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Contextual modeling of collective diagnosis of chronic inflammatory bowel

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ABSTRACT

The paper presents results on the modeling of contextual reasoning of Anatomy and Cytology Pathologists in chronic inflammatory bowel disease diagnosis. The diagnosis is modeled in the Contextual-Graphs formalism that offers a uniform representation of knowledge, reasoning and context. The diagnosis is considered as a mental model that is extracted of a mental representation expressing pathologists' experience on this diagnosis. Building and development of the mental model are intertwined during the contextual nonlinear reasoning held during diagnosis. Modeling of contextual reasoning is particularly relevant for decision-makers that cannot work on formal model. The Contextual-Graphs formalism was applied in several domains, including medicine, for different aspects of cancer (breast, lung, prostate) and at different levels from a synthesis on breast cancer diagnosis to mitosis identification on digital slides, the modeled diagnosis here being between them.

Introduction

Decision making is found in a large number of activities in which there are questions to address like in task realization (with diagnosis as instance) and problem solving. It can correspond to objective or subjective questions if the latter ones depend of an interpretation. The decision-maker first collects contextual elements, then assembles and structures them in a mental model, makes decision and finally acts. The process of decision making is as much important as the final decision. It relies on four sources of context (the actor, the focus, the situation, and the local environment). A general lesson learned is that, beyond knowing the rationale of the object of reasoning, the decision-maker uses contextual reasoning in mental-model development.

The CxG formalism proposed by Brézillon[1] has been used in different situations of cancer diagnosis, such as sample-conformity control at reception and registration at Anatomy-Cytology Pathology Service, a context-based modeling of 13 figures on breast cancer diagnosis in Logan-Young and Hoffman's book[7], contextual graphs of cancer diagnosis for lung and for prostate, and mitosis identification. This work proposes a digital alternative to multiple-objective microscopes for chronic inflammatory bowel disease diagnosis on digital slides by supporting the context-based modeling of diagnosis to palliate the lack of (formal) model of this diagnosis.

The paper is organized in the following way. First, we present the rationale of our research on context and the CxG software that was used for modeling expert in action in different domains. It concerns the contextual approach with the notions used like mental model, decision-making, context, contextual graphs, CxG formalism and contextual reasoning. Second, we present the use of the CxG software for modeling the diagnosis among several experts of this domain, the main results obtained and then give our conclusion on the application of the approach in medicine.

The contextual approach

An operational definition of context is proposed by Brézillon and Pomerol[4:] "context is what constrains the focus of attention without intervening in it explicitly". The first lessons learned are that context and focus are interdependent, one cannot speak of context in an abstract way. Context intervenes for modeling the real-world problems as well as guiding decision-maker's reasoning.

The proposed approach[1] formalizes the concept of contextual knowledge into an operational concept called *contextual element* that is implemented as a pair of contextual and recombination nodes that is achieved in the Contextual-Graphs (CxG) formalism. There are four main lessons learned for this particular work[1]. First, the structure of contextual elements provides the stable operational frame of mental models and of contextual graphs, and instantiations are the dynamic part of the frame in different contexts. Second, contextual elements and instantiations must be processed separately. Third, contextual elements structure the development of a mental model and instantiations tailor its building to the context at hand. Fourth, the exclusive branches between nodes in a contextual element contain alternative units of reasoning in the contextual element. In its implementation, contextual elements are units of contextual nonlinear reasoning (because the units of reasoning are exclusive), and the mental-model development correspond to a sequence of units of contextual reasoning.

The evolution in the contextual graph follows contextual-reasoning modeling and refinement. A contextual graph behaves as a living experience base by accumulation of mental models in the mental

[1] Reference 1 presents a synthesis on 400 publications on 25-year research on modeling and using context (including a software under GNU license). This paper only cites points concerning the modeling of chronic inflammatory bowel diagnosis as a contextual reasoning.

representation. The CxG software contains an editor with the usual functions for managing a contextual graph.

Actors' experience about a focus in different contexts can be assimilated to a mental representation. Mental representations (and contextual graphs) contain mental models corresponding to the focus in specific contexts. The development of a mental model consists of following a path from the input to the output of the contextual graph, and its building comes from instantiation of contextual elements encountered on the path. As a result, the mental model is an expression of the contextual reasoning held by the decision maker for addressing the focus.

From an external viewpoint, a decision-maker first collects contextual elements, then assembles and structures them in a mental model, makes decision and finally acts. A general lesson learned is that, more than knowing the rationale for reasoning on something, the decision-maker also relies on context.

