieval experiment, which fits the assumptions of the presented research. The large compatibility of the STIMONT ontology with the requirements is seen in Table 7.

SSN/SOSA are ontologies that come from a domain not related to human emotions, and as such they do not adequately cover the requirements involving stimuli. Also, concepts such as activity planning, are only covered by these ontologies to a very small degree. Where SSN/SOSA excel is the area of describing devices and their configuration, which is reflected in Table 6.

The choice of the ontologies had to be augmented with the choice of a proper strategy of integrating them with ROAD and its EDA extension. This choice was heavily influenced by the coverage of requirements by the chosen ontologies.

In the case of STIMONT, we made the decision to only adopt selected concepts and reflect them in the hierarchy of ROAD classes, without importing STIMONT *per se*. Despite high compliance with the requirements, the STIMONT ontology is difficult to fit into the ROAD ontology because it models some aspects that are also modeled in the ROAD ontology, but in a different way. This is the case for physiological signals and emotions. Moreover, the STIMONT ontology also introduces the mechanism of describing the semantics of the stimulus, which was not identified in the requirements. Thus, a lower level of integration was applied. The use of a similar conceptualization enables us to tighten the bonds between the ontologies in the future without overwhelming ROAD with the particularities of STIMONT that are only superficially relevant to the EDA domain.

SSN/SOSA, in turn, seem to cover the selected area of interest (hardware configuration of sensors and similar devices) in a very fitting way. Therefore, in this case, we decided to expand the ROAD conceptualization only by a small bridging abstraction of hardware configuration, and then relate this abstraction directly to the concepts of the imported SSN/SOSA ontologies. Contrary to the usual strategy, we decided to inherit SSN/SOSA concepts from ROAD concepts. This last decision was made mainly to enable the users of SSN/SOSA ontologies to directly and immediately use their description of devices in ROAD, without having to perform manual translations.

V. ROAD ONTOLOGY EXTENSION

To describe the ROAD ontology extension, first the domain description is presented in Section V-A, then the implementation aspects are discussed in Section V-B and the method of facilitating the use of the ontology is described in Section V-C.

A. DOMAIN DEFINITION

The domain is presented according to the type of metadata identified during requirements definition, i.e. participant definition, course of the session, source and type of the signal as well as stimulus. Additionally, the domain description for each type of metadata is enriched with the information about the adopted strategy of requirements implementation. One of the three strategies, i.e. development of new version of one of the ROAD modules, creation of a new module connected to the specific extension point, and creating a new module importing the other one, was applied.

1) PARTICIPANT DEFINITION

Fulfilling the two identified requirements (PART_1 and PART_2) demands defining the nationality, race and handedness of the participants. These three state-independent features were chosen as the ones that should be unified.

To define the nationality of the participant, the new object property *hasNationality*, with the concept *Participant* as a domain and the concept *Nationality* as a range, was defined. The instances of the nationality concept correspond to the nationalities defined by the government of the UK at [35].

The handedness of the participant was introduced to the ontology by defining the *isHanded* object property. The domain of the property is the *Participant* concept and the range is the newly added *Handedness* concept. The *Handedness* concept is defined as an iset concept. It has exactly four instances:

TABLE 6. Requirements vs. SSN ontology.

ID	Coverage by SSN
Participant definition	
PART_1	SSN/SOSA only superficially cover the problem of participation in an experiment. The concept that can be used for that is *Procedure*.
PART_2	
Course of the session	
SESS_1	SSN/SOSA only superficially cover the problem of planning/executing activities in an experiment. The concept that can be used for that is *Procedure*.
SESS_2	
SESS_3	
Source of the signal	
SOUR_1	SSN/SOSA contains the *System* class which can be used for a thorough description of the devices used in an experiment.
SOUR_2	In addition to classes such as *Sample* and *Sampler*, SSN/SOSA contains the *Frequency* class which can be used for describing sampling rates.
SOUR_3	SSN/SOSA contain the *SystemCapability*,*OperatingRange*, and *SystemProperty* classes which can be used to comprehensively describe any device configuration.
SOUR_4	
SOUR_5	
SOUR_6	
SOUR_7	
Type of the signal	
SIGN_1	SSN/SOSA rely on other ontologies to describe measures and units of measurement.
SIGN_2	
Stimulus	
STIM_1	SSN/SOSA use a different notion of stimulus, which is not related to affective computing.
STIM_2	
STIM_3	SSN/SOSA contain the notion of *actuation* which represents the way in which devices influence the world, such as displaying a video.
STIM_4	SSN/SOSA only superficially cover the problem of planning/executing activities in an experiment. The concept that can be used for that is *Procedure*.
STIM_5	
STIM_6	
STIM_7	

TABLE 7. Requirements vs. STIMONT ontology.

ID	Coverage by STIMONT
Stimulus	
STIM_1	The STIMONT ontology makes it possible to define a multimedia stimulus using the *Stimulus* concept.
STIM_2	In the STIMONT ontology, each individual can be related to a specific emotion. Emotions are expressed using the *EmotionML* [54] solution.
STIM_3	There is no possibility to express the method of presentation of a stimulus in the STIMONT ontology.
STIM_4	The STIMONT ontology does not make it possible to express any activities performed with the utilization of a specific stimulus.
STIM_5	
STIM_6	
STIM_7	In the STIMONT ontology, there is the *Context* concept which makes it possible to define stimulus metadata.

