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OntoPhaco: An Ontology for Virtual Reality Training in Ophthalmology Domain–A Case Study of Cataract Surgery

BENFERDIA YOUCEF[1], **MOHAMMAD NAZIR AHMAD**[1], **AND MUSHAWIAHTI MUSTAPHA**[2]
[1]Institute of IR4.0, Universiti Kebangsaan Malaysia, Bangi, Selangor 43600, Malaysia
[2]Department of Ophthalmology, Faculty of Medicine, Universiti Kebangsaan Malaysia (UKM), Kuala Lumpur, Malaysia

Corresponding author: Mushawiahti Mustapha (drmusha@gmail.com)

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ABSTRACT Performing a safe and successful cataract surgery greatly depends on the effective training programs of the residents that are commonly offered by several public and private healthcare providers. Virtual Reality Training (VRT) as a training tool for example, expresses potential capabilities to improve the learning curve, increasing trainee confidence and acquisition of skills. However, the success of this tool highly depends on how close this tool is to the reality. Ontology is called as a significant modelling tool which can help to provide a shared and common understanding of a domain, and in this scenario, a standardized terminology for representing the training domain, and actions taking place in Virtual Environment (VE). Recent Systematic Literature Review (SLR) findings show that most ontology designs for VRT are not built systematically and there is no ontology describing the domain knowledge for VRT in the ophthalmology field. There is also a lack of a high achievement rate in implementing ontology driven VRT, calls for systematic and comprehensive steps. Therefore, in order to lower the failure rate of ontology applied to VRT, OntoPhaco was designed and developed based on philosophically grounded foundational ontologies, namely, Unified Foundational Ontology (UFO) and Design & Engineering Methodology for Organizations (DEMO). The evaluation results showed that the use of OntoPhaco was able to improve the student's learning experience, assist effectively in building VR training scenarios, and lead to a successful VRT processes. The lessons learnt from designing OntoPhaco for this domain could generally generate valuable contribution to the theory and practice of VRT, knowledge management and ontology engineering in complex domains.

INDEX TERMS Ontology applications, virtual reality, training and education.

I. INTRODUCTION

Cataract is a well-known disease in the ophthalmology field. In spite of the ease, safety and the availability of good quality services, cataract remains the leading cause of limited vision and visual impairment worldwide [1]–[3]. Khairallah *et al.* [1] informed that 10.8 million blind people and 35.1 million visually impaired people got their eye disorders due to cataract. Although there have been improvements resulting in reduction of the spread of this disease, it still continues to be the major cause of blindness among people due to various risk factors that impede the increasing number of cataract operations over the world, including high costs of equipment maintenance, the availability and training of surgeons, the poor quality of training equipment, and the inadequate members of training faculties [4]. Moreover, although there are several techniques and procedures of surgery in this area including Phaco, the complexity of ophthalmology surgery still makes it a challenge for trainers to transfer their skills to a resident level [5]. For instance, teaching cataract surgery is challenging on a technical level, due to the high skills needed for the psychomotor. Subsequently, it is costly and time consuming. Capsulorhexis, as a major step under Phaco, is another example of a technique requiring difficult skills that new cataract surgeons struggle to master [6].

In the ophthalmology domain, to be a specialist as an ophthalmologist requires a long period of education including residency training and an internship. An initial step during

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the pursuit of this specialization involves observation or assistance during operations performed by one of the experts. This is followed by practicing in wet labs, while the residents need to operate on enucleated animal eyes that help them to reach a certain level of proficiency. At a later stage, with a physician's guidance, the residents start to perform operations on actual patients [7]. Besides this, utilizing simulations using live animal specimens or cadaveric eyes in labs is another classical way of training. The locations where such training occurs are usually named wet labs and are located in separate rooms. Personnel who are highly trained in surgery are required for monitoring students. However, this entire exercise is costly due to the need for providing at least one high-definition surgical micro-scope, special instruments, worktables, and highly qualified supervisors (expert surgeons). Therefore, the adoption of wet labs has been limited in many training programs in many regions over the world such as Mexico, Latin America and more [5] due to the aforementioned requirements. Additionally, there is also the high cost of animals or cadavers that can only be used once for each training exercise. Besides, the coherence of the anatomical properties of animal eyes is never compatible human eyes. Lastly, animal experimentation could also lead to ethical issues [5].

Many countries are still unable to provide successful and safe cataract surgeries for a significant portion of the population. Nevertheless, a comprehensive strategy is needed to address the issues related to availability, quality, accessibility, satisfaction, and affordability of eye care services, while cataract continues to be a challenge factor in many regions, especially in developing countries. VRT was evidently suggested as a tool that has the potential to offer significant levels of skills transfer to novice ophthalmic surgeons [8]. Additionally, it is convenient, safe, has a low stress environment, and can provide repeated training. However, although VR technology is not really a new concept in the healthcare domain, the disciplines in VR application development are still in their infancy stage. The successful rate of its adoption in general [9], and mainly for a domain like ophthalmology [10], is not well reported in the literature. Some reasons for that may be a lack of guidance, supervision, or comprehensiveness in the curriculum used for training [11]. Besides that, VR deals with a very knowledge-intensive task. For example, capturing knowledge on the ''know-how'' among ophthalmologists (experts) conducting a cataract or glaucoma surgery, where any missing of trivial details can lead to blindness. VRT is still relatively expensive [12], with a lack of understanding and capturing training scenarios and learning contents in an explicit manner [13]. Moreover, the process to develop such a VR application for training and learning is tedious work, labor-intensive, and requires a long development life cycle, because of dealing with a very knowledge-intensive task and complex area [12]. Bridging the knowledge between the ophthalmologists and VR experts is essential and has to be captured explicitly and represented in a harmonious and unambiguous form. To facilitate a VR implementation, there is a need to have a modeling tool.

In this context, ontology is leveraged to build a systematic and standardized conceptualization model at a high level of abstract and expressiveness in order to provide a shared and common understanding of the domain. By using agreed terminology, ontology can capture and represent a training domain and the action taking place in a VE with expressive descriptions.

Unfortunately, although ontology is designed for VRT in a variety of domains, currently, there is no ontology that has been developed specifically for VRT in the ophthalmology domain. Moreover, most of the ontologies are not built systematically, due to which all ontologies apply deficient foundational ontologies, languages, and methodologies when developing ontologies for VRT. Additionally, they frequently either misrepresent or inadequately describe perdurant knowledge [14]. This, for example, could accordingly breed high dangers in real life, especially when VRT represents an unforgiving domain like the Phaco technique, where missing trivial details in one step could result in increasing complexities in the next step, leading to the situation becoming more severe [15]. Misusing ontology results in a complicated ontology that limits its ubiquity, which can definitely lead to poor design, and it would then be the root cause of VRT failure. There is an absence of a high achievement rate in implementing ontology driven VRT calls for systematic and comprehensive steps. Therefore, this research attempts to fill these gaps.

A domain ontology for VRT in cataract surgery is a mechanism for providing a comprehensive and expressive view of the real domain that can be utilized by all stakeholders including doctors, students, VR developers and so on. Benferdia *et al.* [14] reported and discussed how ontology should be designed to facilitate a VRT development process by providing a main components design that is considered central for designing an ontology for VRT.

However, ontology evaluation is one of important stages during ontology construction, in order to be widely adopted in other applications [16]. Ontology evaluation methods demand the usage of explicit criteria that corresponding ontology development objectives. Over the years, several evaluation approaches and criteria have been reported to evaluate and verify ontologies [16]. These studies suggested that it is significant to choose the right approaches that fit the proposed ontology and its application domain. In this study, an approach of evaluating and designing domain ontology for VRT in ophthalmology in general and Phaco cataract surgery in particular, is presented. A general review of ontology evaluation approaches existing in literature was conducted, and a proper systematic evaluation process was accordingly proposed for OntoPhaco ontology.

In this article, two major contributions are made as follows.

Firstly, this research presents a review of the current ontology evaluation approaches which are matched to those that are used to evaluate ontology developed for VRT. Accordingly, the process of selecting the applicable method for the evaluation of OntoPhaco is discussed and described.

These consist of the process of empirical testing with domain experts' help. Having these process can help to generate a lesson learned that can finally lead to the refinement and understanding of the applicable ontology evaluation.

Secondly, with a particular emphasis on VRT for cataract surgery, this paper presents an attempt to establish a common understanding on how to design the right domain model for supporting VRT in the ophthalmology domain that incorporates the OntoPhaco ontology, such that it is able to enhance the student's learning experience and facilitate VRT development. This demonstrates the efficacy of the proposed approach for ontology designing and evaluation.

Both objectives can contribute a beneficial insight for researchers and practitioners when they are dealing with such a complex area which contains intensive knowledge and a variety of stakeholders.

The rest of study is arranged as follows. Section II defines ontologies and provides the significant roles of ontologies for VRT. In Section III, an overview of the current ontology evaluation approaches is presented, and accordingly, the selected evaluation methods for OntoPhaco are also provided. The development process, in Section IV, is described with a new proposal for constructing OntoPhaco. Finally, Section V presents the paper's conclusion and recommends some directions for further research.

II. THE ROLE OF ONTOLOGY IN VRT

A classic definition of ontology is "*an explicit specification of a conceptualization*" [17]. The conceptualization is an abstract simplified view of some selected part of the world (portion of a reality), containing concepts and relationships between them. It exists on a community's mind as shared knowledge. The community members in this case are doctors, youths, VR experts, and other stakeholders. Ontology was recently defined by Feilmayr and Wöß [18] as "*A formal, explicit specification of a shared conceptualization that is characterized by high semantic expressiveness required for increased complexity*". The definition means an abstract or simplified view of a selected part of the world, which is explicitly represented using a formal language. This representation should be hugely expressive, shared among other parties and stakeholders, and limited to a particular domain of interest. This entirely means that ontology entirely assists to explicitly provide a world view and shared understanding of a domain of interest, which can be utilized as a unified framework to resolve the problems existing in the specific domain [19].

Ontology can be used in information sharing between humans or between computation systems or between humans and computation systems. It can capture and represent knowledge of a domain of interest in a machine-readable way. Therefore, information represented in the ontology (at the knowledge level) can be understood, interpreted, and reused by humans and machines alike. An ontology is developed with many usage objectives. The main purpose of an ontology is, however, not only to define and classify terminology related to some areas of interest, but to also capture and represent the underlying conceptualizations [20]. The other key role of ontology is to facilitate communication, when both the domain experts and the stakeholders can communicate closely with each other, with the aim of reaching an agreeable specification model. Thus, ontology could facilitate the implementation process during VR design by bridging the gap between IT designers on one hand, and the domain experts on the other hand. Consequently, this approach aids in the earlier detection of any design errors and helps avoid any additional massive investments of time and cost. Enabling the reuse of domain knowledge is another key role of ontology, where designers can reuse or extend the existing ontology to their newly developed ontology. Accordingly, it can help to drastically bypass the redundant effort and time used for building-up new virtual training scenarios.

The core of any VRT is a training scenario and leaning content which come from domain experts. Capturing an explicit training scenario, on know-how and know-what, is vital for an ideal and comprehensive VRT domain. Therefore, in order to capture and represent this knowledge in sequence and in a coherent manner, ontologies were applied to a number of projects of VRT[14]. For example, Peeters *et al.* [21] proposed an Automated Scenario-Based Training (SBT) intelligent system. The latter ontology was used as a tool to provide consistent and unambiguous information and fitted learning scenario to fill the students' needs. Besides that, the reasoning process and reusability across different training domains are enhanced. Using ontology as a common understanding among domain experts and designers was also guaranteed. In the Smart Home Simulator (SHS) project by Baldassini and his colleagues [22], ontology was used to provide elder people a system enabling them to follow a healthy lifestyle. It was applied to manage all heterogeneous data (e.g., devices, users, and environments). In order to ensure that users were following the suitable activities at home, a reasoning process was also enabled to query the desired data. BKOnto [23] was developed to support a virtual exhibition system, which was built based on biographical history. The aim of ontology was to assist virtual presentation by offering structure descriptions and definitions that explicitly present the historical materials, places, and events. This ontology behaves as a storyline that enables users to easily navigate a semantic web with the help of VR technology.

However, most of the studies that used ontology to support VRT in Benferdia *et al.* [14] either did not indicate the methodology or were using immature ones, and they also did not provide sufficient detail on the ontology evaluation process that could be conducted during ontology construction. In the same way, a previous study carried on by Ahmad *et al.* [24] for instance, reported the significance of a rigorous method of ontology development and the shortage of uniformity in current methodologies, which are not generally suggested to be as standard approaches for designing an ontology. Ahmad *et al.* [24] proposed a new methodology that could be flexible and generic for development, and an

TABLE 1. Variety of criteria for evaluation purpose.

Yu et al. [29][30]	**Gomez-Perez** [26]	**Gruber** [31]	**Shanks et al.** [32]	**Vrandečić** [25]	**Raad and Curs** [33]
Clarity		Clarity		Clarity	Clarity
Consistency/coherence	Consistency	Coherence	Conflict-free	Consistency	Consistency
Expandability/extendibility	Expandability	Extendibility		Adaptability	Adaptability
Minimal encoding bias		Minimal encoding bias			
Minimal ontological commitments		Minimal ontological commitments			
Conciseness	Conciseness		No redundancy	Conciseness	Conciseness
Completeness	Completeness		Completeness	Completeness	Completeness
	Sensitiveness				
Coverage				Organizational fitness	
Correctness			Accuracy	Accuracy	Accuracy
				Computational efficiency	Computational efficiency

evaluation ontology that is rooted in Design Science Research Methodology (DSRM).

Therefore, in this study, the approach proposed by Ahmad *et al.* [24] is extended to support the development of an ontology for VRT in ophthalmology in general and cataract surgery in particular. Systematic verification and validation processes are also introduced which include evaluating the design theoretically and hypothetically and utilizing domain expert feedback for verification and revision of the ontology for VRT.

In the next section, an overview of current ontology evaluation approaches is provided, and the selected evaluation methods for the proposal ontology are further described and justified.

III. ONTOLOGY EVALUATION METHODS

Having appropriate and formal evaluation criteria and methodologies are a significant step towards high quality artefacts. It is thus required to choose the proper evaluation approach that fits the proposed ontology and its application area. Therefore, before starting a discussion about this activity, there is a need to take a look into the overall evaluation methods that exist in literature. A critical review of ontology evaluation methods is, thus provided in the next few subsections. This review helps to consider the most suitable approach to evaluate the OntoPhaco ontology.

A. AN OVERVIEW OF ONTOLOGY EVALUATION APPROACHES

Ontology evaluation is defined as the ''task of measuring the quality of an ontology'' in a way to detect the correctness of the ontology to share knowledge, evaluate the ontology's development, and to preserve coherence by applying defined criteria [25] (see Table 1). Over decades, several evaluation approaches have been proposed for evaluating ontology. Gómez-Pérez [26] was the first who introduced the verification term of ontology. He reported that architecture, lexicon, and syntax and content of ontology must be verified based on defined criteria. In addition, currently the verification of the syntax of ontology can be automatically detected by using a tool (e.g., Protégé, OntoUML editor and so on) or by using postulates of used language (e.g., Guizzardi's Postulates). Brank *et al.* [16], on one hand, classified these approaches into four major categories as follows:

1) The 'gold standard' evaluation — this class of evaluation makes a comparison between the designed ontology and other high levels and gold standards, that can usually be an ontologies themselves. For instance, these standards were described by Abramowicz *et al.* [27] as knowledge obtained from domain experts through a series of workshops in order to build a complete and precise ontology. However, one should bear in mind certain significant considerations, that in some cases the access to gold standards may not be available. Additionally, the results of this evaluation can face some difficulties with regards to the selection of a wrong comparison methodology or an inconvenient gold standard [29].
2) Data driven evaluation — It is also known as a corpus-based approach, which is applied to evaluate how far an ontology significantly represents the domain of interest. The basis of this assessment is to compare the ontology with the content of a text corpus that represents a particular domain of knowledge. This can be conducted by performing automated term extraction on the corpus and computing the number of concepts that overlap between the ontology and the corpus [28]. However, this kind of evaluation does not take into account the assessment of clarity, correctness, and applicability of ontology. It is more suitable for the estimation of the coverage of ontology [34].
3) Evaluation by humans — This kind of evaluation utilizes a set of advanced criteria which have been established in advance. For example, Lozano-Tello and Gómez-Pérez [35] suggested the Oncometric method, which is a multilevel framework of characteristics. This kind of approach enables users to measure the usability of an ontology based on the requirement of its system. The measurement includes five dimensions

such as language, methodology, tool, content, and costs. However, this method provides only limited support for ontologies that are built from scratch and evaluated [34].

4) Application-based evaluation — In this method, the ontology is used in an application and then is further evaluated by users. This approach is considered as an effective way to evaluate the ability of designed ontologies to achieve their objectives. Again, it does not verify the quality of the included knowledge or the structure of the ontology [34].