The CxG formalism and contextual graphs

Contextual element and instantiation are two distinct notions: Contextual elements structure a contextual graph, and instantiations, which allow to adjust mental-model development, correspond to the context at hand. The branches, which correspond to different instantiations, contain alternative steps of contextual reasoning in the contextual element (e.g. "Is it raining?" if yes, take an umbrella and if no take a coat). As a consequence, the CxG formalism allows to assemble contextual reasoning step by step.

Figure-1 The four functions of the CxG formalism in the editor tool of the CxG software

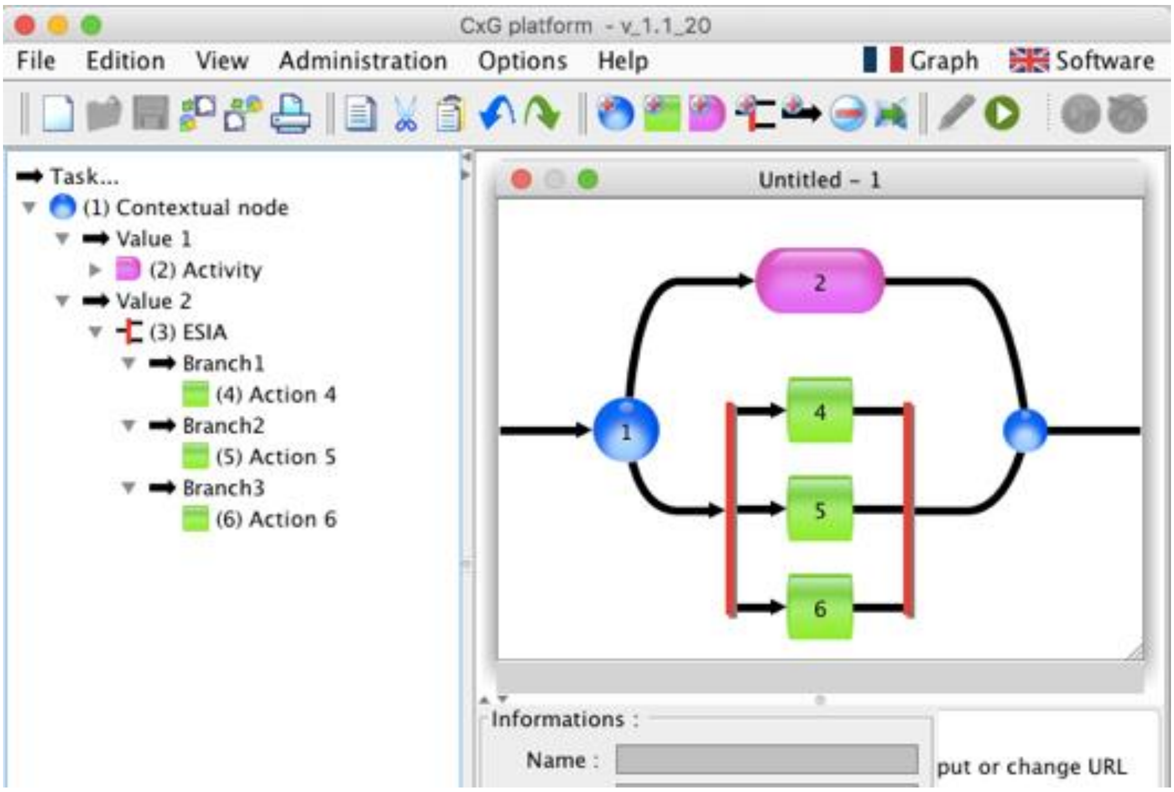


Figure-1 presents the four functions (action, contextual element, activity, and ESIA) that are sufficient for representing complex models via combination and recursivity. An action is a unit of work of an actor and an activity is a specific part of the reasoning that can be isolated in an independent contextual graph. The function "Executive Structure of Independent Activities" (ESIA) is a grouping of parallel and independent activities that requires specific management inasmuch as a nondecomposable unit of reasoning that is different of the global reasoning modeled in the contextual graph. An ESIA is a nondecomposable unit of reasoning, often associated with voting system for working on objects like criteria on which a global structuring is not possible. A voting system allows to model according to different objective criteria that experts used in a personal interpretation (without procedure, practices of different experts present a dispersion higher that a simple set of instantiations for a contextual element).

The CxG software is an interface used by an actor wishing to edit contextual graphs, reading practices for selecting the best one in his working context, browsing alternatives of a practice, exploring a contextual graph at a different granularity (by representing an activity by an item or by the contextual graph representing this activity), analyzing contextual information attached to each item (date of creation, comments, etc.). An interesting function of the CxG software is the possibility to link an item to an external document (Word, PDF, Web page, etc.), and to run an external piece of software. This was used in several medical applications[1].