- *handednessRight* – an individual representing that the person is right-handed,
- *handednessLeft* – an individual representing that the person is left-handed,
- *handednessMixed* – an individual representing a cross-dominance, i.e. the change of hand preference between different tasks,
- *handednessAmbidexterity* – an individual representing equal ability in both hands.

The new object property *hasRace* was introduced to define the race of the participant. Analogically to the previous features, the *Participant* is the domain and the range is defined as a new concept *Race*. However, in contrast to the previous features, the *Race* is defined as an extension point due to the various categorizations of races defined by anthropologists [34]. The categorization introduced by Blumenbach [48] was implemented as a ROAD module assigned to this extension point. In this module, the *raceBlumenbach* concept was defined as an iset concept consisting of five individuals representing the Caucasian, American, Ethiopian, Malayan and Mongolian races, respectively.

Introducing the features that make it possible to define nationality, race and handedness demanding changes in the main module of the ROAD ontology as well as introducing the new module assigned to the extension point that makes it possible to define various categorizations of human races.

2) COURSE OF A SESSION

To fulfill the SESS_3 requirement (SESS_1 and SESS_2 are fulfilled by the previous version of the ROAD ontology), a solution that makes it possible to build activities hierarchies was introduced. Defining various levels of hierarchies allows, above all, the definition of both the activities in the context of a planned experiment as well as activities divided into particular actions undertaken by the experiment participants. For example, one activity can consist of breathing exercises, watching stimuli and tagging. Such a solution makes it possible to assign time series to each activity (both for the one consisting of other once as well as one representing a particular action). Hierarchy definition was introduced by adding the new object property *isPartOf*, which is depicted in Figure 1.

The domain and range of this object property is the union of the two concepts *Activity* and *ActivityExecution*.

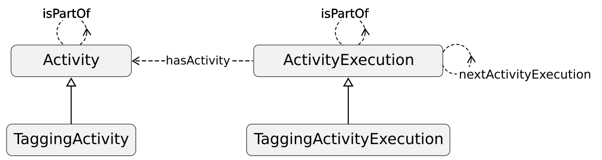

FIGURE 1. **Concepts and properties defining activities.**

Additionally, the two axioms depicted in Equation 1 enforce that *Activity* can only be part of *Activity*, and *ActivityExecution* can only be part of *ActivityExecution*, which is also depicted in Figure 1.

$$\begin{aligned} &\textit{Activity}\ \texttt{SubClassOf}\ \textit{is Part Of only Activity} \\ &\quad \textit{Activity Execution}\ \texttt{SubClassOf} \\ &\quad \textit{is Part Of only Activity Execution} \end{aligned} \tag{1}$$

The analysis of the requirements led to the decision to define a new type of activity and activity execution, i.e. tagging activity and tagging activity execution. This was achieved by defining two new concepts, *TaggingActivity* and *TaggingActivityExecution*, which inherit from *Activity* and *ActivityExecution*, respectively. The hierarchy of the activities and activity executions is implemented as part of the main ROAD module.

3) SOURCE OF THE SIGNAL

The requirements contained within this group comprise mainly the means of expressing information about the configuration of devices and sensors used for affective computing-related experiments. As such, to fulfil them, we pursued the path of adapting the method of describing hardware configurations in the SSN/SOSA ontology.

To maintain the minimal level of independence between ROAD and SSN/SOSA, however, as the first step we introduced a relatively simple abstraction of the configuration description in the form of an additional ROAD module (*configurations*). The details of this abstraction can be seen in Fig. 2, where the classes which belong to it are shown in light blue.

Firstly, the abstraction introduces the concept of a configuration source (*ConfigurationSource*). These are the objects bound with a specific configuration of hardware platforms and devices. To anchor it in the ROAD specifics, the module contains inheritance relationships, saying that ROAD channels, registered channels, and recordings are sources of configuration (effectively meaning that a specific channel or recording used devices in a specific configuration).

The remaining part of the *configurations* module defines the means of expressing configurations. The conceptualization here is based on SSN/SOSA principles. They state that a device (or a system, in general) may present specific capabilities (*ConfiguredSystemCapability*) and be able to provide specific working parameters (*ConfiguredOperatingRange*) under specific conditions. The latter concept was adapted by us into (*InConfigurationConditions*) which represents the entirety of the conditions for a specific experiment and configuration source. The two former ones, naturally, represent the device configuration. In such an arrangement, SOUR_1 can be expressed simply by introducing a device, while SOUR_2-7 can be expressed as system capabilities or (desired/used) operating ranges. The additional configuration element *ConfiguredActuation* was introduced in turn to fulfil the STIM_3 requirement, and is described in more detail in Section V-A5.

Finally, it is worth noting that the *configurations* module in our extension is independent of SSN/SOSA, but is accompanied by a more specific *configuration-ssn* module, which, importing both SSN/SOSA and *configurations*, is a bridge between them and implements the inheritances between the light blue (*configurations*) and darker blue (SSN/SOSA) classes seen in Fig. 2.