On the other hand, Yu *et al.* [29] in their comparison proposed three main approaches for ontology evaluation as follows:

1) The gold standard evaluation — This method overlaps with the previous approach reported by Brank *et al.* 16] which is discussed above.
2) Task-based evaluation— This approach is similar to the application-based evaluation approach proposed by Brank *et al.* [16], where this method tries to measure on how ontology assists in enhancing a result of a particular task; for instance, when a designer builds an ontology in order to improve the effectiveness of a web search engine. For the purpose of evaluation, one can compare the results of conducting queries with and without an ontology. This can help conclude whether the use of ontology helps to generate more relevant documents if a designed ontology is applied [36]. Yu *et al.* [29] recommended that this method should be performed separately for each task, as the evaluations for applications and tasks may provide different results.
3) Criteria-based evaluation — This method has some similarities with the approach by Brank *et al.* [16]. However, this approach is more adaptable and comprehensive. Criteria-based evaluation utilises a set of predefined criteria for evaluating the designed ontology [37], which is used to validate the content and design of the ontology. A variety of criteria in the literature are assigned for evaluation purposes. The majority of the criteria considered by Yu *et al.* [29], [30] are outlined in Table 1.

B. SELECTED APPROACHES FOR ONTOPHACO EVALUATION

On reviewing the various approaches for evaluating ontology and their limitations, this research selected the following three approaches for OntoPhaco evaluation:

1- Guizzardi's postulates-based verification.
2- Criteria-based evaluation.
3- Application based-evaluation.

The evaluation criteria that are presented in Table 1, more specifically, the eight criteria of Yu *et al.*'s [29][30] work, are adopted to meet the objective of OntoPhaco. Three criteria (e.g., sensitiveness, minimal encoding bias and computational efficiency), are not included. Sensitiveness refers to how trivial modifications on definitions can consequently affect other well-defined concepts that are already included and validated. For applying this criterion, a specific tool is needed. However, since OntoPhaco is constructed with a collaboration of domain experts, they have been involved in the iterations of various evaluations. Accordingly, each change, either minor or major was verified and validated. Furthermore, minimal encoding bias recommends that an ontology should not be designed based on any symbol level encoding at the conceptualization level, which is something more suited for implementation tasks. In this case study, OntoPhaco is constructed using OntoUML and UML based DEMO. These are free from any symbol level encoding. Finally, computational efficiency determines how the used tool can work with ontology to provide a fast response to any required task. For applying this criterion, a specific tool is required, especially in implementation phase, when ontology is integrated inside VE to provide some reasoning process. Based on research scope, there is no need for this criteria.

On the other hand, application-based evaluation is a kind of post ante evaluation which evaluates the artefact after designing. It is a technical judgment of the artefact which tests on its applicability within real world situations. The conceptual model's evaluation is commonly performed based on users' opinions in terms of knowledge coverage and utility.

In the next section, an overview of the ontology development process is presented to design and evaluate domain ontology for ophthalmology in general, and Phaco cataract surgery in particular.

IV. DEVELOPMENT OF ONTOPHACO

Several methodologies and methods have been presented for building ontology either from scratch or by reusing an existing ontology. The process of building an ontology is something like a craft rather than an engineering task. Each designing team has the choice to select their own criteria and phases that are required to be applied or surpassed based on the scale size of the proposed ontology that is planned to be designed [38].

Having a methodology in the designing process can generally offer repeatable and systemic guidelines for developing ontologies and provide the ability to share, reuse and extend ontologies by other designers [39]. In literature, a number of methodologies are introduced for a particular domain, which are: Uschold and King's Method, Gruninger and Fox's Method, METHONTOLOGY method and OntoClean methodology.

On one hand, designing a domain ontology for VRT in ophthalmology needs a rigorous ontology development method and also requires an inclusive ontology evaluation approach with domain experts involved. Having a look at the recommended methodology by Benferdia *et al.* [14], exposed that Ahmad *et al.*'s work focused only on ex post evaluation, which refers to artefact evaluation, whereas they totally ignored ex ant evaluation. The latter method is concerned with evaluating the design earlier (e.g., the theoretical and hypothetical evaluation). This is to avoid any kind of risk and effort before the design goes through the construction of an instantiation of the artefact.

On the other hand, including other activity related to designing preliminary conceptualization is fundamental as well, due to the following reasons: it offers the opportunity to domain experts to increasingly get to know what the ontology is about, what is its purpose, and how it works; it provides a chance to the ontology engineer to have knowledge about the domain to easily communicate with the domain expert by using a graphical approach; and it reduces time required to rigorously build an ontology.

It is worth, as well, to note that using preliminary conceptualization activity helped the experts, in that they did not find any difficulties to learn about the purpose of the ontology and the included knowledge. As a result, they had smoothly engaged in communication about included knowledge during all interview sessions.

These steps should be supported by other approaches such as those introduced in Gómez-Pérez [26], (e.g., verification of the syntax), and Raad and Cruz [33] (e.g., cover many criteria). To have that, it should clearly allocate this stage for revising the ontology-based criteria with domain experts involved, and syntactically check and fix the errors to finally enhance the product. Taking in consideration the domain of our ontology, cataract surgery, it was extremely significant to take into account the verification stage before designing the artefact in order to confirm the best quality of design. This stage, therefore, was integrated as the evaluation's part, which is explained in Section 4. Fig. 1 illustrates the development process and its phases as per this paper, which are detailed and explained in the context of a domain ontology for VRT in ophthalmology. The proposed stages for OntoPhaco ontology development are discussed in the following subsections.

A. STAGE 1: PRE-CONCEPTUALIZATION

1) DEFINITION

The ontology requirements specification activity and the production of ORSD are two things that are needed to be focused on in this stage. These considerations are more towards what the intended uses are, who the end users are, why the ontology is being built, and finally which functional and non-functional requirements should the ontology fulfil. Functional requirements refer to content-specific requirements, whereas non-functional requirements indicate the characteristics, qualities, or other general items which are not connected to the ontology content, such as whether the ontology must be designed to support a multilingual system and whether the terminology used must be obtained from certain standards[40]. In order to discover proper functional requirements, writing these requirements in a natural language involving competency questions is the recommended approach. These questions should be answered by the ontology later. In this research's case study, a variety of resources were analyzed and checked (e.g., videos, documents, websites, photos, articles) in order to get an overview about the cataract domain. As a result, competency questions were formulated, and accordingly terminologies such as verb, names, and adjectives can be extracted as source terms for the first glossary, which could be a beginning to answer some competency questions. However, the latter questions should be answered by domain experts as a confirmation part. The ORSD is consequently produced and behaves as a communication tool that aids to create a bridge among stakeholders to find the set of requirements that should be satisfied by the designed ontology[40]. The guideline of Suárez-Figueroa *et al.* [40] is used as a template to identify the production of the ORSD. It is, thus, illustrated in Table 11.

2) PRELIMINARY-CONCEPTUALIZATION

In this stage, it is advised to build a general conceptualization that only focuses on presenting key concepts, sub-concepts, and their relations, without any specific terms related to any kind of modeling language. In this way, it is recommended to include the first glossary of concepts, terms, and relations, which are extracted in the first phase (definition phase). Some sub-steps are reconciled and harmonized to serve the purpose of the research.

3) KNOWLEDGE ACQUISITION

Many methods can be applied to confirm the extracted knowledge form previous phases and identify the right resources that can serve as sources for the ontology development's purpose. Two methods were sequentially conducted for obtaining distinguished resources for developing OntoPhaco. Online interviews with domain experts in the ophthalmology domain were established initially. Accordingly, related documents were reviewed. In this phase, preliminary conceptualization is used as a tool to communicate the competency questions via a graphical approach. It simultaneously provides a chance for the researcher to have knowledge about the domain to easily communicate with the domain expert. The purpose of this approach is to extract other knowledge, and at the same time, it is a chance to confirm the extracted terms and concepts.

However, one should bear in mind certain significant considerations that this phase does not conduct for the verification part, even though domain experts are involved to confirm the extracted knowledge from the definition phase. The reason for this is that most of the knowledge comes from different resources, and these are required to be confirmed by ophthalmologists. Having done that, the first version of the ORSD is updated to produce a new version of the glossary. Therefore, Table 2 shows the glossary of some combined and confirmed terms, which will be used to transfer the preliminary conceptualization to a formal conceptualization.

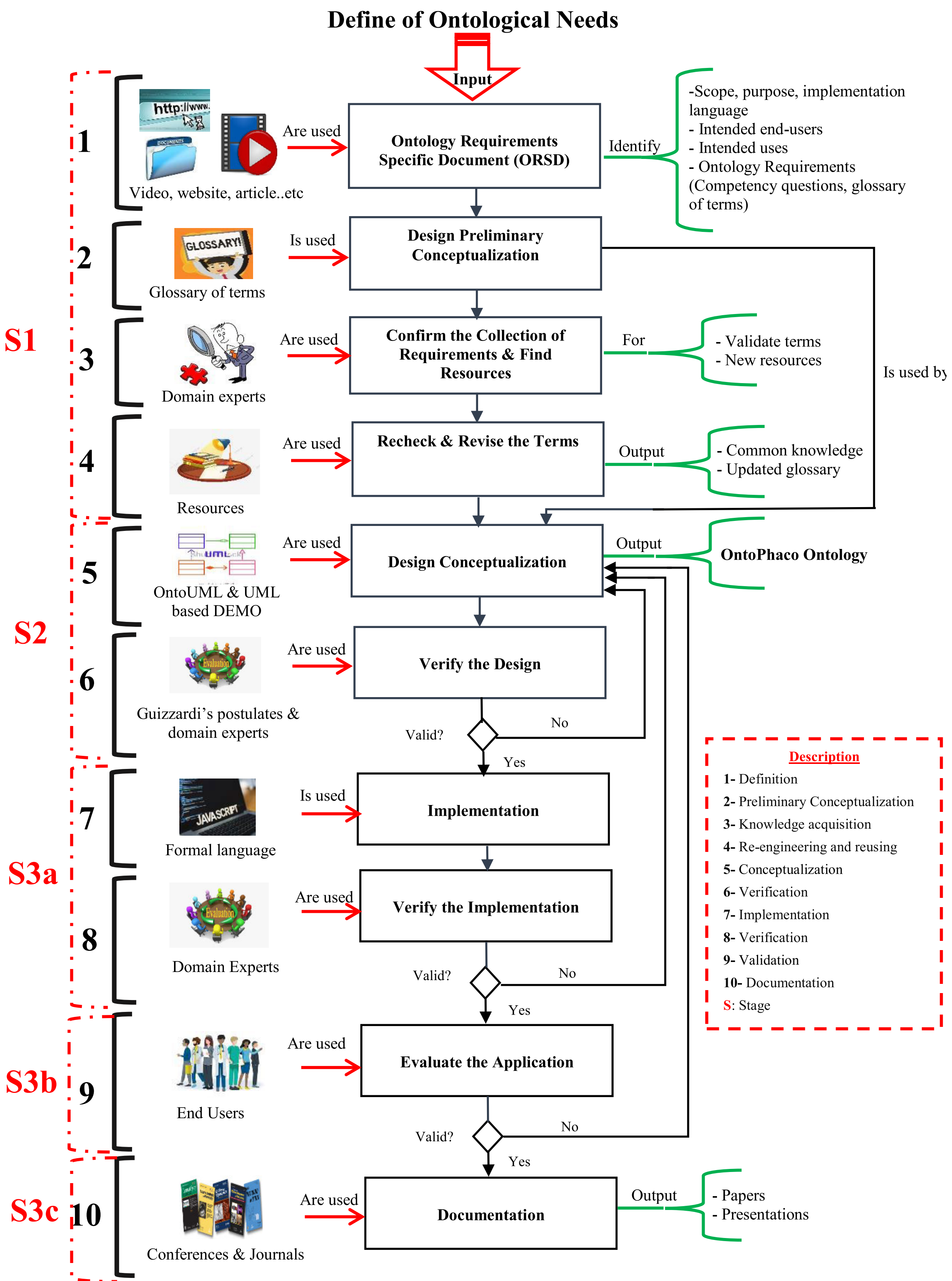


FIGURE 1. Proposed methodology for designing OntoPhaco.

TABLE 2. Glossary of some confirmed terms.

Ophthalmology Training; Human Resources; Theory Training; Practical Training; Patient Care; Procedure; Inpatient; Outpatient; Emergency; Surgical Procedure; Non-Surgical Procedure; Diseases; Knowledge; Experiences; Skills; Qualification; Student; Hand; Acquired knowledge; Student Skill; Understanding; Patient; Resources; Medication; Instrument; Tool; Anatomy; Educational Material; Cataract Disease; Type of Cataract; Causes of Disease; Eye Anatomy; Cataract Medication; Material; Device; Drug; Pe-operative Medication; Intra-operative Medication; Post-operative Medication; Anatomy Information; Instrument Information; Medication Information; Pre-Operative Examination; Intra -Operative Surgery; Post-Operative Complication; Extracapsular Surgery; Intracapsular Surgery; Phacoemulsification Technique; Grasp Instrument; Select Anatomy; Replace Instrument; Select Insertion Place; Enter The Instrument (trapezoidal blade); Create Architecture Of Incision; Guide The Instrument (To The Entire Chamber); Remove The Instrument; Grasp New Instrument; Select Insertion Place; Enter The Instrument; Select Anatomy; Place Instrument; Puncture Anatomy; Replace The Instrument; Grasp Tear of Anatomy; Guide Tear; Create Capsular Flap; Fold The Flap; Re-Grasp The Flap; Begin The Curvilinear; Optimize Control Of The Tear; Remove instrument; …etc

4) RE-ENGINEERING AND REUSING

In spite of the fact that the latter phases assist in the extraction of the required concepts, some current terms are not entirely efficient, as they exist in a way to achieve expressiveness and explicit ontology. Therefore, contents in Table 2 should be checked, assessed, and compared. Thus, the OntoPhaco should only use the most convenient resources. In this stage, the extracted knowledge is reorganized and harmonized into common knowledge that covers the domain of interest for cataract surgery. Table 3 illustrates some of the identified shared knowledge components.

TABLE 3. Samples of the common knowledge for OntoPhaco.

No	Source	Subdomain	Common knowledge
1	Manual for trainees and supervisors	Supervisors Team	Candidate Supervise; Supervise; Evaluate; Send Report;
2	Manual for trainees and supervisors	Student	Mental State; Motivation; Self-Efficacy; Self-Actualize; Emotional State
3	Manual for trainees and supervisors	Evaluation Level	Weak; Satisfactory; Good; Excellent
4	Peeters et al. [22]	Competency Level	New Skill; New knowledge; Attitude

From the above table (Table 2), it is indicated that the pre-conceptualization phase creates a number of concepts that are actions or procedures (perdurants). The latter concepts are the backbone to model the domain of cataract surgery.

Hence representing only an endurant ontology is not enough; however, in order to explicitly represent the whole system, it is significant to initially design the endurant ontology of the top level of the ophthalmology training, as well as an ontology of the low level of cataract surgery.

Based on Table 2, the collection of concepts can be characterized into two groups, endurants and perdurants, based on their prospective attention for each ontology. The endurant concepts will be utilized to develop the OntoPhaco ontology, whereas the perdurants will be used to design the Phaco steps ontology. Bear in mind that some concepts in Table 2 are revised, harmonized, and reconciled to serve the purpose of ontology.

B. STAGE 2 – CONCEPTUALIZATION

1) THE DEVELOPMENT OF ENDURANT ONTOLOGY

The knowledge of ophthalmology is very huge and the exact meaning of key terms of its concepts can occasionally vary among ophthalmologists. For these reasons, domain experts repeatedly check the design in terms of completeness and consistency until they feel that it is complete and coherent. If there is any unreliable usage of concept definitions among sources, then the processes of reconciliation and harmonization to fit the ontology aim are required.

For instance, the concept device that is introduced in the pre-conceptualization stage refers to the instrument or tool that is used to perform some tasks. Whereas, the planned device is a kind of substance that is utilized during cataract surgery. Thereby, the term Material is used to reflect the proposed definition. According to Table 2, at the pre-conceptualization stage, knowledge of the domain is structured and arranged into expressive models at the knowledge level. Therefore, there is enough knowledge and machinery to begin designing the OntoPhaco ontology (endurant ontology). Basically, having a well verified preliminary conceptualization and a glossary of terms greatly assists in rigorously building this ontology.

The upper ontology from UFO [41], [42] has been used to provide the skeleton for OntoPhaco. OntoUML is employed to represent endurant entities (see Fig. 2).

This stage is an iterative one, where it is repeatedly applied until the conceptualization (OntoPhaco) is theoretically validated, and the included knowledge is double checked by the domain experts.

At this level, whereas all concepts are determined and reconciled, relations between top level and low level in the ophthalmology training domain are identified. Based on OntoUML, the syntaxes of individual relations are represented as lines and associations between them. Table 12 illustrates examples of the indicated relationships among concepts in OntoPhaco.