Contextual reasoning

The intertwined building and development of a mental model is the expression of a contextual nonlinear reasoning. In the long-term memory, contextual reasoning is given by the development of a mental model and, in the working memory, is given by the building of the mental model by instantiation of the contextual elements.

Any reasoning is held in context. Facing a new problem, the contextual reasoning starts by gathering relevant instantiated contextual elements, structuring them according to the context at hand for making a decision and acting. Explaining contextual reasoning is possible from the decomposition of the proceduralized context in terms of contextual elements encountered, the instantiations chosen during mental-model development, and abandoned alternatives. When several instantiations exist, it is possible to explore potential paths in a "what if" way.

The voting-system approach allows several actors to reach the same result (e.g., a diagnosis) with different strategies due to different criteria, different weights given to criteria, different interpretations of criteria, and consideration of different assembling of criteria; that is, the different methods applied for diagnosis. This approach is used in the application presented hereafter.

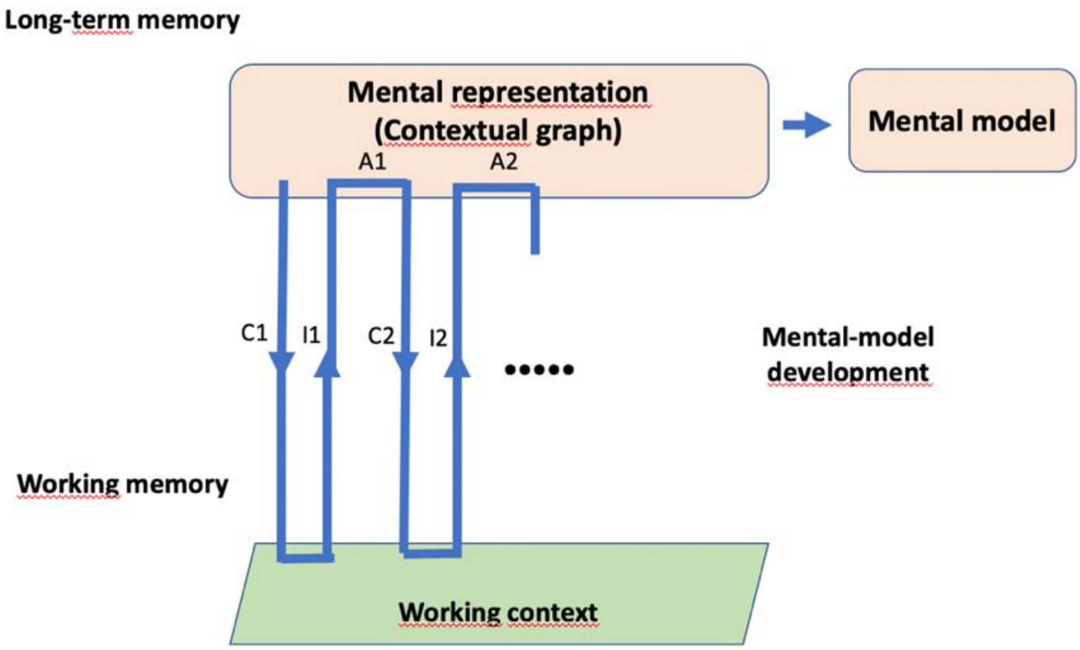
The *glocalization*[2] approach allows reasoning to use an association global and local focuses. The options are (1) a global solution imposes a simplification of local uses (top-down way) with the extreme case of elimination of the local by the global (globalization); (2) homogenization of local solutions at the globalization level; and (3) global (e.g. search of zones of interest) guides local (e.g. zoom in zone of interest). First two options are met in business and economy, and the latter concerns especially pathologists where the global search guides the search of criteria and the zoom allows the identification of features for using these criteria by decision making on magnified images like in mitosis diagnosis. We come back on the notion of glocalization in the section on the application to our theoretical framework to chronic inflammatory bowl diagnosis.

The intertwined building and development of mental models can be explained in the following way.