4) TYPE OF THE SIGNAL

Requirements concerning type of the signal (SIGN) are fulfilled using the new extension module of measure name extension point for EDA measures, described previously in Section V-A3. In the main module of the ROAD ontology, two new concepts inheriting from *MeasureName* and *Measure* are defined as (*SignalDependentMeasureName* and *SignalDependentMeasure*, respectively). These two concepts represent measures related to the specific signals (e.g. EEG, ECG or EDA). For the needs of this research, two new concepts *EDASignalDependentMeasureName* and *EDASignalDependentMeasure*, encompassing measures and measure names representing quantities obtained from EDA signals, inheriting from *SignalDependentMeasureName* and *SignalDependentMeasure*, were defined. Instances of *SignalDependentMeasureName* correspond to quantities defined in the SIGN_1 requirement.

5) STIMULUS

The applied solution that meets the requirements concerning stimulus (STIM_1, STIM_2, STIM_7) draws from the STIMONT ontology and is depicted in Figure 3. Analogically, as in the STIMONT ontology, the *ContinuousStimulus* and *Context* concepts are introduced. In the STIMONT ontology, the concept corresponding to *ContinuousStimulus* is called *Stimulus*. It is a consequence of the decision made during the requirements analysis to emphasize that the solution is limited to continuous action whose aim is to stimulate emotions. The *ContinuousStimulus* concept represents the stimulus itself and the *Context* concept can be regarded as a container to store metadata, which do not express semantics or emotion [28]. In the STIMONT ontology, the *Emotion*, *Physiology*, and *Semantics* concepts are also introduced. The *Emotion* concept is used to express the expected emotion triggered by the stimulus. In the presented solution, an analogical construction is applied. However, to integrate the solution with the ROAD ontology, stimulus is related to the *EmotionStateMeasureName* concept. The *Physiology* concept is not modeled. In the STIMONT ontology, it is treated as

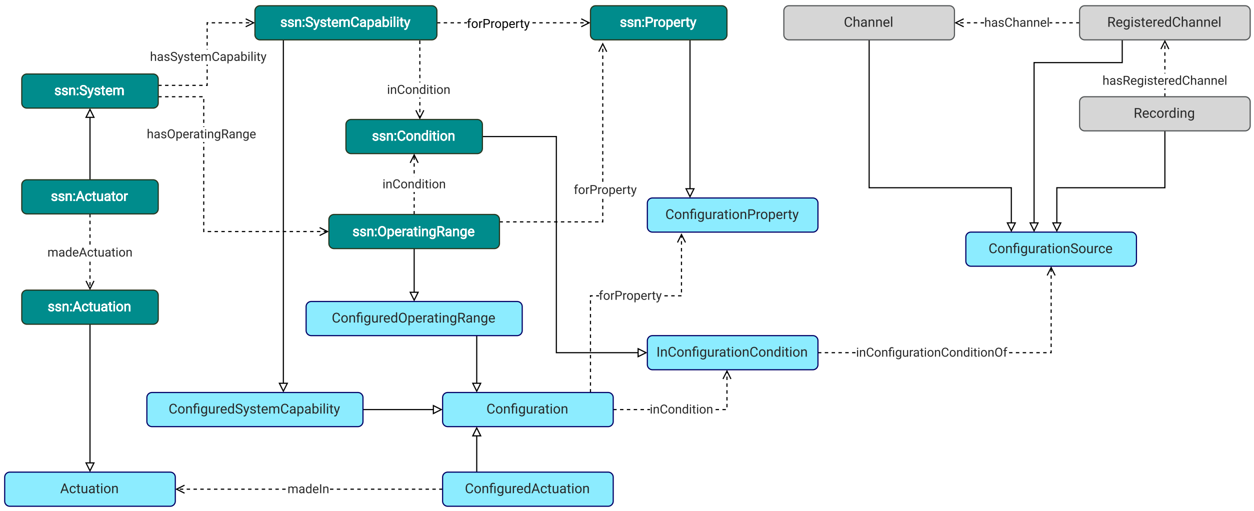

FIGURE 2. **Concepts and properties for describing configurations.**

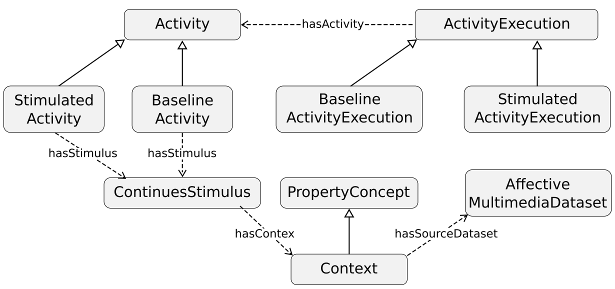

FIGURE 3. **Concepts and properties for the stimulus.**

a container for physiological signals, which in the ROAD ontology are modeled differently as time series related to the specific activity executions. The *Semantics* concept in the ROAD ontology was omitted because it does not correspond to any of the defined requirements.