2) THE DEVELOPMENT OF PERDURANTS ONTOLOGY

In the first glossary it is noted that the initial concepts and terms have a number of concepts that are considered as procedures or actions (perdurants). These concepts are categorized as endurant or perdurant based on their prospective attention for each ontology. Therefore, up to this stage, there is enough knowledge and machinery that can be used in designing the perdurants of cataract surgery (Phaco technique). As indicated in [43], any individual perdurant (Speech Act) is supported by an endurant (Institutional Fact). Both models follow

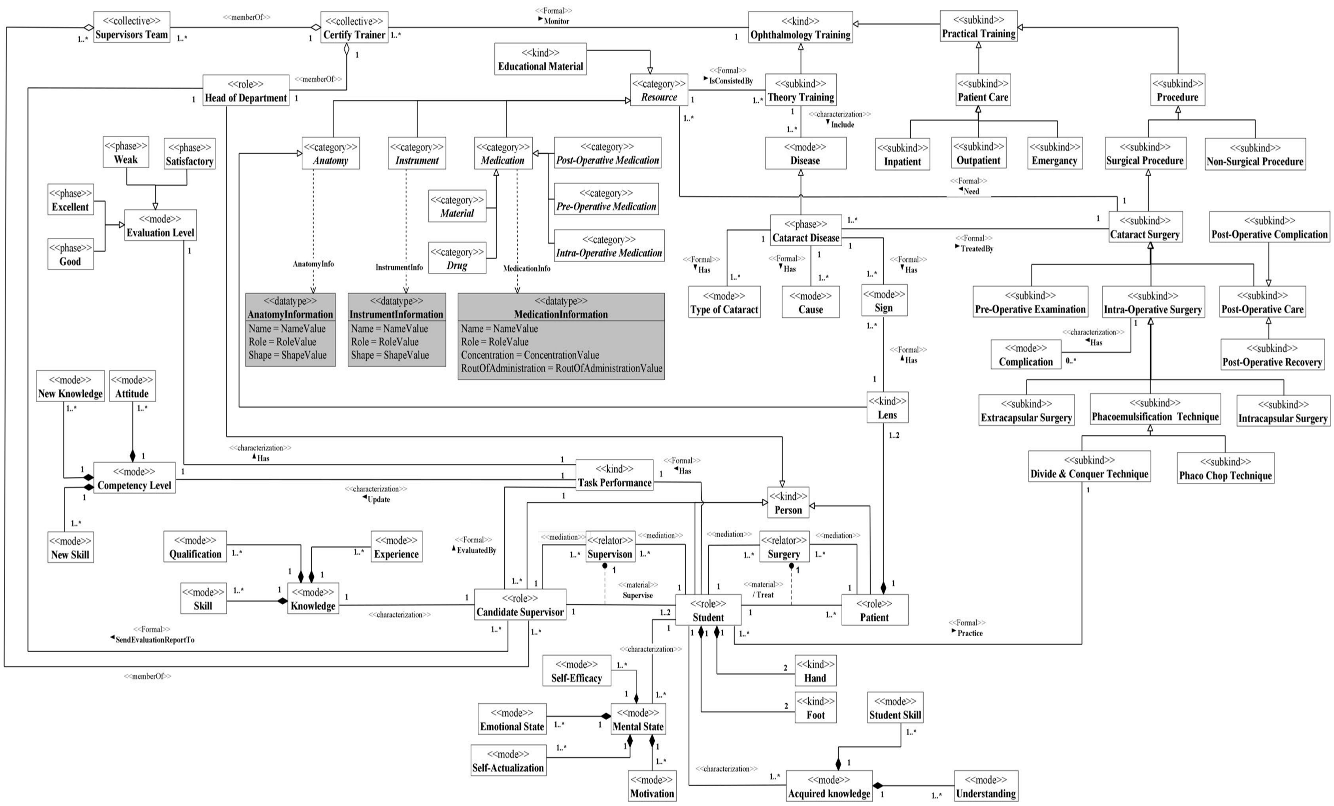


FIGURE 2. OntoPhaco.

TABLE 4. Concepts for Create_1 perdurant ontology.

Perdurant	Concepts
Create_1	Grasp The Instrument; Select Insertion Place; Enter The Instrument; Create The Architecture Of Incision; Remove The Instrument

TABLE 5. Concepts for Create_1 perdurant ontology and their definition.

Concepts	Definition
GraspTheInstrument	To select the instrument that will be used to create incision
SelectInsertionPlace	The place where the incision is to be created, is selected
EnterTheInstrument	The instrument is entered at the located place
CreateTheArchitecture OfIncision	Required architecture of incision (The intrastromal length of the incision equal to the width of the incision) is created
RemoveTheInstrument Out	The instrument is removed from the first incision

the Speech Act, whereas the Classes model is represented using the profile reported by Guizzardi [41]. Therefore, the development of each perdurant for cataract surgery (Phaco technique) is demonstrated in the next sections based on Guizzardi's profile [41] [42] and the Speech Act profile [43].

a: DEVELOPMENT OF CREATE_1 PERDURANT ONTOLOGY

As shown in Table 2, the initial terms contain concepts that are classified as procedures for creating the first incision in the Phaco technique under cataract surgery. Therefore, a list of concepts connected to the create step are presented in Table 4.

As this conceptualization phase is an iterative one, some sub-steps related to the creation of the first incision step in Table 2 are deleted based on the recommendation of ophthalmologists. For example, sub-steps like grasp instrument (Globe), select anatomy, and place globe were frequently used in old techniques and are no longer in use currently. Additionally, as shown in Table 6, that the steps' names are reconciled due to their similarity. For example, in the create incision step, the student should create 2 incisions. In each create incision step, therefore, the number 1 is added to the name in order to distinguish between steps. Additionally, for the other concepts, it has been found that they commonly and completely cover the creating of the first incision procedure. Thereby, the Create_1 step starts by grasping the instrument. Accordingly, student selects the insertion place and enters the instrument. During entering, student should pay special attention to the architecture of the depth and length of the incision, which is important to avoid any complications later on. Table 5 illustrates all the concepts for the create first incision perdurant ontology and their descriptions once they are harmonized.

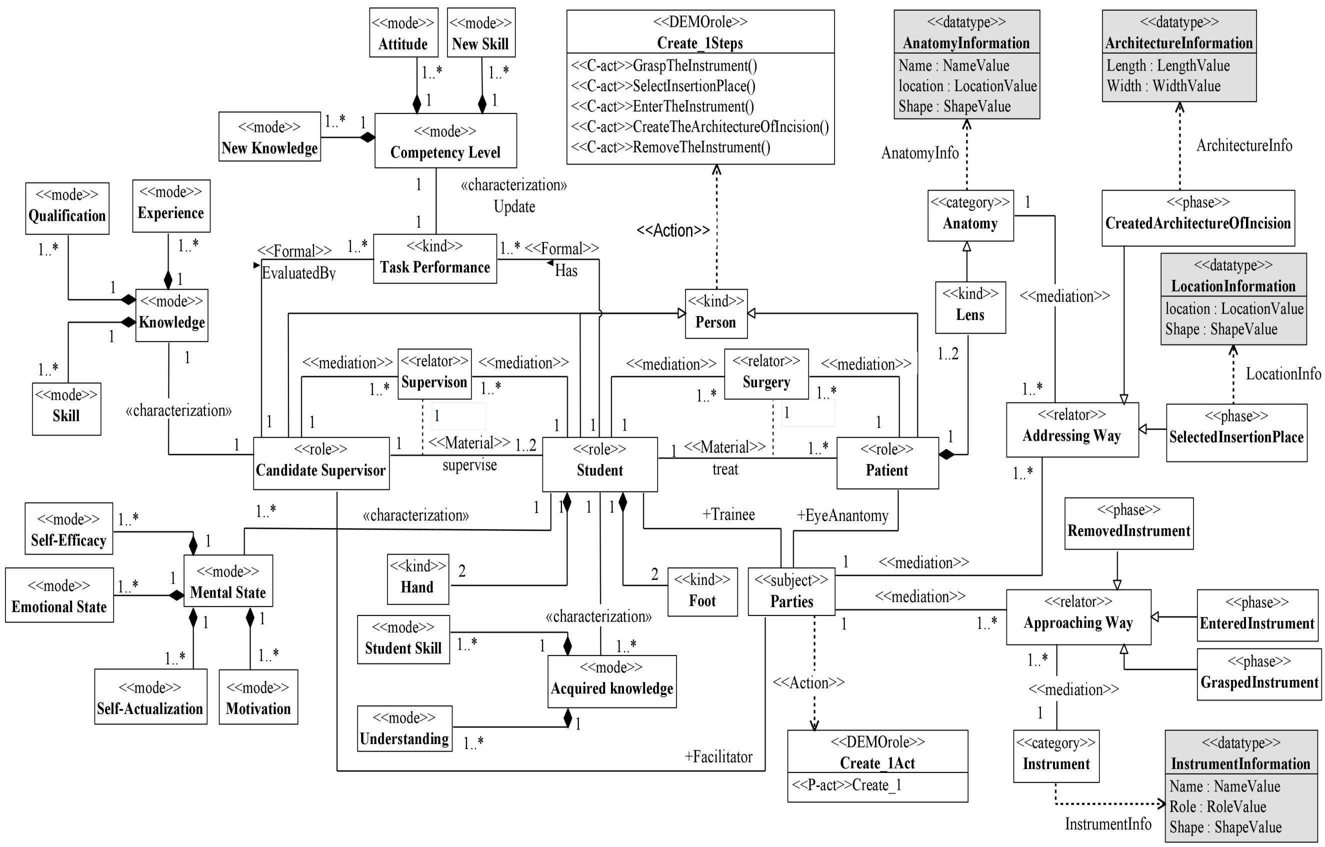


FIGURE 3. Endurant ontology of Create_1.

In the DEMO model, every sub-step in the procedure represents a type of Speech Act referred to as a coordination act or a **C-act**. The **P-act** will only exist if the **C-acts** are successfully established. Therefore, **C-acts** are packaged in a way as to produce **P-acts**. **P-acts** create the institutional facts. Basically, a **P-act** is the creation of an instance of, GraspTheInstrument; SelectInsertionPlace; EnterTheInstrument; CreateTheArchitectureOfIncision; RemoveTheInstrument, respectively.

In Fig. 3 the subjects refer to all the people who have the ability to take responsibility. The **Person** class is stereotyped as ≪**subject**≫, which is appropriate for the model **Person**, utilizing the Guizzardi metamodel. In the OntoUML language, **Person** is also stereotyped as ≪**kind**≫. **Person** is defined as formal organization member. **Role** of a person is described as the way in which the subject can participate in a transaction. This role is specialized by the organizational unit member, whereas he or she is assigned a particular role in the organizational unit. Two interfaces are located in the model. The first is **Create_1Act** that reinforces the operation of **Create_1()**, and the second one is **Create_1Steps**, which carries the procedure of performing the conforming coordinating Speech Acts. **Create_1Act** is stereotyped as ≪**DEMORole**≫ and is executed by a class called **Parties**, which are stereotyped as ≪**subject**≫. **Parties** gather all the subjects who collaborate in the **P-act**. **Create_1Steps** is stereotyped as ≪**DEMORole**≫ and is implemented by **Person**. The class **Parties** has three properties, **Trainee** of type **Student**, **Facilitator** of type **Candidate Supervisor**, and **Eye Anatomy** of type **Patient**. **Student** performs cataract surgery following the Phaco technique steps. Each step consists of several sub-steps, and it requires involvement of some objects to ideally perform surgery, including instrument and anatomy.

A trainee connects the **Instrument** and **Anatomy** entities using an intervening.

The latter individual is called a **Relator**. **Approaching Way** and **Addressing Way** are classes that are stereotyped as ≪ **relator**≫, connecting **Instrument** and **Anatomy** with **Student**, respectively. Each relator has several classes stereotyped as ≪**phase**≫, which represent partitions of a relator. For example, **Approaching Way** has different phases on how **Student** uses an instrument to perform surgery. We start and explore this further by conducting the first **P-cat** which is about the **Create_1** incision as followings:

1) **Student** from **Parties** begins the step by conducting the first **C-act** from the **Create_1Steps** interface; thus, the instrument is grasped as a first activity **Phase** under **Approaching Way**. The instrument has specific attributes (e.g., name, role, shape) based on the **InstrumentInformation** that is stereotyped as ≪**datatype**≫.

FIGURE 4. Perdurant ontology of Create_1.

2) **SelectInsertionPlace** is the second **C-act**, whereas **SelectedInsertionPlace** is the phase of **Addressing Way**. The latter phase has its own datatypes that allocate the right location of insertion of the instrument, as well as provide a shape or image showing the insertion's location.
3) The third **C-act** is about **EnterTheInstrument** through the selected place of insertion. The **Phase** of **EnteredInstrument** is a one of a kind event under **Approaching Way**.
4) **CreateTheArchitectureOfIncision** is the fourth **C-act**, which also has specific information and a specific width and length. This dimension is important to avoid any complication later on.
5) Finally, the **Student** performs the last **C-act** by removing the instrument. **RemovedInstrument** is the last phase in **Approaching Way**, where the **Student** finalizes the endurant ontology **Create_1** incision as the first step and produces the **P-act** by making one wound in the eye anatomy.

Fig. 4 displays the perdurant ontology. This consists of substeps of **Create_1()** whose (UML) context is **Create_1Act**, which is stereotyped as ≪**P-act**≫, the same as the declaration in its interface. **Create_1()** has five sub-step nodes. All sub-steps are stereotyped as ≪**C-act**≫. Each **C-act** has a local pre- and post-condition to specify the **C-acts**. This approach helps in providing more semantic knowledge on the DEMO profiles. For example, the **C-act**, **CreateArchitectureOfIncision**, has pre- and post-conditions. This approach notes that the post-condition of a **C-act** is the precondition for the next **C-act** or **C-acts** (in some cases there is fork). The activities of **Create-1** are represented in sequence and logical progression. Each activity node has a local precondition. This approach enables the instance of Person to implement the actions of the appropriate person; this can be achieved from the instance of **Parties**, which is in charge for performing the included activity. For instance, in **Create-1**, the first activity node has a pre-condition which mentions "Student executes number of tasks"; from here, it can be understood that the instance Student is involved in the first activity.

The action **Create_1()** transfers two instances of the phase subclass **SelectInsertionPlace** to the phase subclass **CreateArchitectureOfIncision**. It can be concluded that a system of phase subclasses is inadequate without the sub-steps of **Create_1**, which can change objects from one phase to another.

All the following models for the designed perdurant (Speech Act) and associated endurant (Institutional Fact) follow a similar approach. Table 6 presents the main steps of

TABLE 6. P-Acts in Phaco technique and the institutional facts created by them.

The Main Steps	Steps Based HUKM	Perdurant		Endurant	
		P-Act	Figure	Created Institutional Facts	Figure
Corneal incision	Create Incision (2 Incisions)	Create_1	4	Created first incision	3
		Create_2	See Table 7	Created second incision	See Table 7
Capsulorhexis	Create an Opening	CreateOpening	15	Created an opening on the lens	16
Phacoemulsification	Create a Groove	Groove_1	17	Created a groove on cataract	18
	Divide the cataract	Divide_1	19	Divided the cataract into half	20
	Rotate the cataract	Rotate_1	21	Rotated the cataract	22
	Groove the first half of cataract	Groove_2	See Table 7	Grooved the first half of the cataract	See Table 7
	Divide first half of cataract	Divide_2	See Table 7	Divided the first half of the cataract into a quadrant	See Table 7
	Rotate the cataract again	Rotate_2	See Table 7	Rotated the cataract again	See Table 7
	Groove second half of cataract	Groove_3	See Table 7	Grooved the second half of the cataract	See Table 7
	Divide second half of cataract into quadrant	Divide_3	See Table 7	Divided the second half of the cataract into a quadrant	See Table 7
Intraocular lens implantation	Inject artificial lens	Inject	23	Injected artificial lens	24

Phaco technique and correspondent figures of the perdurants and endurants

The Table 6 consists of some steps that have similarities in activities. In this article, therefore, only one example is presented, and the others can follow a similar ontology. Table 7 shows the similar steps and their differences among each other

TABLE 7. Similarities and differences among steps.

Step	Similar to	Differences
Create_2	Create_1	At the first activity in Create_2, one should choose a different instrument than what is used in Create_1
Groove_2 & Groove_3	Groove_1	In Groove_2 and Groove_3, there is no need to grasp another instrument and set it. It only requires using the inserted instrument directly and sculpting the first and second half of the cataract, respectively.
Divide_2	Divide_1	Here, there is a need to crack the first half of the cataract in Divide_2
Rotate_2	Rotate_1	Only one difference which is about rotating the second half of the cataract in step Rotate_2
Divide_3	Divide_2	Here, there is only a need to crack the second half of the cataract in Divide_3

3) VERIFICATION

Verification is kind of an ex-ante evaluation (see Fig. 1) which is assigned to evaluate the design conceptualization. This stage is the continual and iterative activity of conducting a technical judgment of the designed ontologies, with respect to the ontology requirements specifications document, during the conceptualization phase. This verification is the first evaluation of the included knowledge that is extracted from the previous stages. Here, the domain experts repeatedly check the design in terms of completeness and consistency until they feel that it is complete and coherent. OntoPhaco is further verified using Guizzardi's postulates and ontology experts.

a: EVALUATION OF ONTOPHACO USING GUIZZARDI'S POSTULATES

This stage is included before the implementation of OntoPhaco, which is considered as an ex-ante evaluation. All designed ontologies were evaluated using Guizzardi's postulates and had further undergone criteria-based evaluation.