[2] From Wikipedia (https://en.wikipedia.org/wiki/Glocalization): **Glocalization** represents the fusion of "globalization" and "localization," emphasizing the need for global entities to tailor their offerings to suit the unique characteristics of individual regions or communities. **Glocal**, an adjective, by definition means "reflecting or characterized by both local and global considerations". The term "glocal management" in a sense of "think globally, act locally" is used in the business strategies of companies, in particular by Japanese companies that are expanding overseas

Figure-2 shows a conceptual model of contextual reasoning in the spirit of glocalization with (1) mental representation and mental-model development in the long-term memory, (2) the contextual elements met on the followed path in the contextual graph (C1, C2, …) are instantiated (I1, I2, …) in the working memory and (3) the reasoning step that is executed (A1, A2, …) in the long-term memory again. The cycle is repeated at the next contextual element encountered. The mental-model development follows the ordered sequence of instantiated contextual elements C1(I1), C2(I2), … (the proceduralized context).

Figure-2 A conceptual model of contextual reasoning



Explaining contextual reasoning is possible by decomposing the proceduralized context in its instantiated contextual elements encountered and the instantiation chosen during mental model development, and other alternatives (i.e., mental models corresponding to values of contextual elements on other paths). Moreover, making explicit the proceduralized context allows us to automatically identify the sequence of actions to perform in the specific context. It is obtained by changing the graph representation in a tree representation[1].

The Contextual Graphs (CxG) formalism has been used in different aspects of cancer diagnosis[1]. This article presents a digital alternative to approaches based on multiple-objective microscopes for chronic inflammatory bowel disease diagnosis by focusing on its context-based modeling to palliate lack of (formal) model.

The CxG formalism of representation plays the role of a "concept revealer" in a model. Rogova[9] acknowledged it in the following way: CxG formalism incorporates action and context nodes (variables and relationships) as well as paths through them. Although a contextual graph is not free of weaknesses, e.g. lack of direct time representation, the formalism offers the advantage over other approaches for a representation of knowledge and reasoning that is directly comprehensible by users. Thus, information in contextual graphs is useful and usable for users.

Modeling of medical practices in chronic inflammatory bowel disease diagnosis

The FlexMIm project[3] (2012-2015) aims to provide Anatomy and Cytology Pathologists with a platform for collaborative work (initial diagnosis, tele-expertise, remote learning) based on the technology of "digital slides" (30-Go scanned images of a microscope).

Twenty-seven Departments of Pathology in the area of Paris initially participated in the project to evaluate and validate the effectiveness of the collaborative-work model, leading to its ownership in its scale and spread after drafting a trade repository. Anatomy Pathology is a play of macroscopic and microscopic examination of patients' tissue samples and cells to establish diagnosis and factors of severity of the disease. A gross examination concerns visual examination of organs, dissection and sampling of surgical specimens according to standardized protocols, and a microscopic examination is interested in stained tissue sections. In the FlexMim project, the macroscopic examination is on intestinal lesions, and a microscopic examination on focal polymorphic with alternating damaged beaches and healthy beaches. The heterogeneity at microscopic level justifies multiple and staged biopsies.

Based on normal anatomy, histology and cytology, Anatomy-Pathology activity aims to identify by analogy macroscopic and microscopic morphological abnormalities. Several techniques such as immuno-histochemistry, cytogenetic and molecular biology are used to identify such abnormalities in cells or tissues. An important consequence is to tackle all data and their temporal contexts as a whole. Thus, the term glocalization, as introduced in the theoretical part, offers a robust framework to analyze jointly macroscopic and microscopic morphological abnormalities.

Apparently, is not usual in the literature about virtual microscopy. Some authors[12,13,8,5] look for: Individual diagnostic paths automatically performed during the routine diagnostic process in virtual slides; Reconstruct the movements of the pathologist on the whole slide images and to create the observation path; Automating region of interest retrieval with a computer-aided diagnosis system; propose a learning method (zoom without criteria), but with high inter-observer variability (20%). Melo-Thoms[7], in the closest view of our work, discusses a "search-and-focus" strategy with the use of different criteria to determine pathologists' zone of interest, this approach requiring a high level cognitive constructs for interpreting images.

The modeling of medical practices in chronic inflammatory bowel disease diagnosis aimed to identify a consensual methodology[3]. The main goals of the project are: (1) to facilitate consultation of digital slides and pre-annotation of regions of interest for downloading and/or pre-analyzing in priority; (2) to develop and implement a cognitive approach to integrate into hospital workflows between patients, pathological reports and image archiving system; (3) to identify regions of interest on digital slides; and (4) to record manual annotations of pathologists for completing the automatic annotations.

The proposed approach

The modeling of chronic inflammatory bowel diagnosis leads to a contextual graph corresponding to a consensual methodology. Knowledge-acquisition phase and expertise modeling were organized around the choice of diseases to study, observation of how pathologists worked, identification of similarity in pathologists' approaches and proposal of a unified view. The "knowledge manager" of the group was a physician knowing the expert knowledge used by experts but without their experience.