The *Stimulus* concept is related to the specific activities, not activity executions – remembering that the activity is defined as a pattern. To fulfill the requirements (STIM_4, STIM_5, STIM_6), two new types of activities, *Baseline-Activity* and *StimulatedActivity*, are defined. The *Baseline-Activity* is the type of activity whose aim is to achieve the neutral emotional state of the participant. *StimuluatedActivity* is understood as a pattern describing an activity whose aim is to achieve a specific emotional state (other than neutral). The union of these two concepts is the domain of the *hasStimulus* object property. The *ContinousStimulus* concept is the range of this property. The *hasStimulus* object property makes it possible to assign the stimulus to the specific activity.

Analogically, as for activities, two concepts inheriting from *ActivityExecution* are defined: *BaselineActivityExecution* and *StimulatdActivityExecution*. When defining instances of *BaselineActivityExecution* and *StimulatedActivityExecution*, one principle must be obeyed. If the instances are defined at the lowest level of the activity executions' hierarchy (there is no other activity execution being a part of it), the duration is equal to the duration of the stimulus. This rule is introduced

TABLE 8. **Datatype properties for context concept.**

Stimulus metadata	Datatype property	Range
Source	hasSource	xsd:string
Filename	hasFilename	xsd:string
Link	hasLink	xsd:string
Source link	hasSourceLink	xsd:string
Clip start timestamp	clipStartTimestamp	xsd:unsignedLong
Clip end timestamp	clipEndTimestamp	xsd:unsignedLong
Duration	hasDuration	xsd:unsignedLong

to easily identify time series associated with the specific stimulus.

Each stimulus has its context, which is obtained by introducing the *hasContext* object property. The *Context* concept has a list of data type properties, which corresponds to the basic stimulus metadata which are presented in Table 8. The only exception is the source dataset metadata which is implemented as the *hasSourceDatatset* object property. The range of this property is *AffectiveMultimedia-Database*, whose instances are widely used affective multimedia databases, mainly taken from [28]. The values of the datatype properties *clipStartTimestamp*, *clipEndTimestamp*, and *hasDuration* should be expressed in milliseconds. In the case of *clipStartTimestamp* and *clipEndTimestamp*, the value defines the number of milliseconds from the start of the source multimedia to the start/end of the excerpt of it. This solution was designed by introducing a new module to the ROAD ontology.

A stimulus is often assigned in the datasets to the quadrants (HVLA, HVHA, LVLA, LVHA, where H and L stand for high and low, and V and A stand for valence and arousal). To allow modeling of quadrants and preserve the rule that the stimulus is related to the emotion measure name (not to its specific value) the measure names of the PAD model were divided between the two concepts *PADModelMeasureNameDimension* and *PADModelMeasureNameQuadrant*. The first of these two concepts is the iset concept consisting of valence, arousal and dominance (the instances defined in the previous version of this extension) and the second of the two concepts being also an iset concept, consists of four newly introduced individuals representing four quadrants. The analogical hierarchy of concepts is kept for the *PADModelMeasure*, i.e. *PADModelDimension* and *PADModelQuadrant*. Both of the hierarchies are depicted in Figure 4, and were introduced in the new version of the PAD model measure name extension.

To fulfill the STIM_3 requirement, a means of integration between stimulus and configuration modules had to be introduced. To describe it in more detail, it is necessary to discuss first one factor that might make it difficult to understand the naming conventions used within the two modules.

The concept of *stimulus* is used throughout this paper in a specific context of affective computing-related experiments with participants. Looking at it from this angle, it seems natural to say that the participants are being stimulated, which is also the perspective we assumed here. Our *configuration* module, however, is very strongly based on SOSA/SSN, which assume the perspective seen from the point of view of a device. From this device perspective, "the stimulus" is in fact an actuation, thus a change in the state of the world that has to be made by a device (such as displaying a video on the screen).

To reflect this in a way that does not break any major assumptions behind the models we are using, we decided to introduce another element of configuration within an experiment. This element, described by the class *ConfiguredActuation*, specifies that during the experiment, a specific actuation is performed by a device (a special kind of device that can influence the state of the world – an *Actuator*). Therefore, the integration we performed consists in specifying the desired stimuli (stimulating people participating in the experiment) as actuations made by devices.

B. IMPLEMENTATION

Web Ontology Language (OWL) [40] was used to represent the EDA ROAD ontology extension. OWL 2 was chosen as it is the language recommended by the W3C to describe classes and the relations between them, and the ROAD ontology was expressed in this language. Analogically as for the ROAD ontology, the OWL DL sub-language is used as it allows for maximum expressiveness to be achieved without losing the computational completeness of the reasoning systems, as it corresponds to description logic – a particular decidable fragment of first-order logic [8].

The ROAD ontology with EDA extension falls within the computational heavy part of the Description Logic spectrum, being of $\mathcal{ALCROIN}(\mathcal{D})$ expressiveness, which implies NExpTime-hard class of inferencing problems. Nevertheless, the use of Description Logics guarantees the soundness and completeness of reasoning and its eventual termination.

Analogously to the ROAD ontology, the Protégé [30] editor was used to implement the EDA ROAD ontology extension as it is a free, open-source platform that provides a suite of tools to construct domain models. It provides visualization of an ontology and its validation using several reasoners. The built-in OntoGraf tool was used to visualize the ROAD domain which was also created with the use of OntoGraf, though the original visualizations have been altered to present only the subsumption relations and the names of the properties, and to use uniform colors. The ontology's consistency was checked using the HermiT reasoner [22].