Four postulates were specified in Guizzardi's work [41] that any designed conceptual model using OntoUML must fulfil in order to be semantically and syntactically correct.

A. *Postulate 1*: "*Every individual in a conceptual model (CM) of the domain must be an instance of a* *conceptual modeling type (CM-Type) representing a sortal*''.

The meaning of Postulate 1 is that each object that is represented in a CM using the OntoUML modelling language, must be an instance of a Kind, either directly or indirectly. A substance sortal is stereotyped as a ≪ **kind** ≫ in OntoUML, to which it supplies a principle of identity and individuation for its instances. Consequently, every object in the OntoPhaco ontology must be an instance of a Kind.

B. *Postulate 2*: ''*An individual represented in a conceptual model of the domain must instantiate exactly one CM-Type representing an ultimate Substance Sortal*''.

Based on Postulate 2, every single object in a CM using OntoUML as a modeling language cannot be represented as an instance of more than a unique ultimate **kind**, whereas it is understood that two kinds supply different principles of identity. Fig. 5 displays an example that explains how one representation of a CM breaks this postulate.

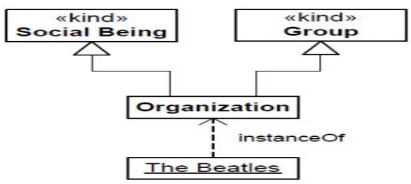


FIGURE 5. Example presenting an instance receiving different principles of identity [42].

In order to verify and evaluate the research's models according to Postulate 1, Postulates 1 and 2 are combined for briefness in order to easily conduct the verification on extracted excerpts from different models. Therefore, by merging both Postulate 1 and 2, it becomes, ''*Every single object in a conceptual model which is represented by OntoUML, must be an instance of a Kind, either direct or indirect (Postulate 1), and it cannot be represented as an instance of more than one ultimate Kind (Postulate 2)*''. Fig. 6 presents anthologies of conceptual models of OntoPhaco ontologies for **kind** stereotypes, and their positions with respect to both postulates. Anthology (1) presents that **Inpatient**, **Outpatient** and **Emergency** are ≪**subkind**≫ specializing in **Patient Care**. An instance of **Inpatient** could be any patient who needs to stay in a hospital for more treatment, and an instance of **Outpatient**, conversely, refers to any person who does not need to stay, whereas **Emergency** could be any patient who needs immediate examination. **Theory Training** is also a ≪**subkind**≫ specializing in **Ophthalmology Training**, and its instance could include educational materials or resources. All existing objects are instance of a **kind** (e.g., **Ophthalmology Training**), which is either direct or indirect (Postulate 1). In the same way, it is obvious that every possible object is an instance for only one ultimate **kind** (postulate 2).

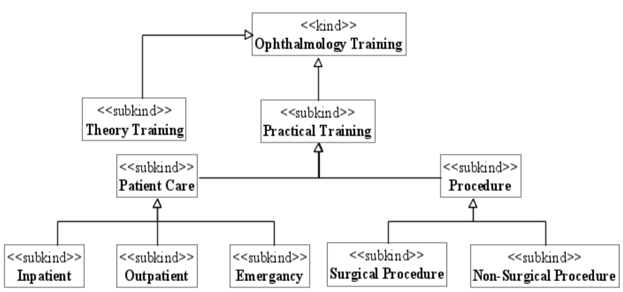


FIGURE 6. Anthology (1) of a conceptual specification of OntoPhaco ontology.

C. *Postulate 3*: ''*A CM-Type representing a rigid universal cannot specialize (restrict) a CM-Type representing an anti-rigid one*''

The Third Postulate proposes that anti-rigid universals which are stereotyped as **role** and **phase,** cannot be represented as super-type of a **kind** in a conceptual model. For instance, Fig. 7 presents a problem where a **Customer** as anti-rigid is represented as a super-type of a **kind** (e.g., **Person** and **Organization**). This issue fractures the third Postulate.

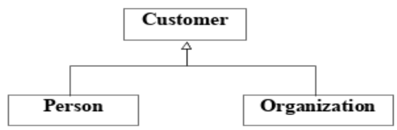


FIGURE 7. Problematic in representing Role in conceptual modeling [42].

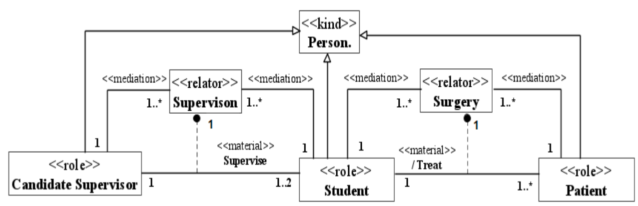


FIGURE 8. Anthology (2) of conceptual specification of OntoPhaco ontology.

Fig. 8 presents that all existing anti-rigid universals and roles (e.g., **Candidate Supervisor**, **Student** and **Patient**) are modeled as subtypes of a **kind** (Person). As shown, all Roles are not represented as a super-type of a **kind**.

D. *Postulate 4*: ''*A CM-Type representing a dispersive universal cannot specialize a CM-Type representing a Sortal*''.

Postulate 4 means that every class, which is stereotyped as ≪**mixin**≫, cannot appear as a subclass to any object that is stereotyped as **kind**, **phase**, or **role** in a conceptual model. **Mixin** has the ability to represent the top types like entity, element, and thing. Additionally, a few mixins describe fundamental properties that are common to all of their instances, and these themselves are a rigid type, as illustrated in Fig. 9. In this case, the stereotype ≪**category**≫ is used to represent a rigid mixin that subsumes several kinds.

Some mixins, on the other hand, are stereotyped as ≪**roleMixin**≫. The aim of this anti-rigid is to represent

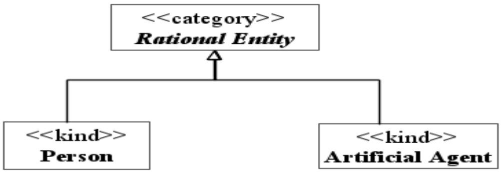


FIGURE 9. An example of category a rigid mixin [42].

abstractions of common properties of roles. Additionally, a few mixins describe properties that are fundamental to some of their instances, and coincidental to others (anti-rigid non-sortal). Hence, all mixins cannot be represented as subclasses of phases, kinds, or roles.

Additionally, based on postulate 3, rigid mixins (categories) can only be subsumed by other ≪**mixin**≫ or ≪ **category**≫. In a UML conceptual model, a **mixin** must always model as an abstract class due to the absence of direct instances. Fig. 10 shows the anthology of a conceptual model of OntoPhaco and endurant ontologies, where all mixins do not appear in the conceptual model as a subtype of a **kind**.

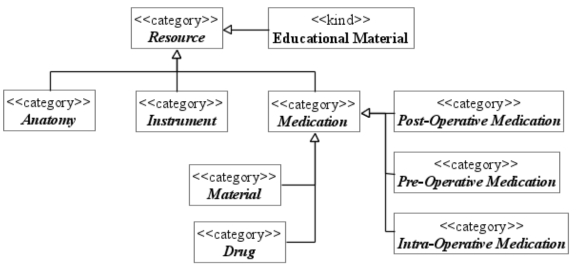


FIGURE 10. Anthology (3) of a conceptual specification of OntoPhaco ontology.

b: CRITERIA-BASED EVALUATION OF ONTOPHACO ONTOLOGY

As previously indicated, a conceptual model is commonly represented by a graphical design. It often represents the individual's or team's design perceptions of the domain of interest. Consistence, coherence, expressiveness, and completeness are some crucial criteria that should exist in any conceptual model. Any single defect could have serious consequences in terms of cost, time, and effort. For example, it can lead to a misunderstanding or wrong interpretation of user requirements, resulting in poor system design. As such, it can definitely be one of the root causes of application failure.

After OntoPhaco was syntactically and semantically evaluated, in this section, the ontology was evaluated based on a variety of criteria. In order to achieve that, each individual concept was reviewed based on the selected criteria by conducting interviews with the Subject Matter Experts (SMEs). The latter experts verified the content of the proposed ontology with regards to coherence, expandability, minimal ontological commitments, conciseness, completeness, coverage, and correctness. The details and the results of the interview sessions are subsequently presented in the next sub-sections.

Methods and Data Collection for Ontology Verification: The interview method is one of the most significant techniques used in collecting valuable and accurate qualitative data. In this research, individual online interviews were conducted to collect more data and to verify the knowledge level that is represented in OntoPhaco and all the perdurant ontologies (Phaco Steps). Online interviews were selected as there were no opportunities to conduct face to face interviews, due to the movement and meeting restrictions imposed because of the Covid 19 pandemic. The meetings were conducted with highly experienced domain experts in the ophthalmology field, who were selected to contribute to this phase with regards to data collection and ontology verification. Using this approach helps in avoiding long and difficult questionnaires which would have to be used to verify about 37 ontologies (endurants and perdurants) and would consist of more than 150 concepts. For verification and refinement of OntoPhaco, two ophthalmologic experts were involved as participants from the ophthalmology domain department. It is worth noting that the choice of participants was based on some criteria, including professional experience in the field of ophthalmology, qualifications, knowledge about the domain, and positions. The aim of this verification was to utilize their feedback and recommendations to verify the proposed ontology that was built based on OntoUML, and UML based DEMO, and to subsequently enhance and refine it.

At first, an overview of the OntoPhaco ontology was presented to the domain experts. Then, the main concepts, their subclasses, and relationships between them, either endurant or perdurant, were shown and discussed with them. Consequently, feedbacks and proposed changes were reordered and considered. These suggestions included changing names and deletion of some concepts, as well as addition of new concepts.

Results of Verification and Refinement of OntoPhaco: In the following sub-sections, ophthalmologists' feedbacks are discussed in order to refine the designed ontologies as part of the criteria-based evaluation stage.

Clarity: In this criteria, ontology, as defined, should "*effectively communicate the intended meaning of the defined terms*" and the definitions should be, as much as possible, indicated formally [31]. In the perspective of formal definition of included terms in the proposed ontology, since the terms were mostly extracted from several sources related to the domain, the availability of formal definitions is confirmed for the majority of the terms. On the other hand, the involvement of SMEs was significant in the way to entirely review the terms and accordingly provide feedback. The ontology was hence refined efficiently.

Examples — As mentioned before, the terms in an ontology should be defined clearly in a way that there is no ambiguity. For instance, having the consideration that OntoPhaco ontology had a "**Device/Material**" as a key concept under "**Medication**". The first concept had two terms that were extracted from publication sources. Both terms are used as kinds of substances that are either utilized to treat cataract disease or used during cataract surgery. In order to avoid any conflict between the term device, which refers to an instrument, and device, which refers to a substance, the term "**Material**" was selected to enhance the clarity.

TABLE 8. The changed concepts based on criteria-evaluation.

Old Concept	New Concept
Device	Material
Human Resource	Certify Trainer
Symptom	Sign
Post-operative surgery	Post-operative care

The concept of "**Human Resources**" had also been included to monitor the **Ophthalmology Training**. In the online interview, it was found out that this concept was holding an ambiguity. There could be a specific type of manpower of human resources involved in the ophthalmology training domain. The previous concept is commonly observed to be the responsibility of monitoring ophthalmology in general, rather than in a particular domain like ophthalmology training. Since the OntoPhaco ontology selected ophthalmology training as the domain of interest, this term was changed to "**Certify Trainer**". In this way it assists to avert the ambiguity and to preserve clarity.

***Consistency/coherence*:** The included concepts and terms in ontology should be a logical coherence and without any ambiguity and conflict. This helps to avoid building of an incoherent ontology. Gruber [31] reported that "*If a sentence that can be inferred from the axioms contradicts a definition or example given informally, then the ontology is incoherent*" (P.909).

Examples — Primarily, **Cataract Surgery** was broken into three subclasses including **Pre-operative Surgery**, **Intra-operative Surgery**, and **Post-operative Surgery**. On the other hand, a ≪**formal**≫ relationship was created between **Post-operative Surgery** and **Post-operative Complication**. According to [44], the **Post-operative Surgery** concept is about a recovery process that every patient should follow, where some recovery instructions are given in order to avoid any risk. Whereas, **Post-operative Complication** is a procedure that is conducted to manage some complications that might appear on the patient after cataract surgery. Examples of this procedure include management of the small pupil, YAG, managing posterior, capsular rupture, preventing postoperative infection, and preventing postoperative inflammation. Hence, patients, after surgery, take recovery time at home. However, they are strongly advised to follow the instructions of the eye doctor. If any problem is encountered, they are required to report to the doctor immediately. This approach helps to keep them at low risk from any complications of the cataract procedure. It is also worth indicating that cataract surgery has a great success rate with less complications. The above representations and inferences, however, were considered inconsistent and conflicting with the defined concepts. According to the feedback, the concepts of **Post-operative Surgery** were changed to be as **Post-operative Care**, and a **Post-operative Recovery** class was added to cover the missing knowledge.

***Conciseness*:** This criterion measures whether all the knowledge included in an ontology is accurate and meets the requirements of domain experts. It should additionally avoid any unnecessary redundancies [26]. The consideration of this criterion was carefully carried out through the ontology development and verification process.

An example — The only unnecessary term utilized in the ontology was "**Symptom**". This term was initially used to specify the concept Patient's situation. Hence, a ≪**characteristic**≫ relation was held between the latter concepts. Based on domain experts, this term was considered redundant and it should be replaced, because during surgery, there is no need to know about symptoms anymore. The only thing that the student needs to know are the signs that exist in the lens. Therefore, the concepts of "**Lens**" and "**Sign**" were included. "**Lens**" is represented as **ComponentOf** "**Patient**", which has a ≪**formal**≫ relationship with **Sign**.

***Expendability*:** This criterion refers to the ability to extend an existing ontology by adding new definitions. It is also defined as the effort required to add new information to a definition without modifying the set of well-defined terms and concepts that are formally verified with domain experts [26]. Two roles are adopted in this research to support the expendability criteria. On the one hand, reusability is one of the distinguished roles in the ontology domain that can drastically minimize the effort and time needed for building up new learning scenario models. Considering this benefit is highly promising in order to speed up the development of VRT processes and simultaneously reduce the cost. On the other hand, separating knowledge from both system and domain is essential. This role enhances the reusability of the body of knowledge across divers of systems design. However, it should be supported by a separation of an upper ontology from a lower ontology. Using a top ontology would increase the vocabularies and limit difficulties in extending or integrating with existing ontology. Therefore, OntoPhaco was, as a result, built based on UFO and DEMO theory to develop a well-structured domain ontology and an independent application in a way that it can be used across training domains.

Examples—The ophthalmology domain consists of many diseases such as cataract and glaucoma. Let us assume that the ontology for cataract surgery has already been designed. If any ontology engineer wishes to design an ontology for glaucoma disease, they need to only use the existing ontology and extend it with the process of glaucoma surgery, because the domain knowledge is already there. Note that, the feasibility of this role can exist through the application of an upper ontology. This includes UFO with the help of its language (e.g., OntoUML), as they are the most truthful and explicit [45]. This approach enables us to separate the general knowledge from the specific knowledge, and to build the skeleton of the whole domain. As a result, the chances of reusability will be substantially increased. Therefore, selecting the right upper ontology and its language is highly recommended. This would help promote the effectiveness of reusing an existing ontology, which would assist in drastically avoiding any redundant efforts and time spent for building up new virtual training scenarios.

***Correctness*:** This criterion indicates that the valid conceptualization of real-world concepts is correctly represented by the ontology [29]. The correctness of OntoPhaco had been the central emphasis of the verification stage. The recommendations and documents provided were extremely guided to verify this criterion.

An Example — In OntoPhaco, ''Intra-Operative Surgery'' is a sub kind of ''Cataract Surgery''. The first concept, in turn, has several subclasses like ''Phacoemulsification Technique'', ''Extracapsular Surgery'', and ''Intracapsular Surgery''. The previous concepts were specifically reviewed according to the provided documents and the feedback of domain experts.

Minimal Ontological Commitment: Minimal ontological commitment means that the designed ontology should provide more freedom and flexibility to parties committed to the ontology in order to specialize it, where there is a need of that. One approach to achieve such criterion is to assure ''*as few claims as possible about the world being modelled*'' [31]. This criterion was notably revised by using UFO. It is a good candidate as a foundational ontology to build the skeleton for the VRT domain, and a strong modeling language (e.g., OntoUML) in order to guarantee interoperability, significant quality, and semantic meaning. Additionally, it deeply takes the human cognition into account. Having OntoUML, on the other hand, supports human activities such as communication matters and problem solving.

Completeness: Completeness is applied to check whether the individual definitions of the ontology are complete [46]. As suggested by Yu *et al.* [29], this criterion can be revised by competency questions that were used in the beginning to identify the most related terms and concepts. The answers to these questions generate an ORSD (see Table 11). The latter document, as per an agreement, must be completely fulfilled by the ontology. Owing to the fact that the size of the OntoPhaco is huge, only some examples of the competency questions are presented in Table 9.