The decision-making process was likened to a glocal search with a global exploration for detecting zones of interest, and a local search by a zoom inside zones of interest. The search concerned contextual elements at different granularity identified from analysis of digital slides. The rest of the decision-making process includes the application of a set of criteria that are managed by a voting system offering flexibility to address the variety of seventeen-expert approaches. We focus now on the modeling of pathologists' contextual reasoning during their analysis of digital images because it is more important to follow experts' viewpoint than components in the process.

It is relatively easy to find a consensus among experts on the choice of criteria for making decision, but their interpretation stays personal, that is, different. Voting system brings a solution for this situation. pathologists select and combine features as criteria in favor of presence, absence or uncertainty on features based on their experience. Generally, the local observation is with a zoom of magnification at either x20 or x40.

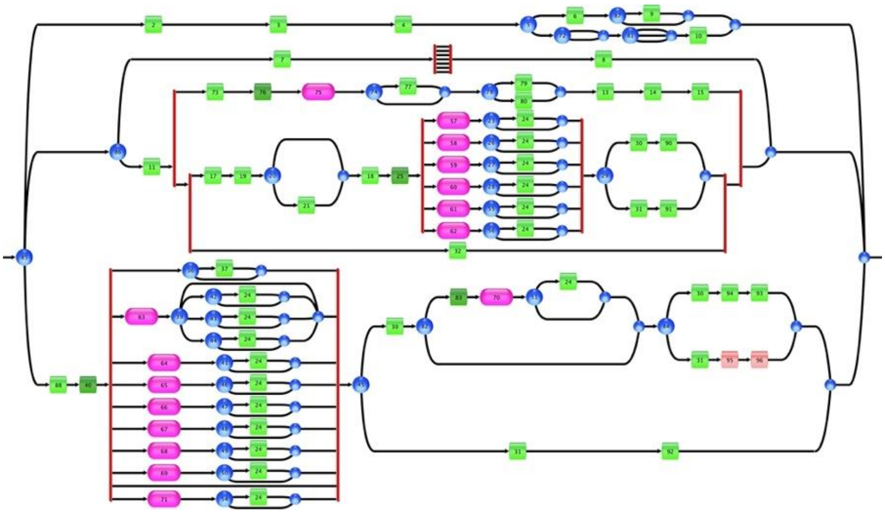
Decision-making is a two-steps process, decision makers collect and structure contextual-information, then make decision and finally act[8]. The contextual-information gathering depends on the focus that covers medical knowledge at different granularity levels, from morphological information about zones of interest to cytological criteria (e.g. mitosis identification). Contextual information comes from sample preparation to the report sent to the surgeon.

Knowledge acquisition phase and expertise modeling were organized around the choice of diseases to study the observation of how pathologists worked, the identification of similarity in pathologists' works and the proposal of a unified view. Exiting the contextual graph, the expert either is able to make decision or not. In the latter case, the pathologist must provide the specific action to perform in the new context corresponding to either a missing contextual element(s) and/or a missing instantiation of an existing contextual element.

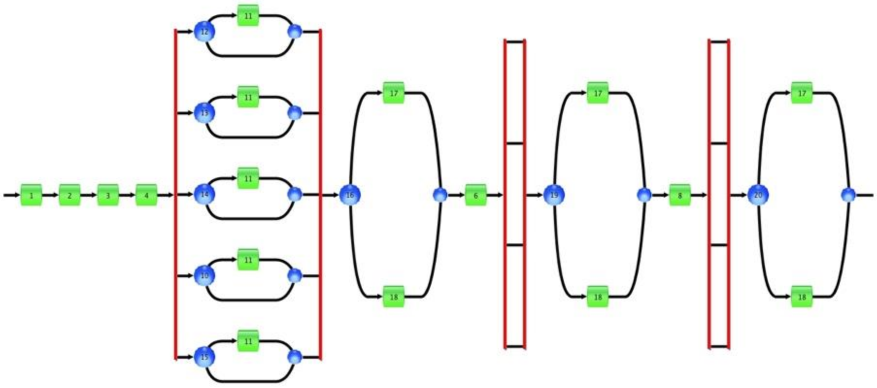
Results of chronic inflammatory bowel diagnosis modeling

Brézillon, Attieh and Capron describe the three workshops for initiating the collective work of 17 pathologists[3]. Our first objective was centered on formalizing how pathologists identify areas with dysplasia in chronic inflammatory bowel diagnosis, i.e. modeling their work practices. We model three pathologists' expertise as contextual graphs. The general organization of their expertise in the contextual graphs shows that, if the three pathologists reach the same conclusion on a set of digital slides, it is at the end of different practices. Figure-3 presents the organization of the three contextual graphs of expert models named CxG-1, CxG-2 and CxG-3, and legends are not made explicit on the figures because we focus the discussion only on the differences of structures. However, Figure 5 gives most of the legends.