Fragments of the ROAD ontology are presented in Manchester OWL Syntax [26] in the variant used in Protégé. This syntax is easy to read and write (does not use the mathematical symbols used in the DL syntax) and was chosen to increase the readability of the paper, including for the readers without broad knowledge of description logic.

Following the convention adopted in the first version of the ROAD ontology, the functionalities were divided into particular modules. All of the modules are depicted in Figures 5 and 6. The modules, except those being extensions of the specific extension points (depicted in Figure 6), are presented in Figure 5. Those defined in the first version of the ROAD ontology are depicted in gray rectangles. Some of these modules are unchanged and others are modified and published as a new version, which is indicated by adding "(N.V)" to the name. Additionally, the new modules are illustrated as orange rectangles. Moreover, the external (imported) ontologies are presented in blue rectangles.

The list of the modules available in the presented version of the ROAD ontology is depicted in Table 9.

C. FACILITATING THE USE OF THE ONTOLOGY

Three categories of interest have been identified in regard to the facilitation of the use of the ontology: its documentation, ease of maintenance and the possible extension points and adjustments to fit the needs of the users. These areas have also been recognized in the literature [19] as a critical part of ontology development. The issues of the ease of use and extendability of the ontology have been addressed in the original ROAD ontology [75], while the primary focus of facilitation of this extension is to provide comprehensive documentation.

The ontology documentation was constructed through the use of standard documentation techniques, such as annotations and online documentation. This documentation is available online to anyone and can be found on the official ROAD Web page https://road.affectivese.org and in the Github repository https://github.com/GRISERA/road.

VI. EVALUATION

The validation was performed for the MAHNOB-HCI dataset. For the purposes of validation, part of the observation of participant 1 (represented as subject no 1) was expressed in ROAD. The whole observation (carried out on 2009-07-09 and starting at 17:54:17) consists of 40 activities, alternating between one unstimulated and one stimulated, according to the information given in the manual to MAHNOB-HCI. The sequence of the two sessions (one unstimulated and one stimulated) was chosen as the design methods are analogical for any other such pairs. The sessions represented in

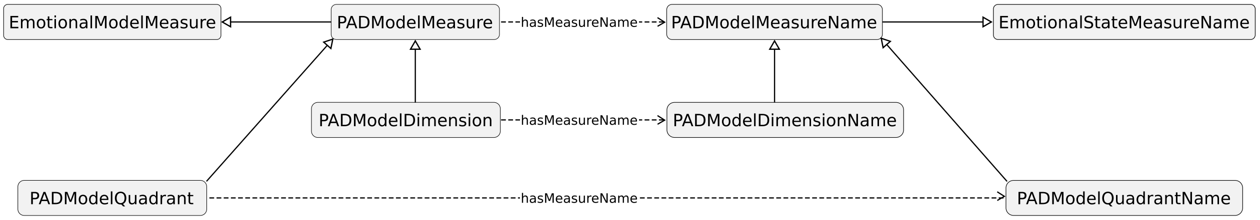

FIGURE 4. Quadrants introduced to PAD measure name extension.

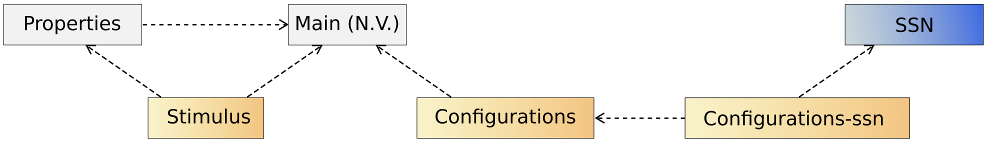

FIGURE 5. Decomposition of main modules.

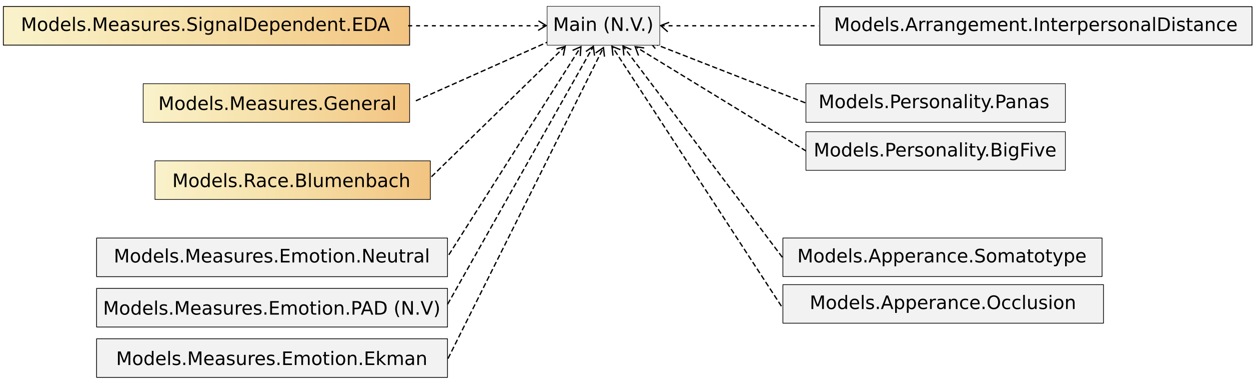

FIGURE 6. Decomposition of extension modules.