***Coverage*:** Coverage refers to the extent of completeness and coverage of the terms and concepts that are used to represent the domain knowledge [29]. This criterion is much proper for a data-driven evaluation, which is applied to evaluate how far an ontology significantly represents the domain of interest. The concepts of OntoPhaco centrally focus on the Phaco technique surgery. For this reason, the key steps of surgery were firstly provided by the domain experts. All knowledge related to the surgery was then identified manually from different resources (e.g., videos, articles, and websites). Lastly, the overall extracted knowledge, especially the Phaco technique steps and its details, were mostly verified and compared with domain experts and content in the ophthalmology guideline. Based on the feedback, the ''Rout of Administration'' was forgotten. This attribute is very significant and enables students to gain information on how to administer drugs or materials during cataract surgery (e.g., topical (eye drop), intracameral (injecting), intravitreal). It was hence included under ''Medication Information''. The ''Hydrodissection'' step was also missed out. This is one of the most fundamental steps, and without it, cataract surgery cannot be performed. It was therefore recommended to be added. However, one should bear in mind certain significant considerations; based on the ophthalmologist, this step is not included in current VR technology that was designed for the ophthalmology department in Hospital Universiti Kebangsaan Malaysia (HUKM). This is one proof that OntoPhaco is more comprehensive, and it is able to enhance the current VR technology.

TABLE 9. Some examples of competency questions utilized to evaluate completeness criteria.

Competency Question	Concept	Relation
If you have surgical treatment, what kind of surgeries do you have under this one?	Pre-operative surgery, Inter-operative surgery, Post-operative care	IsSubClassOf
What essential information do students need to know about the medication?	Name, Role, Doze, Concentration, Rout of Administration	MedicationInfo
What kind of competency do students need before starting training?	Student Skill, Understanding	«characterization»

The overall feedback regarding OntoPhaco, from ophthalmologists, was good and encouraging. One of them said ''it is relevant…understandable and all highlighted things look good.'', and further commented ''we don't have a nice map like this''. The second SME remarked that ''the first time when I saw it, it was quite complete''. After positive comments, the proposed ontology was sent to the implementation phase in order to prepare for demonstration and evaluation tasks.

C. STAGE 3a: POST- CONCEPTUALIZATION

1) IMPLEMENTATION

In this stage, an approach of visualizing OntoPhaco describing cataract surgery Knowledge is introduced. This ontology is designed using the OntoUML and UML based DEMO, and the visualization is developed using the D3 library under the JavaScript language. In this research, an interactive tree diagram was chosen. The example of Mike Bostock [47] was significantly edited and enhanced to create a proper interactive visualization for the OntoPhaco ontology.

The knowledge-based tool was developed with the aim of meeting the needs of domain experts and students. Besides that, this visualization could also help during the development

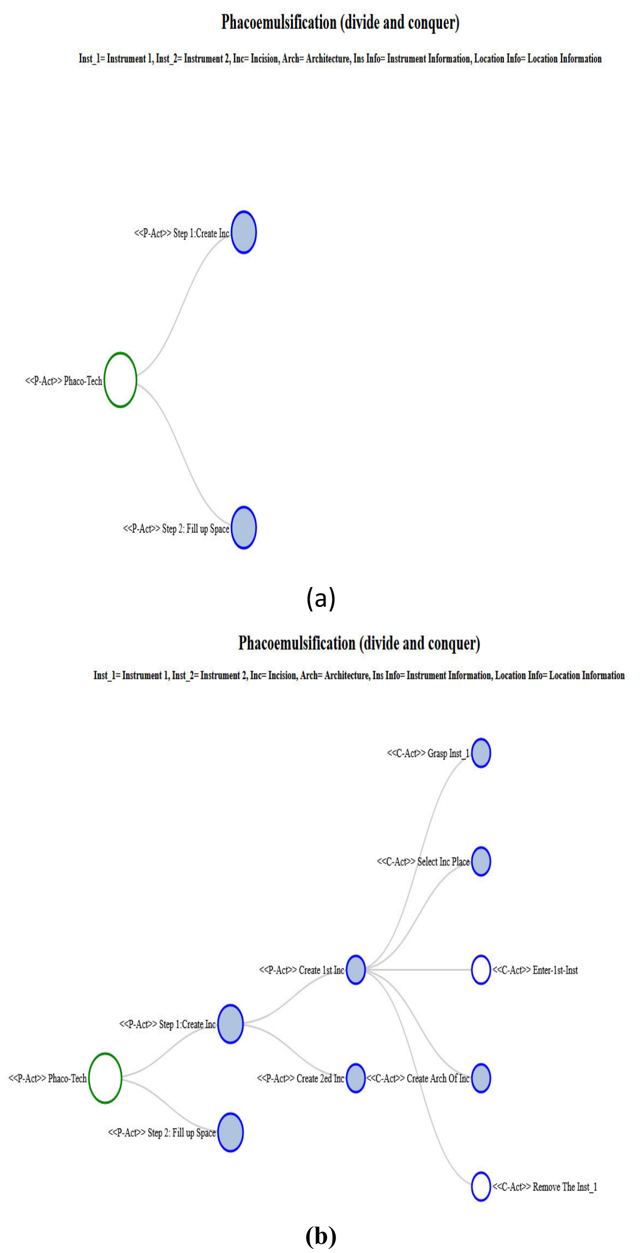


FIGURE 11. Examples of OntoPhaco visualization.

process (knowledge engineering process). A quick overview of the knowledge part could be significantly obtained by developers to select the most related knowledge base. It also assists the ophthalmologic experts in extending knowledge and ideally detecting whether the represented knowledge is complete and up to date. In an OntoPhaco application, the visualization is only limited to two steps related to create incision (Create_1 and Create_2) and fill up space (FillUp_1). Fig. 11 shows part of a collapsible tree presentation. In this case, students can browse any particular step. Reciprocally, they can collapse branches of the tree diagram in one single screen without the need to scroll down. For instance, as shown in Fig. 11a, at first the users display both the steps, and when they click for example, on step1, the node is collapsed into other sub-steps (e.g., Create 1st Inc and Create 2nd Inc). Clicking on the "Create 1st Inc" node produces other sub-steps. Each latter sub-step has its own detailed information that is required by the student to ideally establish the Phaco surgery technique (see Fig. 11b).

An Example— During the process of performing corneal incision, the incision location and architecture of the tunnel are the major concerns. This is because any change in the required dimension of the incision results in difficulties in making visualizations of the anterior chamber, and increases the possibility of astigmatism, where the incision is more likely to leak [15]. The integrating of visual guidance (OntoPhaco application) provides explicit knowledge and a comprehensive guide to assist students in performing safe corneal incision. This application visualizes and presents the ideal location (Limbal Arcade) and architecture of incision (Intrastromal length of the incision equal to the width of the incision) as a guide for students to conduct the incision, as presented in Fig. 12.

It is worth noting that, as the implementation of OntoPhaco applications in VR is out of scope, this study adopted an alternative approach by recording videos during the visualization of the OntoPhaco application on a laptop. Then, the recorded videos were integrated into the VR environment, where the students can use the VR training features and see the videos of OntoPhaco system in parallel. The latter system sequentially directs and reminds users about the surgical steps involved and knowledge related to each procedure. The aim of this dual system is to enhance and preserve awareness and concentration of the students during cataract surgery procedures.

2) VERIFICATION

This stage is like post ante evaluation. Its main aim is to verify the OntoPhaco implementation. It mainly checks whether the ontology is correctly built and whether the ontology requirements and competency questions are correctly implemented. An online interview was conducted with an ophthalmologic expert to review the OntoPhaco implementation. Having such visualizations significantly helped to ideally detect whether the represented knowledge is complete and up to date.

An example— During verification, the domain expert identified unnecessary steps under the Create_1 procedure. These steps were, grasp instrument (Globe), select anatomy, and place globe. Based on the expert's explanation, these steps were frequently used in old techniques, and no longer existed in the new techniques. According to the feedback, the unnecessary steps were deleted to maintain the conciseness criteria.

D. STAGE 3b: POST- CONCEPTUALIZATION

1) APPLICATION BASED- EVALUATION

This kind of approach is under post ante evaluation, which evaluates the artefact after construction. It is a technical

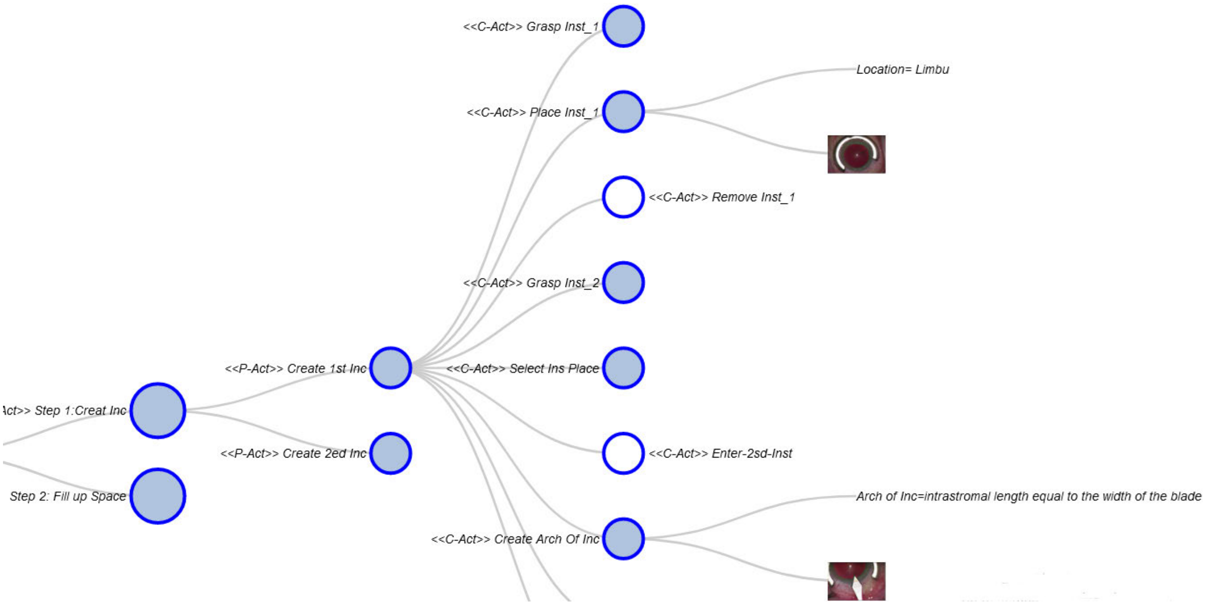


FIGURE 12. The explicit knowledge of incision location and architecture of tunnel.

judgment of the artefact by measuring how well the solution to the problem is being supported by the designed artefact. In order to check the application of ontology, the OntoPhaco visualization is integrated into a VR environment to test its applicability within a real-world situation. A conceptual model is evaluated based on users' opinions in terms of knowledge coverage and utility. This stage requires the involvement of a comparison between the solution's objectives to the current results observed from the utilization of the artefact in the demonstration stage.

In literature, there are no evaluation standards exist that can be used for all sorts of design science research artefacts. A set of evaluation criteria should be, therefore formulated based on the requirements of each project. Thereby, in this stage, mixed mode research was selected to achieve the purpose of the evaluation. The sub-sections below provide more details.

a: EXPERIMENTAL METHOD

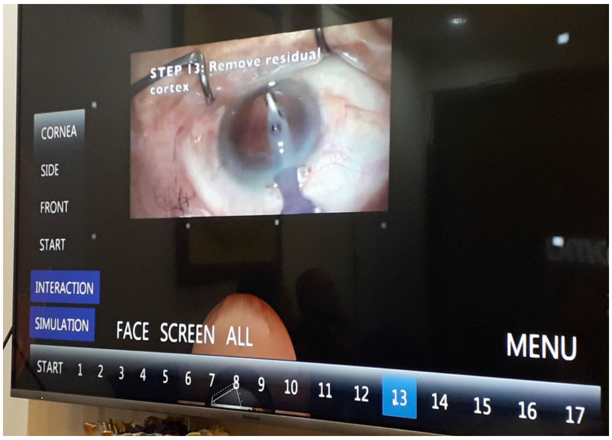
Experimental research is a kind of comparative research. In the experimental method, groups are divided into two dimensions of experimental research designs. The first is the within-subjects dimension, and the second is the between-subjects dimension [48]. Having these two approaches at hand is enough to make basic experimental research design. However, it is worth to note that each method mentioned has its own advantages and disadvantages. Some researches use the within-subject, and some utilize the between-subject methods, and others try to combine. It was recommended by Budiu [49] that if the number of participants are fewer, it is better to use the within-subjects approach. On the other hand, Randolph [48] reported that experimental research can be followed by qualitative methods, which has been seen in different works [50], [51]. In this study, the within-subjects dimension, and a combination of focus groups with experimental method, were selected to further understand, "how the use of OntoPhaco visualization in VRT environment has affected the training experience of students".

b: METHODS AND DATA COLLECTION FOR ONTOPHACO VALIDATION

Before starting the interview, a workshop and a brief session about the study and its objectives was conducted. All the participants were guided to make them more familiar with techniques of maneuvering VR devices and to adapt them to the scene of cataract surgery and OntoPhaco visualization inside the VR environment. Later on, each student was asked to use VRT without the OntoPhaco application at first, and secondly, with visualizations of OntoPhaco (see Fig. 13). Then, an interview was conducted in order to collect data about the experience.

The participants were randomly chosen to participate in this research, where they were recognized as doctors and students who have experience and much knowledge about cataract surgery, especially about the Phaco technique. The proposal of the experiment is that using OntoPhaco visualizations in a VR environment can guide students during the cataract surgery procedure. This experiment does not attempt to evaluate students' experience and knowledge background. Rather, it aims to understand more about how this ontology helps them by providing comprehensive knowledge about the Phaco technique for learning and acquisition of this knowledge during VRT. Therefore, online focus groups were used to collect data about the usability of OntoPhaco visualizations inside VR, as well as to gather learners' experiences of using this visual guidance. In this method, the participants are able to react to what each individual says, whereas the agreement

(a)



(b)

(c)

FIGURE 13. Part from experiment's session.

among the members is not the study's target [52]. 15 doctors and students under ophthalmology departments (HUKM) participated in the experiment. The participants' answers were recorded accordingly and were later transcribed and analyzed based on a selection of themes.

c: THEMATIC METHOD

In this study, thematic analysis was selected as a suitable method for analyzing the findings. Braun and Clarke [53] provided step by step guidance on how to smoothly conduct a good thematic analysis procedure. It is well known in literature, and includes describing, analyzing, and reporting themes in data. This study used an inductive (bottom-up way) and semantic approach. This can be possible by allowing the data to define the theme and only focusing on the explicit content of data.

In their work, Braun and Clarke [53] explained their guidance, which firstly involves familiarizing ourselves with data by reading and re-reading the transcript. Accordingly, they suggested to make notes of first interpretations. As per the guideline, initial codes should then be produced, and the relevant data should also be collated to each code in a systematic manner. Next, the defined codes should be combined together based on suggested themes, and these themes should be further refined to check whether they are logical in connection to the entire transcription. Defining and naming the themes is the last step, which is also when researchers should define the essence of each theme.

For credibility purpose, different approaches were designed by the researchers to minimize bias. However, there is still a continuing debate about terms like validity and reliability, and whether these can be used in qualitative research [54][55]. Due to the lack of universally agreeable concepts and criteria for evaluating qualitative findings [56], this study used the reported strategy in Long and Johnson's [57] work to confirm credibility, which allows respondent validation. In this case study, participant was invited to comment on the defined themes and concepts. This approach helped to check whether these themes and concepts satisfactorily reflected the phenomena.

TABLE 10. Demographic information of participants.

Number	Qualification	Number of Year in the field
10	Doctor	3 - 9
4	Research Assistant	4 - 6
1	Student	4

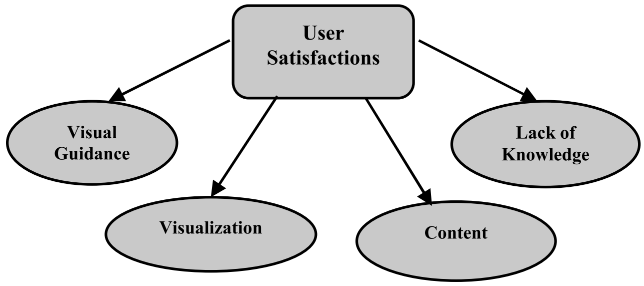


FIGURE 14. Relation among themes.

d: RESULTS

Demographic Findings: Table 10 provides the extracted demographic information that was collected during the experimental session. It is worth noting that the experience years for doctors presented in Table 10 are after 5 years in general

TABLE 11. Ontology requirements specification document.