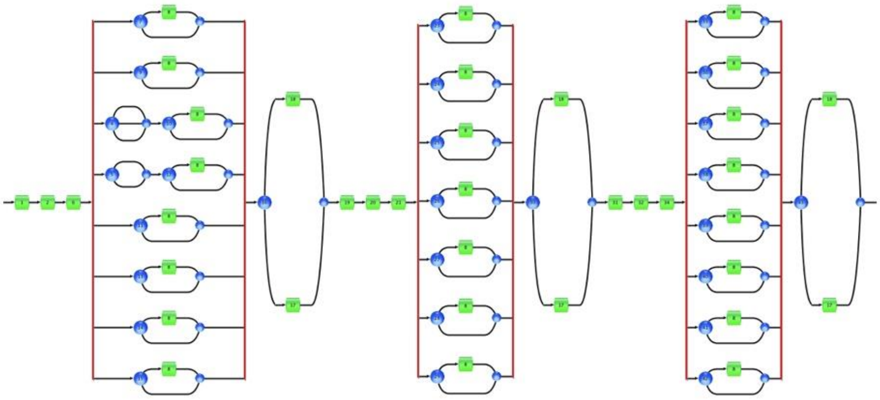
Figure-3 The three models of the diagnosis as contextual graphs (without legends to focus the discussion on graph structures).



CxG-1



CxG-2



CxG-3

Each contextual graph was developed according to expert's reasoning during digital-slide analysis of potential diagnosis as a first-line reader by a reasoning aloud. Oral analysis of each pathologist was commented and questioned by the two colleagues to clarify points in order to reach a consensus. Context operates in a global-to-local manner and implies high interactivity between their top-down and bottom-up approaches in the modulation of the focus of attention. At the global level, pathologists' expertise guides exploratory phase to identify zones of interest. At the local level, zoom magnitude (either x20 or x40) affects what they can discern but also what becomes indistinguishable, thus permitting the mind to ignore confusing details.

We retain two main lessons on the modeling of individual expert's diagnosis. Object identification is made from selected features taken as criteria in favor of presence, absence or uncertainty on features. Criteria are checked by groups in an ESIA represented by vertical red bars in figures (content of all ESIA are not given by lack of room). Figure-4 shows that (1) graphs CxG-2 and CxG-3 have similar approaches that differ on the choice and number of features to consider, and, conversely, CxG-1 uses a different approach; (2) the number of criteria is different from an expert to another one, and (3) criteria groups can be used several times. For most of criteria, pathologists choose a value of the feature (or ask for a biochemical analysis of the feature) for evaluating the criterion, depending on their experience.

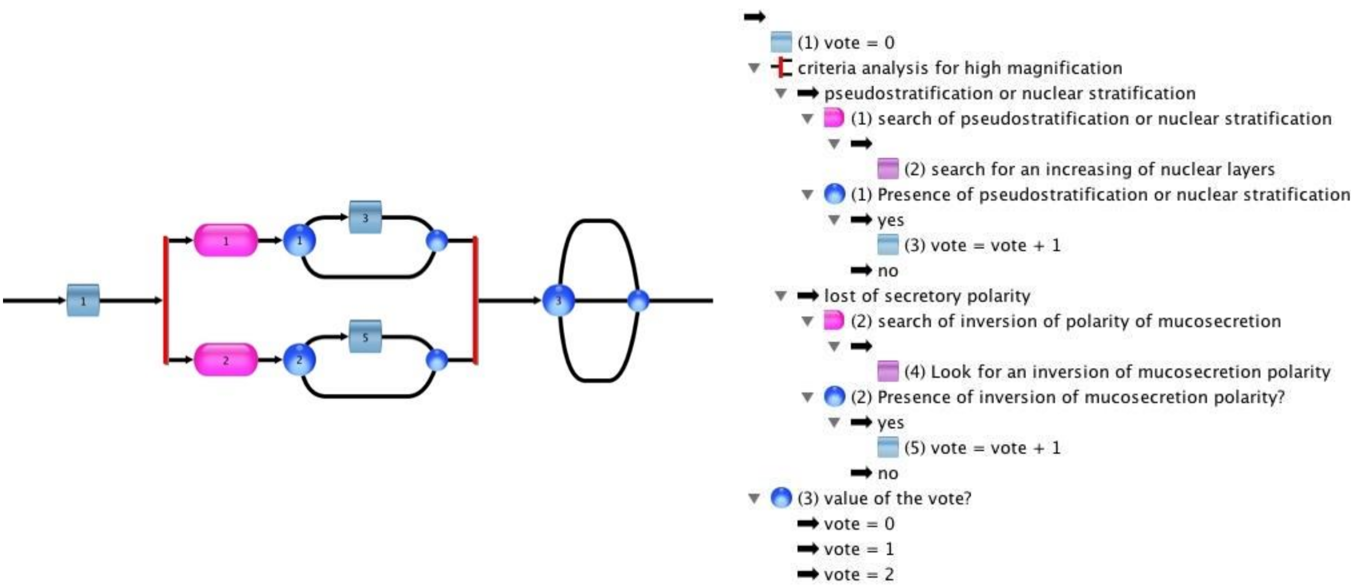
The second objective of the modeling was a unified picture of individual contextual graphs based on similarity of their characteristics because, if they are rather different according to expert's personalities, they are similar in the methods used. As a result, there was a collective consensus on (1) an analysis at a global level to browse the digital slide and find zones of interest, and (2) an analysis at a local level to make decision based on a selection of criteria and their interdependency based on observation of features. The common aspects in the three contextual graphs of Figure-4 are: (1) two magnifications (looking for zones of interest and zooming for evaluation), and (2) a voting system (a decision made based on the presence or absence of features). Their main difference comes from criteria exploitation (instantiation, relative weight, combination, etc.).