MAHNOB-HCI as 3 (unstimulated) and 4 (stimulated) were chosen because the two emotions represented in the Ekman model are assigned to the applied stimulus in session 4, i.e. anger and sadness. The observed participant is a male person, without glasses, with beard and moustache. The ethnicity of the participant is Caucasian and he is of Greek nationality. He was born on 1978-12-8. The stimulus is an excerpt of *The Pianist* movie lasting 1 minute 17 seconds and 1 millisecond. The excerpt of the movie starts at 0:54:33.3 and ends at 0:55:50.4. The name of the file with the video is 55.avi. Sessions 3 and 4 start with the video presentation and for session 4 the tagging process then follows. Session 3 is a bit longer than the video duration as it is calculated to the beginning of the presentation of the video stimulus in session 4. The video presented in session 3 is recorded in the file seagulls_Final.avi. The start and end times of the video presentation are given as well as the start and end times of the sessions. The other information are common for all observations and are previously described in Section III-A2 (device: Biosemi active II, active electrodes, the electrodes were positioned on the distal phalanges of the middle and index fingers, 1,024 Hz, resistance [Ohms]).

To express the Mahnob-HCI excerpt, the modules depicted in Figure 7 were used.

First, the participant (expressed as *subject1* being an instance of *Participant*) was defined. To do this, the main module of ROAD ontology (not depicted in Figure 7 as the other modules import it) and the Race.Blumenbach module were used. Features not changing over time were defined for that individual, i.e. sex as a *hasSex* object property instance, nationality as a *hasNationality* object property instance and date of birth as a *dateOfBirth* datatype property instance.

To express the appearance of *subject01*, the participant state instance corresponding to *subject01* is connected with the instance representing the appearance of *subject01* in the occlusion model (the Apperance.Occlusion model is used).

The two chosen sessions are expressed as a sequence of baseline and stimulated activities, designed as a hierarchy of simpler activities, as depicted in Figure 8. This hierarchy can be expressed using the main and Stimulus modules. The first level of the hierarchy represents the two activities design in the experiment protocol. The second level of the hierarchy is designed according to the assumed principle that the duration of the stimulated activity (including the baseline activity) is exactly the same as the duration of the stimulus. The *baseStimulusWatchingBA* is followed by the *taggingTA* activity representing the process of tagging. The duration of the activity represented by the individual *session4DA* is longer than the duration of the stimulus displayed during this activity, thus the *idleBA* is designed, representing a short idle time before starting a new activity.

The two stimuli (*seagullsFinalBS* and *thePianistS*) are assigned to *baseStimulusWatchingBA* and *stimulusWatchingBA*, respectively. For the *thePianistS* stimulus, two emotions are assigned – anger and sadness – via the

TABLE 9. Modules of the ROAD ontology.

Module name	Description
Main	The main module that contains concepts and roles that are the core of the ROAD ontology. Concepts and roles defined in this module are common for various types of signals and Affective Computing experiments.
Properties	The module that assigns additional properties to various concepts modeled as key-value pairs.
Stimulus	The module that defines stimuli and assign them to the special types of activities: baseline and stimulated.
Configurations	This module contains a basic abstraction for hardware configurations and configuration sources.
Configurations-ssn	The module that imports Configurations and SSN/SOSA ontologies and creates relations between the classes from both (stating that SSN specifications are valid descriptions of ROAD configurations), effectively being a bridge between the ROAD and SSN/SOSA ontologies.
Models.Measures.SignalDependent.EDA	The module that implements the measure extension point introducing unified measure names for EDA signals.
Models.Measures.General	The module that implements the measure extension point introducing a unified measure common for various types of signals.
Models.Measures.Emotion.Neutral	The module that implements the emotion measure extension point introducing the neutral state.
Models.Measures.Emotion.PAD	The module that implements the emotion measure extension point introducing measure names characteristic for the PAD emotion model.
Models.Measures.Emotion.Ekman	The module that implements the emotion measure extension point introducing the basic Ekman's emotion states.
Models.Appearance.Somatotype	The module that implements the appearance extension point introducing the somatotype model.
Models.Appearance.Occlusion	The module that implements the appearance extension point introducing the occlusion model containing information about such occlusions as beard, moustache and glasses.
Models.Race.Blumenbach	The module that implements the race extension point introducing the race categorization defined by Blumenbach.
Models.Personality.BigFive	The module that implements the personality extension point introducing the big five model.
Models.Personality.Panas	The module that implements the personality extension point introducing the Panas model.
Models.Arrangement.InterpersonalDistance	The module that implements the arrangement extension point introducing the arrangement model describing the distance between participants of the experiment.