1	**Purpose** The purpose of designing the ontology is to provide comprehensive and agreed-upon knowledge of cataract surgery that can be used or reused to design VRT for the ophthalmology domain.
2	**Scope**
	The ontology should only focus on cataract surgery and the ophthalmology domain. The level of detail is directly linked to the CQs and identified terms.
3	**Implementation language**
	The ontology will be for human use and not for computational purpose. It will be implemented by using OntoUML as the modeling language, which will assist in representing the conceptual model.
4	**Intended end-users**
	User 1: Ophthalmologists. Who need to communicate with the developers User 2: Medical students. Who use VRT as a training tool User 3: VR developers of VRT in the ophthalmology domain. User 4: Researchers in the field of VRT in the ophthalmology domain.
5	**Intended uses**
	- The designed ontology has to be the foundation for building VRT in cataract and ophthalmology domain. - Promote reusability of the domain knowledge. - To assist the domain experts in assessing cataract surgery training. - To assist the domain experts and designers in providing comprehensive and explicit training of cataract surgery. - To guide medical students during training inside a VR environment.
6	**Ontology requirements**
	a. Non-functional requirement - The ontology must be written in the English language, and it will not support a multilingual scenario. - All used concepts must be taken from the literature reviews of the ophthalmology and cataract domains.
	b. Functional requirements: Groups of competency questions
	1- What are the overall concepts of the top level of an ophthalmology training area? There may be **monitoring**, **regulation**, **treatment**, **teaching**, **academic program**, and **registration**. 2-What kind of training techniques or practices are being used for training in cataract surgery? **Training practice** may include **real patient training**, **wet lab**, and **simulation training**. 3-What kind of competency do students need before starting training? **Students** might **require attitude**, **step knowledge**, **student skill**, and **understanding**. 4- How do you name the trainee in the ophthalmology training domain? Trainee can take a name as a **student**, **medical student**, **novice**, or a **resident**. 5-What types of treatment does ophthalmology have? There are **medical** and **surgical treatments**. 6-If you have surgical treatment, what kind of surgeries do you have under this one? These are **pre-operative surgery**, **inter-operative surgery**, and **post-operative surgery**. 7- If you have intraoperative surgery, what kind of surgery do you have under this one? These are Phaco (e.g., **divide and conquer**, **Phaco shop**), **manual extracapsular cataract**, and **LASER**. 8- What are the main steps of Phaco technique (divide and conquer)? The **step-by-step** approach for the **divide and conquer** Phaco technique is as follows:The four main procedures of phacoemulsification cataract surgery, namely **corneal incision**, **capsulorhexis**, **phacoemulsification**, and **intraocular lens implantation**. 9-Who monitors the trainee during cataract surgery training? There may be more options including **surgeon**, **expert doctor**, **ophthalmologist**, or **trainer**. 10-Where does trainee get the knowledge for training purpose? He or she may get knowledge from department **resources** such as lectures, courses, suggested articles, and so on. 11-What things can you include in the resources? The resources may include **human resources**, **diseases**, **tools**, **educational material**, **medications**, and **instruments**. 12-If resources include human resources, what are their characteristics? They may have **experiences**, **qualifications**, and **skills**. 13-What parts of the anatomy are involved in the cataract operation? The operation involves eye parts and any system that helps the eye. There are a variety of parts such as **cornea**, **iris**, **pupil**, **lens**, **retina**, and so on. 14-What essential information does the student need to know about anatomy? They should know about **name**, **location**, and **image**. 15-What are the types of tools involved in cataract surgery? These are all things that are utilized to perform cataract diagnostic testing, treatment, or surgery. There are several instruments like ultrasound **device**, **YAG laser**, **surgical blades**, **sharp capsule forceps**, **keratome**, and so on. 16-What is the essential information that the student needs to know about the tools? They may need to know about **name**, **role**, and **image**. 17-What are the types of medications involved in cataract surgery? The medications are a component of the drugs that are given by the physician. There are various kinds of medications such as **dilating eye drops**, **antibiotic drugs**, **Ophthalmic Viscoelastic Devices (OVDs)**, **viscoat**, **Healon**, and **Balanced Salt Solution (BSS)**.

TABLE 11. *(Continued.)* **Ontology requirements specification document.**

18-What essential information does the student need to know about Medications? They may be required to research knowledge about **name**, **role**, and **dose**. 19- When does the patient get medication for cataract surgery? It is possible for the **patient** to get medication before, during, and after the cataract operation. 20- What are the common cataract diseases? Common **cataract diseases** are **Nuclear Sclerotic**, **Posterior Subcapsular Cortical, Anterior**, **Subcapsular**, **Posterior Polar**, **Traumatic Cataract**, **Congenital Cataract**, and **Diabetic Snowflake**. 21- What types of risk factors do cataract diseases have? **Risk factors** are all things that increase cataract problems, which include many types such as: **- Diabetes** or **elevated blood sugar.** **- Steroid** use (oral, IV, or inhaled). **- Ultraviolet exposure.** **- Smoking.** **- Ocular diseases**: Retinitis Pigmentosa, Uveitis. **- Ocular Trauma.** **- Prior ocular surgery.** **- Genetic predisposition.** **- Blepharitis** and **meibomian gland dysfunction**. 22- What type of symptoms do cataract diseases have? **Symptoms** are signs of getting cataract diseases like: **- Blurred vision** at a distance or nearby. **- Glare** (difficulty seeing in the presence of bright lights). **- Difficulty seeing in low light situations** (including poor night vision). **- Loss of contrast sensitivity**. **- Loss of ability to discern colors**. **- Increasing near-sightedness** or **change in refractive status** (including "second sight" phenomenon). 23- What kind of medication is the patient provided for cataract surgery? Two categories of medications are provided to the patient including **drugs** and **devices**. 24- What are the types of complications that may emerge in cataract surgery? **Complications** may arise in **postoperative surgery**, which may include **management of the small pupil**, **YAG**, **managing posterior**, **capsular rupture**, **preventing postoperative infection**, **preventing postoperative inflammation**, and **managing challenging clinical situations**. 25- Who will evaluate **student performance**? 26- How do you classify student level? (e.g., **Classification** name: **High**, **medium**, **low**)

TABLE 12. **Examples of relationships among concepts in OntoPhaco ontology.**

Concept 1	Relationship	Concept 2
Practical Training	Specialization “isSubClassOf”	Ophthalmology Training
Inpatient	Specialization “isSubClassOf”	Patient Care
Procedure	Specialization “isSubClassOf”	Practical Training
Non-Surgical Procedure	Specialization “isSubClassOf”	Procedure
Cataract Surgery	Specialization “isSubClassOf”	Surgical Procedure
Candidate Supervisor	Specialization “isSubClassOf”	Person
Acquired knowledge	«characterization»	Student
Understanding	ComponentOf	Acquired knowledge
Hand	ComponentOf	Student
Student	«characterization»	Mental State
Candidate Supervisor	<<Material>> “supervise”	Student
Candidate Supervisor	<<Mediation>>	Supervision
Student	<<Mediation>>	Supervision
Supervisors Team	IsMemberof	Certify trainer
Candidate Supervisor	IsMemberof	Supervisors Team
Medication Name	«characterization»	Medication
Cataract Disease	<<Formal>> “TraetedBy ”	Cataract Surgery
Cataract Disease	<<Formal>> “Has”	Type of Cataract

medicine study. These samples of people were chosen due to their experience and knowledge about the ophthalmology domain in general and cataract surgery in particular.

Usability Findings: Five themes emerged by analyzing the results of the interview transcripts, which included user satisfaction, visual guidance, visualization, content, and lack

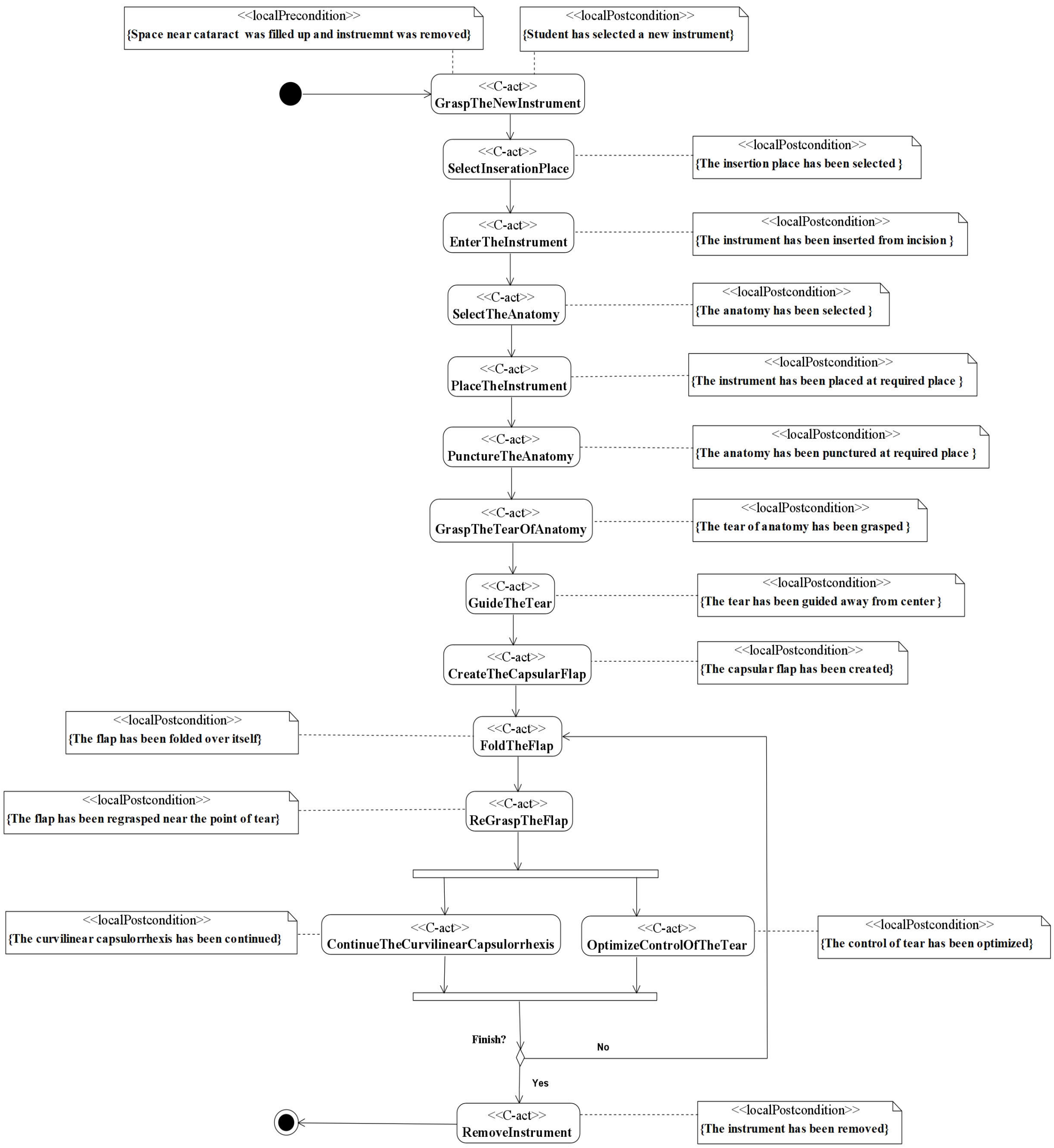


FIGURE 15. **Perdurant ontology of CreateOpening.**

of knowledge. All these themes were entirely validated and were found to be consistent with what was discussed during the interview.

- Theme 1: User satisfaction

User satisfaction described the participants' reactions to use OntoPhaco visualization inside a VR environment. The majority of trainees declared that they would like to use it, which is beneficial and more interesting, especially for students, as stated by one student:

''*I think for me as student ... it is quite interesting to learn OntoPhaco visualization using VR so make learning interesting for me. I think is for me, it is useful*''

Another research assistant mentioned:

''*I think OntoPhaco visualization with VR is helpful for seeking knowledge because we can see the real picture with VR and very practical*''

- Theme 2: Visual guidance

The second theme focuses on the participants' experiences on how OntoPhaco visualization can be used to guide them during VRT. These experiences were positively expressed on how this visualization can serve as a visual guide to assist users during simulation. A doctor mentioned:

''*new video was very good an overview about what is going to happen talking like explain steps and what's is going to happen first what's instrument used then enter and exit*''

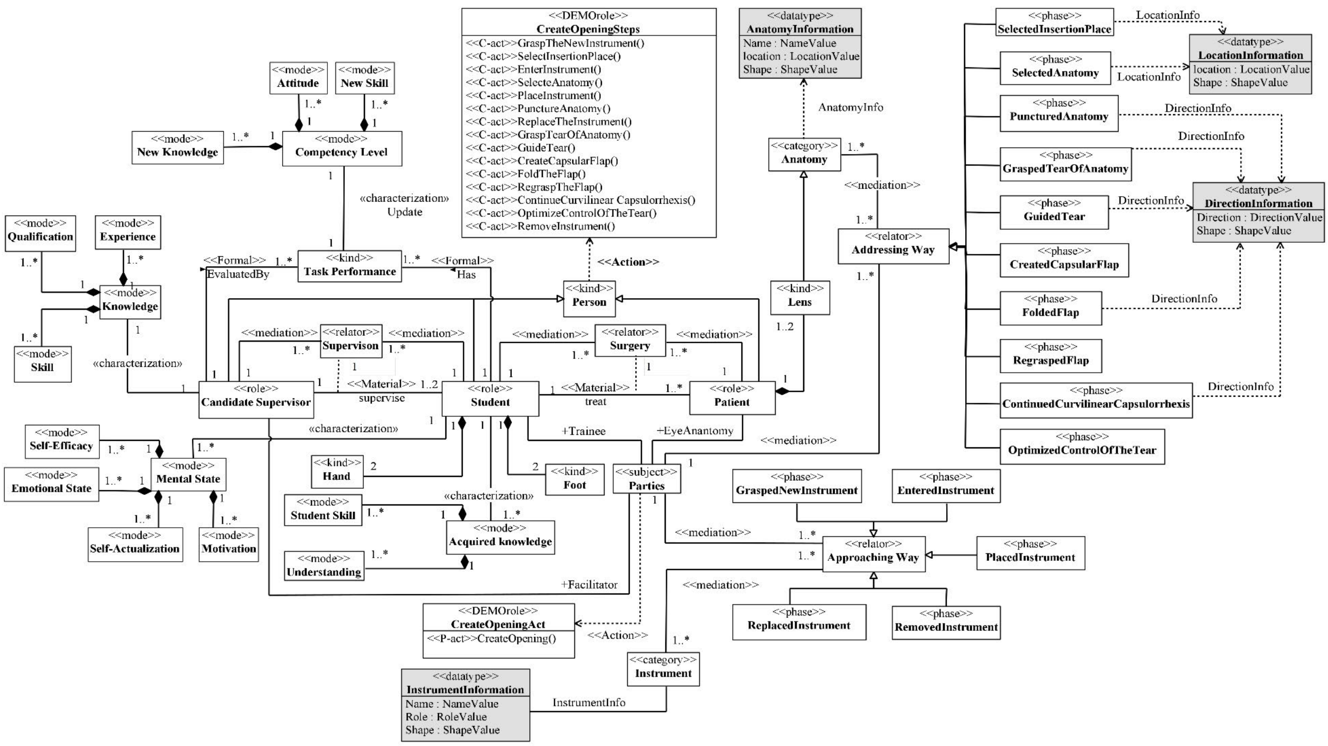


FIGURE 16. **Endurant ontology of CreateOpening.**

Another doctor said:

"It helps to provide step by step guidance and allows me to visualize the steps"

- Theme 3: Visualization

This theme explores methods to visualize the knowledge of the Phaco technique and to take into account further enhancements that were highlighted by participants to make for an exciting learning experience. Many of them believed that if the simulation and OntoPhaco visualization are presented concurrently with audio, it could be more beneficial. One doctor mentioned:

"…can have a both video, audio and also visualization at the same time would be more…more beneficial"

Some participants provided some recommendations with regards to fonts and image types and quality. An example of this is what a doctor mentioned:

"If you can use real eye rather animation I think it will be a good idea..the animation sometimes are not same as the patient eye I think take patient eye rather than animation "

Another research assistant commented:

"…But some improvement need to be done by increasing the wording size to make it more clearer…while the picture/video…maybe you could improve the quality like HD or 1080p to make the picture more real and nice color of visualization"

- Theme 4: Content

This theme is concerned with how the presented knowledge about Phaco cataract surgery can serve the needs of the participants. As one doctor remarked:

"The provided steps are explained together with some clinical anatomy relevance"

Some requirements related to content enhancements were also suggested by doctors to provide precise and comprehensive knowledge.

"add measurement the wound size and depth angulation of knife once creating wound … so it can be better to visualize how the angulation of the wound…add measurement how to insert the knife and give exact angle because the insertion has multiple approaches."