A fourth expert helps us to organize expert knowledge (glocal search and criteria) contained in the three contextual graphs in a unique contextual graph by a bottom-up analysis. The main shared technique among pathologists was the glocal search, i.e. the frequent switch between a low magnification (to identify a zone of interest) and a high magnification (to evaluate features of the zone of interest according to criteria). Indeed, we identified three orders of magnification, namely low, intermediate and high, although intermediate magnification was used for supporting the low magnification for some criteria only.

However, if all experts agree on a common list of features, each pathologist has a personal apprehension of features (ordering, individual importance, relationships between features, eventually absence of a characteristic is considered as a strong argument against chronic inflammatory bowel diagnosis). For ensuring flexibility, criteria are evaluated in an ESIA to determine if the feature is of interest or not for a pathologist. The expert looks each criterion for the presence (or absence) of the concerned feature. The status of the feature is checked in the activity on a branch of the ESIA corresponding to the feature. Clearly, there is no procedure like in Engineering, but rather work practices based on actors' experience and preferences. Figure-3 illustrate the situation we faced.

The principle of the voting system can be shown on the following example with two criteria in an ESIA (Figure-4). The first action A1 of the contextual graph initializes the contextual element "vote" at 0. Each branch of the ESIA (between the two vertical red bars) just after A1 aims to evaluate a feature from activity 1 (pink elongated oval) for determining the instantiation of the criterion. This instantiation may be obtained directly by observation or may require an external analysis. The first checked criterion concerns "pseudostratification or nuclear pseudostratification". The activity on the branch aims to obtain this contextual information (i.e. presence or absence of pseudostratification). This instantiation then is used to modify the contextual element "vote" that may be incremented (vote = vote + 1 in Action 3) if the expert judges that the criterion is verified.