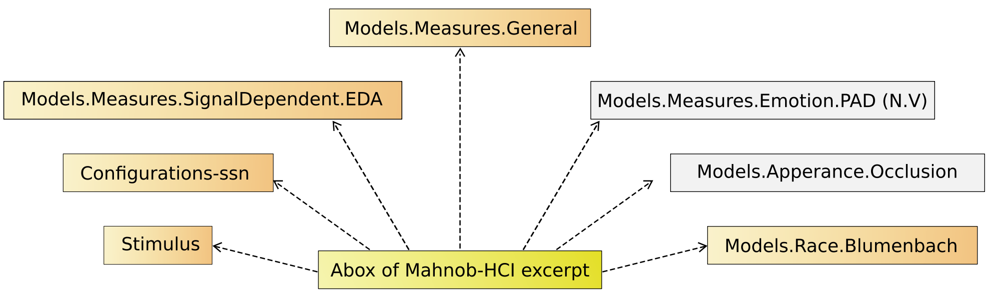

FIGURE 7. Modules used to implement ABox of Mahnob-HCI excerpt.

hasMeasureName object property. For each stimulus, the corresponding context is defined. For both stimuli, file names and durations are expressed. Additionally, for *thePianistContext*, the value of *hasSourceDataset* is stated (individual *HHAD* representing Hollywood Human Action dataset) and *clipStart/EndTimestamp* representing which part of the clip is displayed as a stimulus.

For each activity, there is the corresponding individual representing the activity execution. For each activity execution, the individual representing the execution of the activity by the participant in the particular state is defined. Further, knowing that each activity is an individual activity (performed by exactly one participant) there are individuals representing the participation of *subject01* in the particular activity execution. For each participation, the specific recording is defined. Analogically, for each recording, instances of the *ObservationInformation* concept are added. All of these instances relate to *modalitySkinConductance* and *lifeActivityPerspiration*. The particular time series are related to these observation information. Each time series is defined as regularly spaced (instances of *RegularlySpacedTimestampTimeSeries*) and is related via the *hasMeasure* object property to the *galvanicSkinResponseMeasure* measure as an individual with the measure name *galvanicSkinResponseResistance*, which is defined in the Measures.EDA module. This measure is expressed in Ohms via the *measureUnit* data type property), and its values can be in the range <0,10000000>, which is expressed using the *measureRange* data type property.

The rest of the requirements are covered by the use of descriptions of hardware configurations. For this, the module *configurations-ssn* is used, which integrates the configuration conceptualization with the SSN/SOSA ontologies. For describing devices, instances of *System* are used and, consequently, four instances of this concept are introduced in the validation ABox: *biosemiActiveTwo*, which represents the device, *biosemiActiveTwoElectrodes*, which describes its electrodes, and two additional generic devices, *genericDownsampler256Hz*, and *genericProjector*.

biosemiActiveTwoElectrodes is a *Sensor* and a subsystem of *biosemiActiveTwo*. Its configuration within the experiment is denoted by the individual *biosemiActiveTwoElectrodesOperatingRange*, whose system properties (connected through

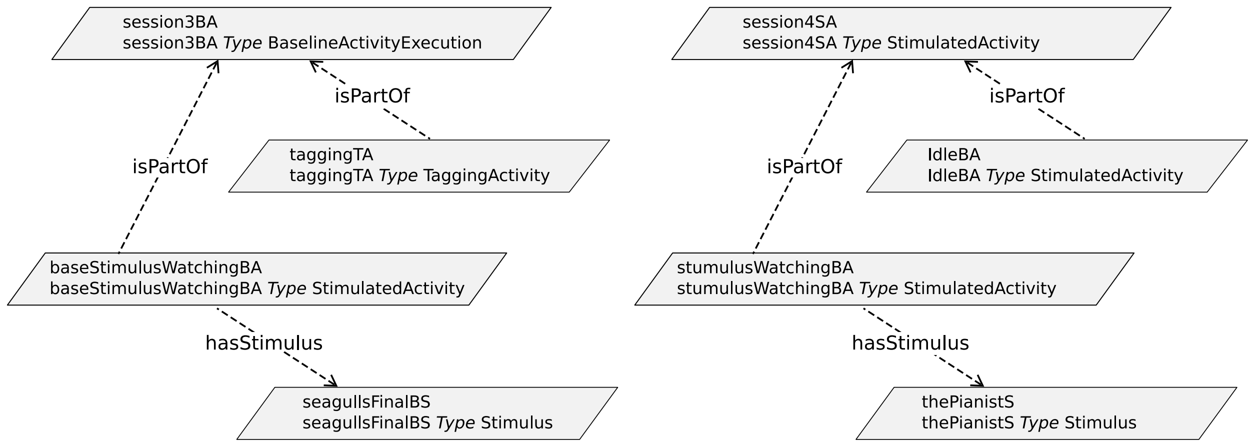

FIGURE 8. Activity hierarchy for excerpt of MAHNOB-HCI ABox.

the role *hasSystemProperty*) specify readiness for measurements of Galvanic Skin Response in the full range (from 0 to 10 megaohms; individual *configurationPropertyGSRFullRange*) and electrode placement on the distal phalanges of the middle and index fingers (individual *configurationPropertyElectrodesPlacementDistalMiddleIndex*). This configuration (*biosemiActiveTwoElectrodesOperatingRange*) is then associated with the whole EDA channel.

genericDownsampler256Hz is a generic *Sampler*, whose presence in the configuration description reflects the fact that in MAHNOB-HCI, all of the measurements have been downsampled to 256Hz to preserve space. Similarly to the previous case, the device has a specific operating range, *sampling256Hz*, in the experiment and this operating range is associated with the configuration for the whole experiment.