Another doctor mentioned:

"It was a new experience and would like to explore further using different procedures like glaucoma surgeries, eye lid surgeries or cornea surgeries"

- Theme 5: Lack of knowledge

This theme is concerned with some problems faced by the participants in the first stage, which led them to feel a lack of control of the VR devices during the experiment. A doctor commented:

"I took much time to adapt the simulation in term for remote control"

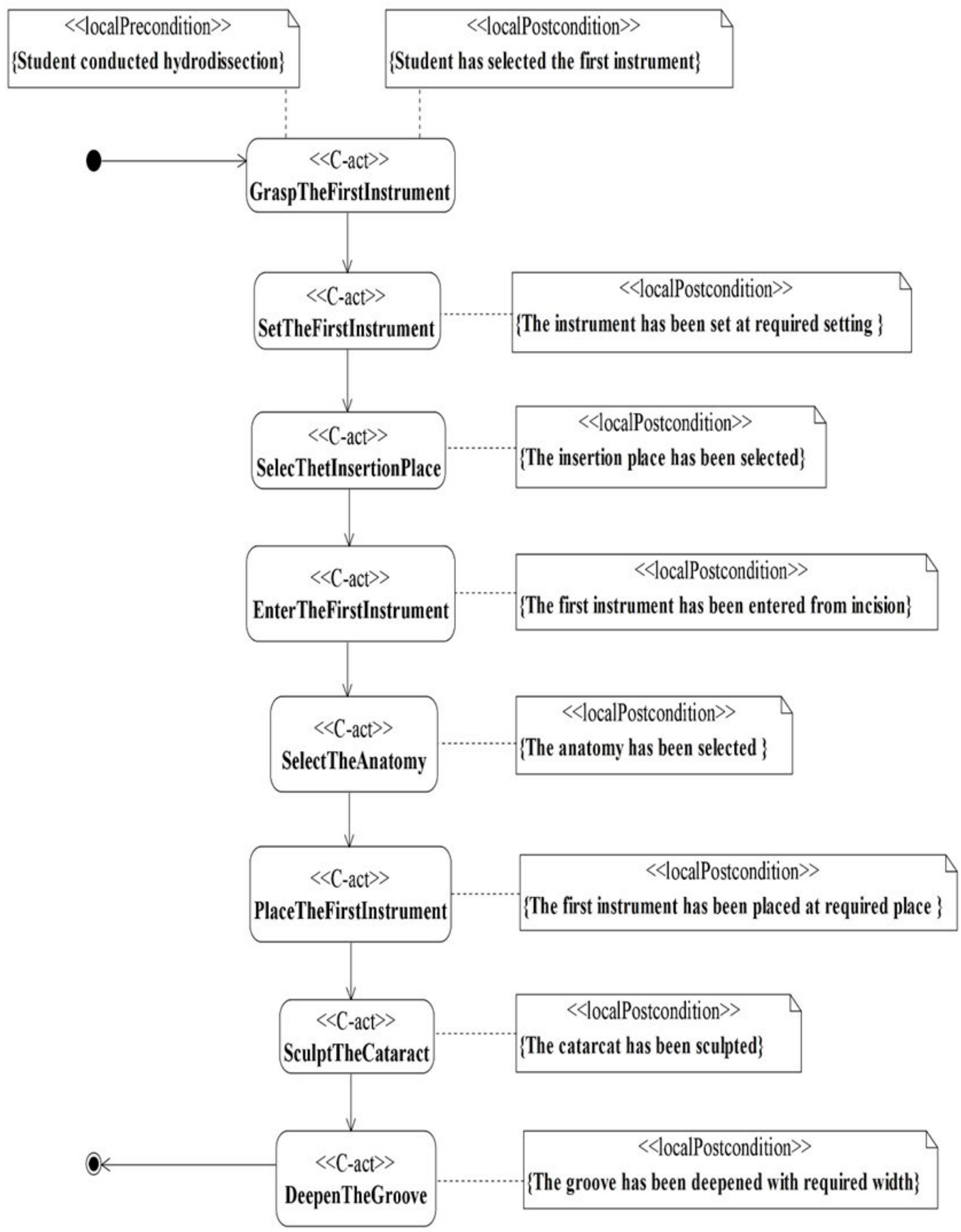


FIGURE 17. **Perdurant ontology of Groove_1.**

A research assistant also remarked:

"*If we can have manual on how to use VR for awareness of beginner...*"

e: DISCUSSION

This experiment delivers an insight into the experiences of using OntoPhaco visualization with VR technology for helping users to enhance the learning curve during Phaco training surgery. To help respect the significance of these findings, recommendations are generated to allow ontological engineers, VR developers and researchers to think about practical ways that can guide students to conduct very successful training using VR technology. Additionally, the findings are reflected in some ontology and VRT literature, such as the following.

User Satisfaction: A previous study by Tessier et al [58] defined user satisfaction as a concept and it was "*ultimately a state experienced inside the user's head*" (p.383), and therefore was a response that "*may be both intellectual and emotional*".

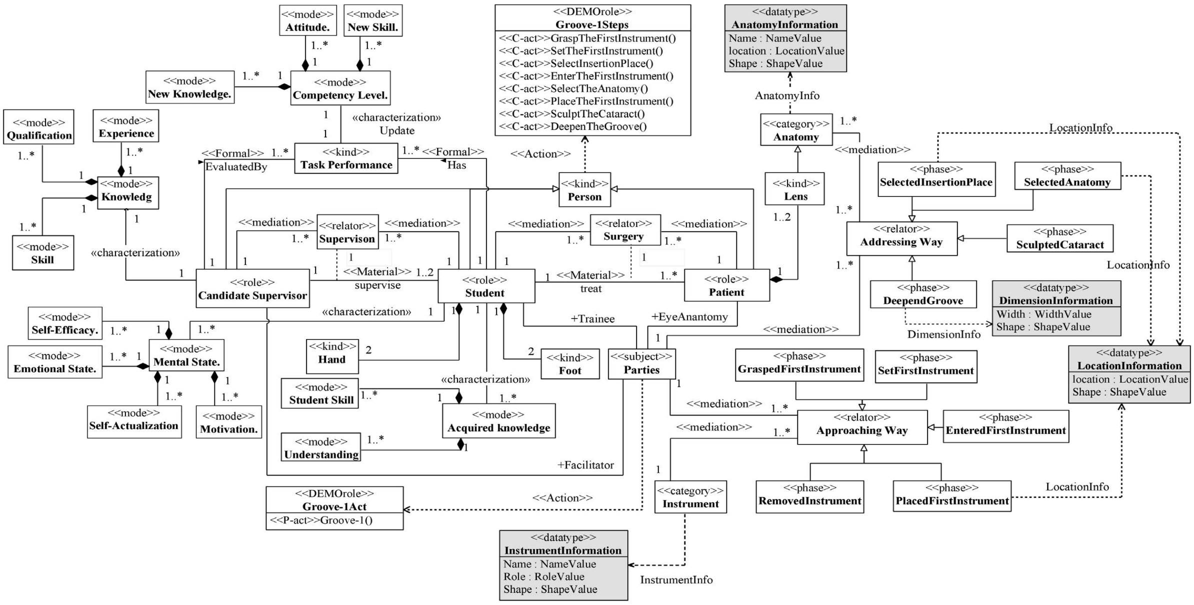


FIGURE 18. Endurant ontology of Groove_1.

Therefore, for improving the OntoPhaco visualization, it is important to know how participants in the experiment interact with it, and where the weak points are located. The findings of the experiments give an opportunity to design relations among the emerged themes as presented in Fig. 14. Overall, all participants agree to use the OntoPhaco visualization in VR, as it enables them to have a good learning experience.

Visual Guidance: According to Benferdia *et al.* [14]'s study, it was reported that "*Provide Guidance*" in VE is one of the important roles of ontology. It was also declared in the same study, that previous works such as Elenius *et al.* [59] and Vincent *et al.* [60] tried to provide guidance on how to do tasks inside VE. However, these studies did not provide enough evidence due to missing roles like "*Enhancing Communication among Stakeholders or Applications*" and used languages and methodologies that were deficient and not enough to capture, represent, and structure explicit knowledge. Thanks to UFO, its OntoUML language and data visualization greatly assisted in providing a comprehensive representation of the domain.

In literature, Lam *et al.* [61] in their work tried to provide visual guidance in VRT of Phaco cataract surgery. However, this study only offers some colored highlights over places of insertion and capsulorhexis. Whereas, the knowledge related to instruments, name of location, architecture of wound is missing. On the other hand, the ontology in this experiment plays a storytelling role by providing visual guidance in the form of step-by-step explanations of the Phaco technique, which covers areas like what is going to happen first, what is the instrument used and its role, what is the location for inserting the instrument, and architecture of the incision, and so on.

Visualization: Visualization is a way of translating data into visual context by using different approaches like images, graphs, and video, to communicate a message to the intended users. The major goal is to provide information in an easy and visually presentable manner, that enables the human brain to understand and extract the overall ideas about the data being presented [62]. Using video with audio was something that was well appreciated by all the participants. Although the usage of video inside VR made for a good learning experience, some users faced some difficulties in seeing the images and the words. Consequently, they suggested to increase the font size and the quality of the photos. Here, there is a need to highlight significant issues related to lack of knowledge's theme. The difficulties appeared because some participants did not move to the right position, which is more comfortable for the viewing angle. If they had moved closer and smoothly conducted the zoom in and zoom out activity, they would have surely been able to see the texts and images clearly. Other recommendation was to provide certain highlights over the cornea wound, and simultaneously, visualization and audio explanation were presented. This method of using highlights was previously conducted by Lam *et al.*'s [61] work. This method can be further improved in this study by providing a legend. For example, if users want to grasp the instrument, some highlights with text can emerge informing them about the name and the role of the instrument. Therefore, all the suggestions can be adopted and refined so that the students can learn and benefit significantly more. These suggestions are summarized as follows:

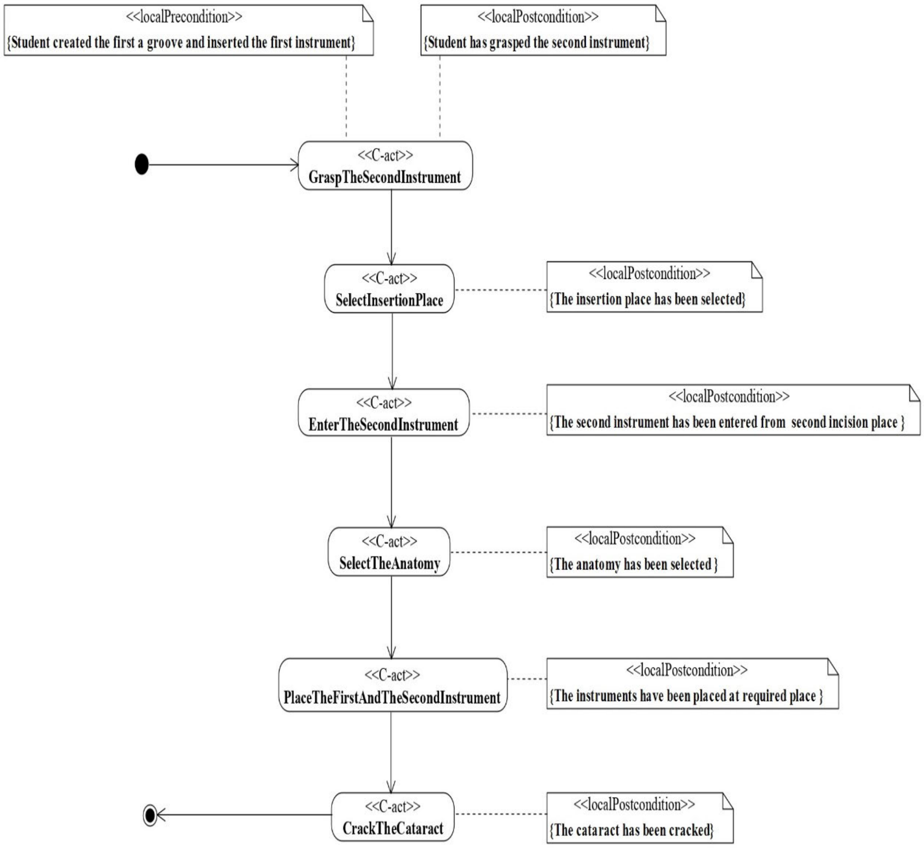


FIGURE 19. **Perdurant ontology of Divide_1.**

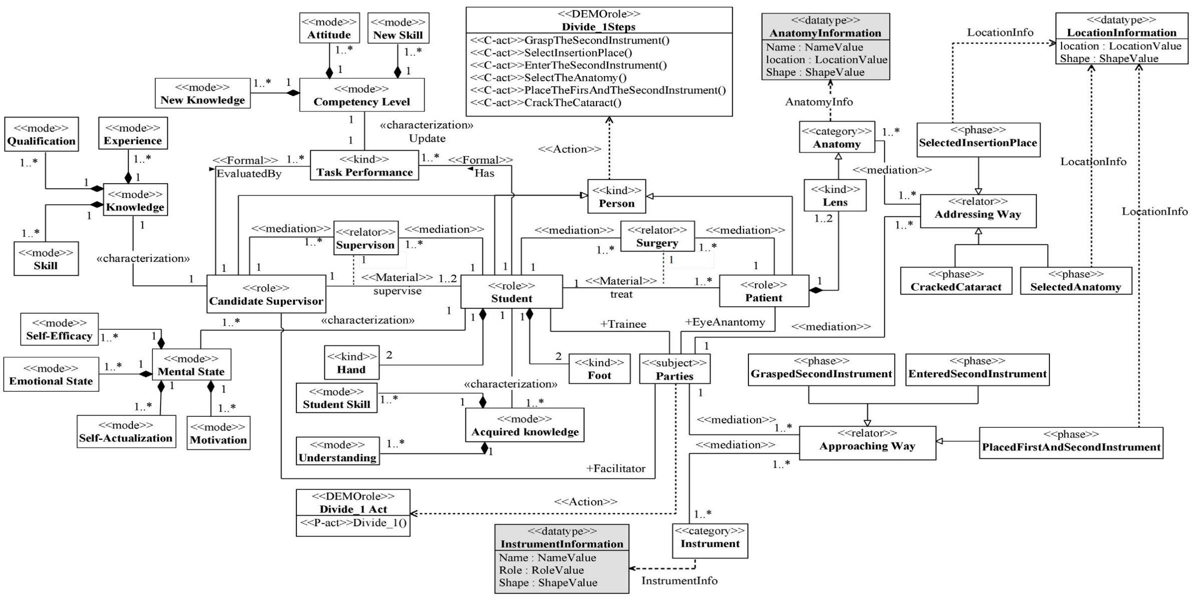


FIGURE 20. **Endurant ontology of Divide_1.**

1- Visualization, audio, and highlights with a legend can be presented inside the VE concurrently.

2- To improve the quality of OntoPhaco visualization and the included images (e.g., HD or 1080p) in order to make the picture appear more real and also for the visualization to have nicer and vibrant colors.

3- Using a real eye rather than an animated or photographic one.

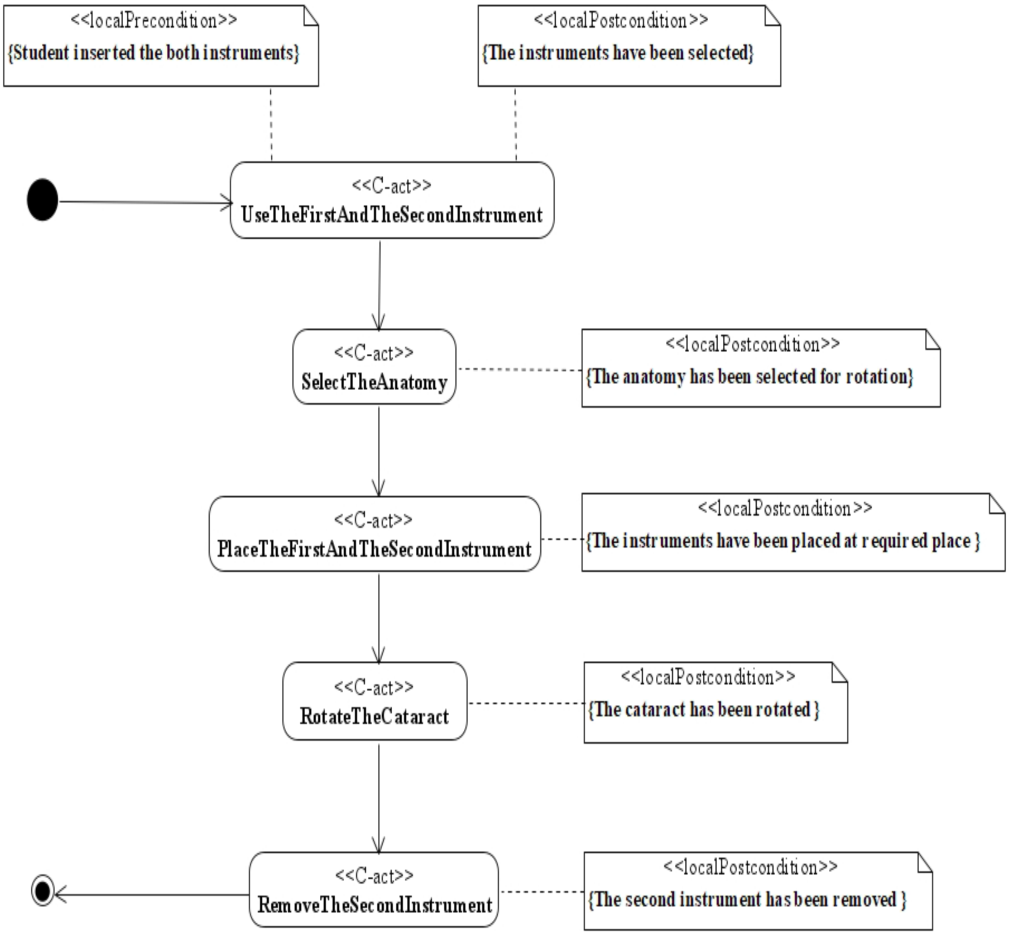


FIGURE 21. Perdurant ontology of Rotate_1.