To cover the STIM_4 requirement, we also had to introduce *genericProjector*. This device is an *Actuator*, which changes the state of the world by presenting video stimuli to the participants of the experiment. Unlike in the previous cases, for this device we had to introduce two operating ranges, each associated with a different stimulus (*seagullsFinalBS* and *thePianistS*, respectively). These operating ranges are associated with configurations for the recordings for their respective sessions (*recSession3BAE* and *recSession4SAE*).

VII. CONCLUSION

The ROAD ontology aims at offering a unified means of describing data obtained during various affective computing-related experiments. Such a unified description is expected to facilitate searching for datasets, finding potentially conflicting results, and identifying research gaps. The ROAD ontology allows to store data origin from various channels and modalities.

In the article, we present a formal extension of the ROAD ontology for describing signals obtained from EDA devices. While focusing on electrodermal activity, this comprehensive extension also introduces major improvements in specifying general settings of experiments, by enabling users to define hierarchical and sequential activities, stimuli for participants, and hardware configurations. It is important to notice that the ROAD ontology is not limited to the EDA signals and this research defines the extension of the ROAD ontology allowing to define the metadata related to EDA signals in details. The same is done for other signals but ti is out of scope of the presented work.

The scope of the work was defined within a multi-staged process, whose first and very important phase was the specification of the requirements. This specification was created as a result of a careful literature review and analysis of existing databases containing EDA signals. The specification was then used to identify the range of changes and expansions that should be applied to ROAD and to find other ontologies that could be integrated into the framework.

The organization of the process was not easy because the problem lies at the intersection of two important domains: knowledge management (especially knowledge acquisition) and emotion analysis (including specialized knowledge about electrodermal activity). This difficulty has been overcome by careful selection of the research team members and frequent meetings whose purpose was exchanging points and aligning points of view. What was also helpful was the organization of the process, which promotes systematic knowledge and requirement analysis. The classical waterfall structure of the process made it easier to establish a single vision. However, the drawback of this approach was the length of the process which results in its inherent inability to include the newest result in the field, and the necessity of periodic validation of the solution.

The extension has been validated through the creation of a description of the well-known MAHNOB-HCI dataset. During the validation, we concluded that the experiment settings and signal description could be sufficiently described. Some limitations of the specification were the result of assumptions made during requirement analysis, and embraced:

1) Narrowed set of participant features (limited to date of birth, sex, ethnicity, nationality, handedness, age, appearance, and personality),
2) Ability to design only the continuous kind of stimuli (those that last throughout a whole activity).

Despite the limitations, the presented extension of ROAD makes it capable of capturing a broad range of metadata about EDA signals acquired during affective-related experiments in addition to metadata previously defined in the ROAD ontology. Thanks to the existence of the model it is now possible to develop protocols, user interfaces and software tools based on the unified data structures and notions. Currently, at Gdańsk University of Technology (GUT), there are carried out such works as:

1) design and development of access interface for data creation and retrieval,
2) analysis of performance and flexibility of different back-end stores like graph-, document- or relational-oriented,
3) development of a complete user experience solutions.

All these works aim at dissemination of the solution to various researchers, not familiar with ontological representation of knowledge. The ROAD ontology and availability of solutions based on it are a significant step leading to improvement of the findability, accessibility, interoperability, and reuse of datasets [71].

The process of extending ROAD turned out to be successful and can be reused for future endeavors. Therefore, subsequent families of signals can be incorporated into ROAD in a similar way. Thus, the next works must be done for other signals, especially EEG and ECG, which are widely used in emotion recognition. Such works are also carried out at GUT. Still, the road ontology can be further expanded with:

1) unified and formal description of annotations constituting the ground truth in emotion recognition methods,
2) meta description of processes leading to creation of new time series from the original ones such as re-sampling, filtering etc.

Another challenge is keeping ROAD and the existing extensions up-to-date and useful for prospective users, while maintaining traceability of changes in the evolving ontology. It should be stressed that the methodology proposed in this paper is appropriate for creating new extensions, while much effort will and should probably be devoted to the maintenance of the existing artifacts. To this end, another methodology should be proposed, probably taking advantage of on-line systems for issue tracking and similar solutions. In this regard, the idea of keeping the requirement specifications public and open to review is especially compelling, as it enables wider discussions about the scope of the ontology, and allows everyone to assess it. All of these features are extremely valuable for a broadly used, open and extendable framework for describing affective computing experiments, which ROAD strives to be.

ACKNOWLEDGMENT

Financial support of these studies from Gdansk University of Technology by the DEC-2/2022/IDUB/III.4.1/Tc grant under the TECHNETIUM TALENT MANAGEMENT GRANTS - "Excellence Initiative-Research University" program isgratefully acknowledged. Portions of the research in this paper use the MAHNOB Database collected by Professor Pantic and the iBUG group at Imperial College London, and in part collected in collaboration with Prof. Pun and his team of the University of Geneva, in the scope of the MAHNOB project financially supported by the European Research Council under the European Community's 7th Framework Programme (FP7/20072013) / ERC Starting Grant agreement No. 203143.

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