Content: In the literature, various studies reported some problems with regards to the comprehensiveness of the learning content in the context of VRT. For instance, Radianti *et al.* [13] in their study in the higher education domain, recommended for further research to conduct workshops, focus group discussions with students and teachers to extract the right knowledge. Benferdia *et al.*'s [11] work also mentioned about limitation factors, elaborating that VRT in ophthalmology lacks an integrated comprehensive training curriculum inside VE. Thus, ontology was called to address these kinds of issues.

According to Benferdia *et al.* [14], it was identified that the role of "*Capturing and Representing Training Scenarios or Learning Contents*", was the dominating role in ontology for VRT. OntoPhaco visualization, which is based on UFO and DEMO, successfully assists in explicitly describing the sequence of steps, and information for training scenarios in the form of storytelling. Having such a visualization method assists in reducing complexity, and hence users can obtain a comprehensive overview about Phaco cataract surgery. This is one of the reasons why a majority of the participants were satisfied with the contents presented in the Phaco visualization.

Some comments were provided that can be applied for further enhancement of the knowledge presentation, as follows:

1- To add some measurements on how to insert the knife and to give an exact angle because the insertion has multiple approaches.

2- To further explore different procedures like glaucoma surgeries, eye lid surgeries, or cornea surgeries.

Lack of knowledge: This theme is considered as a weak point of VR in general. Benferdia *et al.* [11] reported that a lack of guidance and supervision is a critical factor. The highly advanced technology used in VR like the excess level of realism and the new immersive technology, increases its overall complexity. In the experiment, some participants faced some difficulties in using the remote control and adjusting the right view and position to make for a nicer learning experience. Most of them did not know how to interact inside the VR or how to use VR devices. Some of them took much time to formalize themselves with the VR devices. Guidance and supervision should be provided at the first

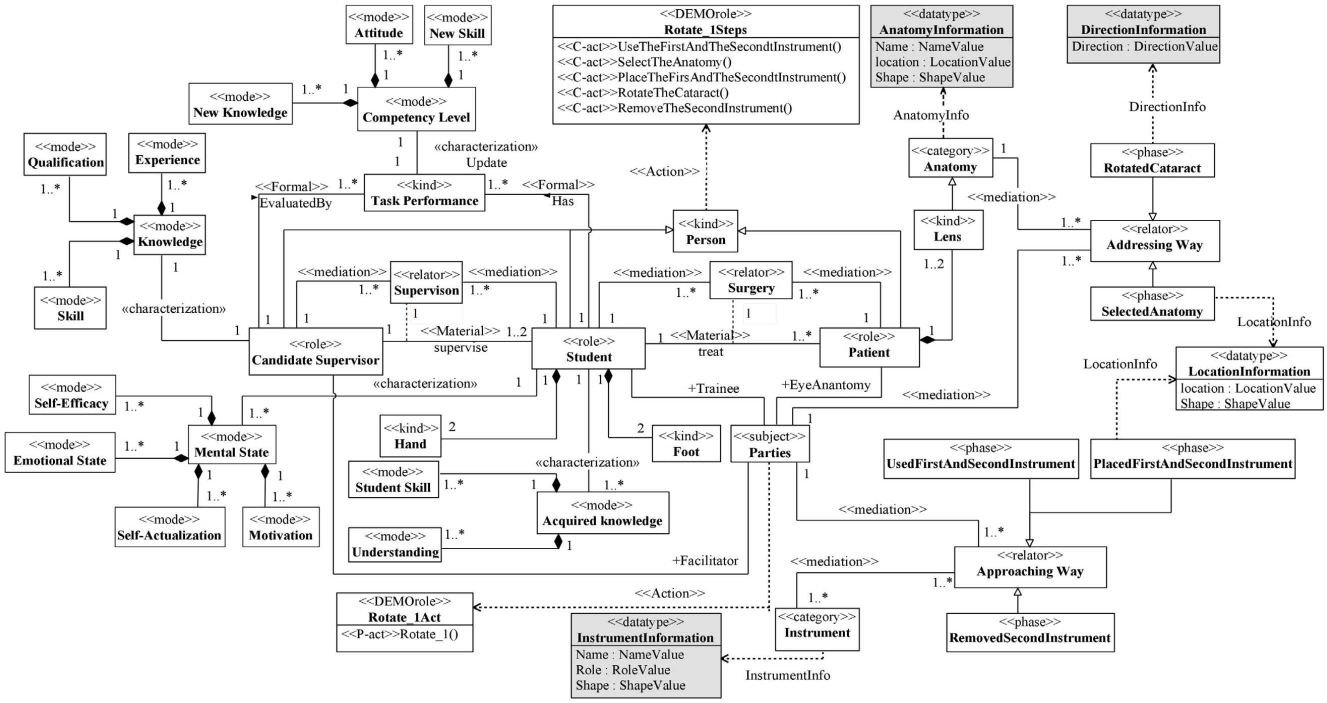


FIGURE 22. Endurant ontology of Rotate_1.

stage of training so as to avoid any failure in the VRT project.

A majority of the doctors found that using OntoPhaco within VRT is beneficial and provides a good experience for those seeking knowledge and guidance on how to do cataract surgery, especially for beginners. Not far from these respondents, research assistants declared their motivation on utilizing this kind of technology during their training. However, both the respondents suggested some improvements, as are presented earlier, that need to be considered for further works (e.g., font, quality of photo, including other procedures). Research assistants additionally declared that they usually need to queue for a long time in order to have a chance to enter the operation room. This environment with OntoPhaco can really help these students in maintaining their knowledge and training themselves before being involved in real surgery. Like the above respondents, students also expressed their interest in learning OntoPhaco visualization using VR.

The overall feedback regarding OntoPhaco from ophthalmologists and students was good and encouraging, who were highly satisfied by the integration of OntoPhaco visualization into the VR environment. Results confirm the significance of OntoPhaco, which plays a role in enhancing learning experience. This study opens a new opportunity for research, in investigating user experiences, on one hand, by employing behavioral science research in order to include more items and collect data from a larger responder sample. It can be put as further work and can trigger more empirical work from the behavioral science community, instead of design science research. On the other hand, there is a need to consider that there are some challenges commonly faced in implementing training scenarios in VEs. As we know, VRT, particularly in the ophthalmology domain, varies meaningfully from frequent training. As also mentioned before, trivial details in cataract surgery are crucial, whereas any missing details could lead to the patient being blind. Therefore, the contents and procedures should be communicated and integrated in the learning and training scenarios, in a proper manner, such that students are not swamped. Some works including technical scaffolds [63], cognitive apprenticeship [64], and visible thinking [65] have attempted to provide approaches and frameworks in order to motivate students and make learning more interesting by connecting it to real application. These frameworks are significant instructional paradigms, specifically when VRT applications are used to train students for fairly complex activities. In future work, these frameworks may be considered in designing training scenarios and developing learning environments.

V. CONCLUSION

An ontology is a unified representation of reality of the world that shares a common understanding of the domain of interest. It provides vocabularies that represent knowledge of a given domain with explicitly and formally defined meanings. This tool can be used to organize and structure information, as well as to support semantics interoperability and communications among different stakeholder teams in ophthalmology.

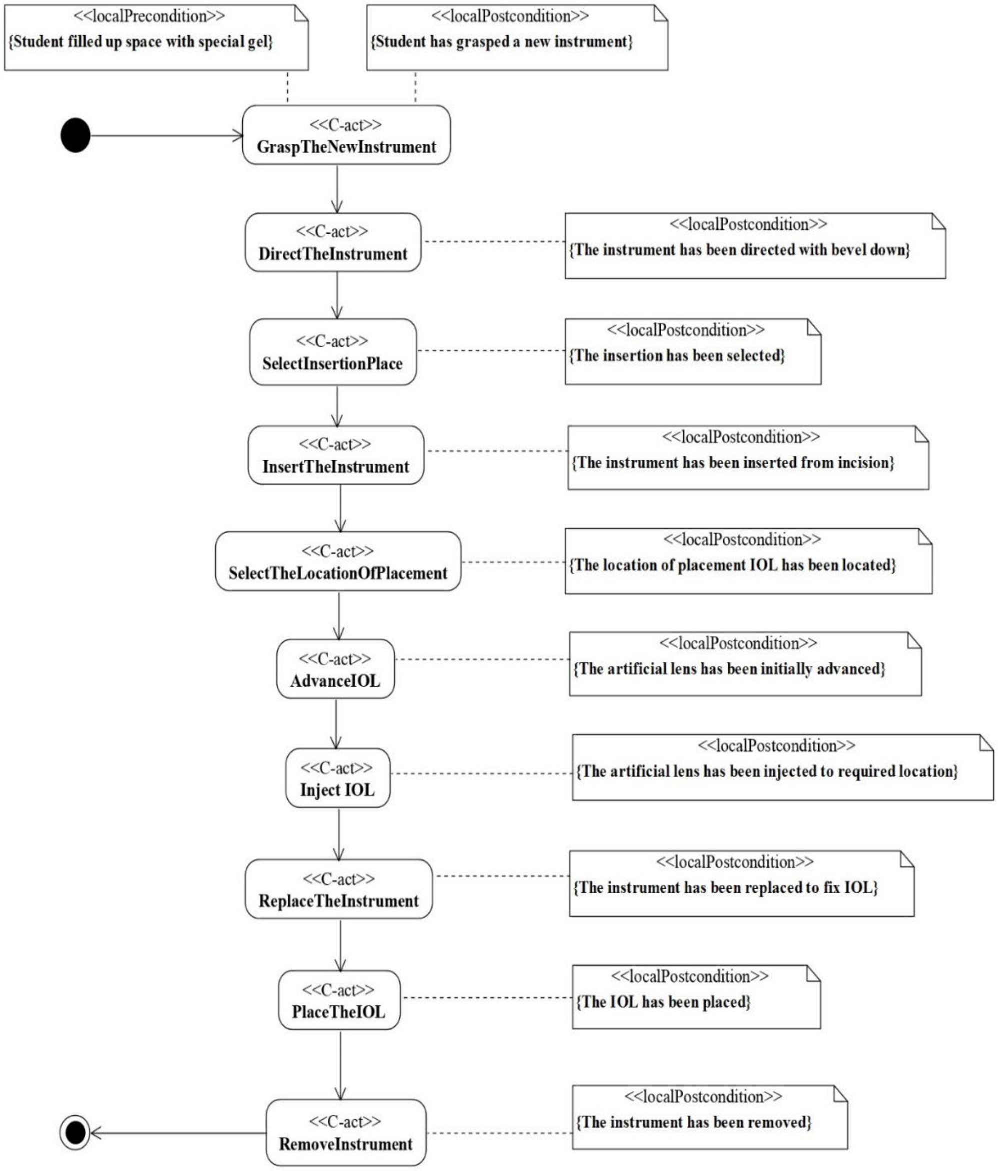


FIGURE 23. Perdurant ontology of inject.

Despite the number of ontologies designed for VRT, there is still a misunderstanding on how they should be designed in the most systematic approach to assist effectively in building VR training scenarios, leading to successful VRT processes. When utilizing ontologies for supporting VRT in the ophthalmology context, such as the Phaco technique in cataract surgery, it is fundamental to determine whether they provide a valid representation of the reality.

In this article, the processes of designing and evaluation of OntoPhaco were described based on synthesis and analysis of existing approaches of ontology construction and evaluation. The designed ontology was evaluated based on three major approaches; Guizzardi's postulates-based verification, criteria-based verification and application-based evaluation. As part of the validation, the results show that the use of OntoPhaco was able to improve the student's learning experience in retrieving fundamental information on the related steps, sub steps, and particular details on demand. It also enables all users to acquire overall knowledge about the steps of the Phaco technique and detect specific details for each step. Overall, it assists effectively in building VR training scenarios, leading to successful VRT processes.

In future, as it is obvious that OntoPhaco provides many possibilities to reuse it several times in order to make a huge ontology that can cover the whole ophthalmology domain; therefore, the foundation ontology can be made possible by reusing, extending, and mapping the designed ontology to

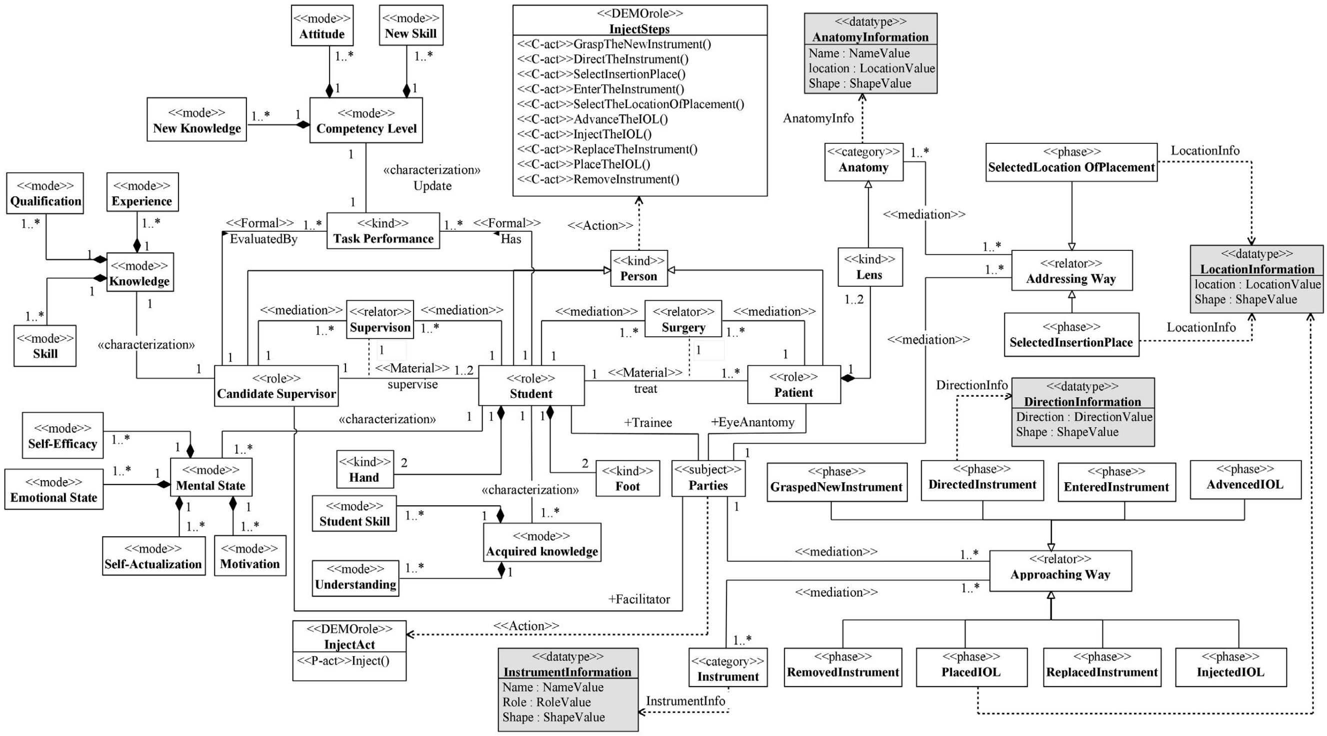


FIGURE 24. Endurant ontology of inject.

build a foundation ontology for the whole ophthalmology domain (a single large domain ontology for ophthalmology). In this study, the OntoPhaco visualization was used to provide visual guidance. It can be further implemented to offer reasoning in order to query and retrieve information in a VR environment. Having OntoUML in hand gives an opportunity to transfer graphical designs to many implemented languages such as OWL [66]–[68].

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BENFERDIA YOUCEF received the B.Eng. degree in mechatronics from Mohamed Boudiaf University at M'Sila, Algeria, in 2006, and the M.Sc. degree (Hons.) in IT management from the Department of Computing, University Technology Malaysia, in 2015. He is currently pursuing the Ph.D. degree with the Institute of IR4.0, Universiti Kebangsaan Malaysia. His current research interests include ontology, virtual reality, IT project management, and healthcare informatics. He was awarded the Best Student Award from University Technology Malaysia.

MOHAMMAD NAZIR AHMAD received the Bachelor of Information Technology degree in industrial computing from Universiti Kebangsaan Malaysia (UKM), in 1998, the M.Sc. degree in information systems from Universiti Teknologi Malaysia (UTM), in 2002, and the Ph.D. degree in information technology from the University of Queensland (UQ), Brisbane, Australia, in 2009. He is currently an Associate Professor at UKM. He has been active for many years in the fields of ontology and knowledge management areas.

MUSHAWIAHTI MUSTAPHA received the Medical degree (M.D.) from UKM, in 2000, and the Master of Ophthalmologist degree, in 2007. Her fellowship in vitreoretinal diseases at Royal Victorian Eye and Ear Hospital, Melbourne, in 2013, allows her to advance as a Lecturer and an Ophthalmologist at Hospital Caunselor Tunku Muhriz (HCTM), where she is currently an Associate Professor of vitreoretinal (VR) surgery. Since then, she has been active in the field of ophthalmology in which she conducts numbers of researches and supported by total grants of almost RM 2,000,000.