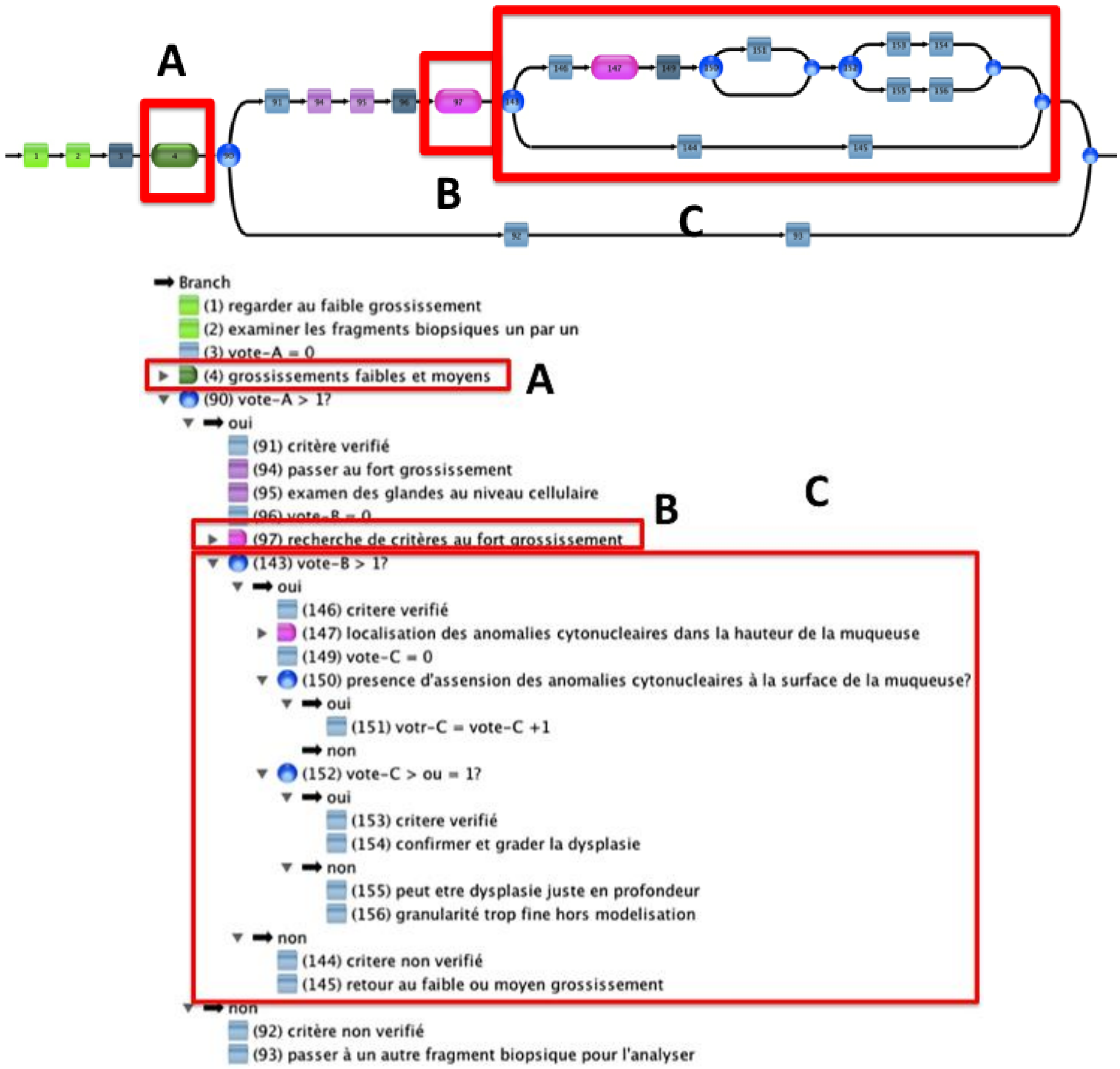
Figure-4 Example of use of the voting system.



The last contextual element "value of the vote?" proposes three possible conclusions: no dysplasia (vote = 0), dysplasia (vote = 2) and possible presence of dysplasia (vote = 1). Thus, the voting system allows, on the one hand, actors to obtain a quantitative estimation (instead of their previous qualitative estimation), and, on the other hand, actors reach the same conclusion by different interpretations of a given image. Moreover, the weight given for a vote may be different of +1 for another actor. For example, an expert may decide to give "+ 2" if the expert considers a feature more important than another one or finds relevant the combination with another feature. Conversely, the absence of a feature may be meaningful for the pathologist who may give a weight "-1" to the corresponding vote. (Weights can be modified by editing the contextual graph.)

Figure-5 presents the unified model obtained from the three contextual graphs in Figure-3, and Figures-6 and -7 detail the content of the boxes A, B, C on Figure-5. A (arbitrary) color code is used to distinguish the different types of magnification: Green for low magnification, Pink for Intermediate magnification, Red for high magnification, Blue for the voting system. Figure-7 presents the two steps of the glocal search in Activity-4 (Box A) for the low and intermediate magnification. If the separation with the high magnification is evident, it is not possible to distinguish low and intermediate magnifications because often intermediate magnification is not necessary for observing all the features and all experts do not use the same intermediate magnification (either x25 or x40). Figure-7 presents the local search represented in Activity-97 (Box B) for the high magnification.

Figure-5 Model of a general chronic inflammatory bowel diagnosis. See meaning of the Boxes in the text



Note that branches of some contextual elements are not filled for avoiding a too high complexity of the Figures, and legends of the items are not given for Figure-6 and -7 for concentrate our discourse here on structure of our models not their contents for respecting limit constraints.

Figure-6 Box A in Figure-5 shows Pink items representing intermediate magnification with low-magnification before.

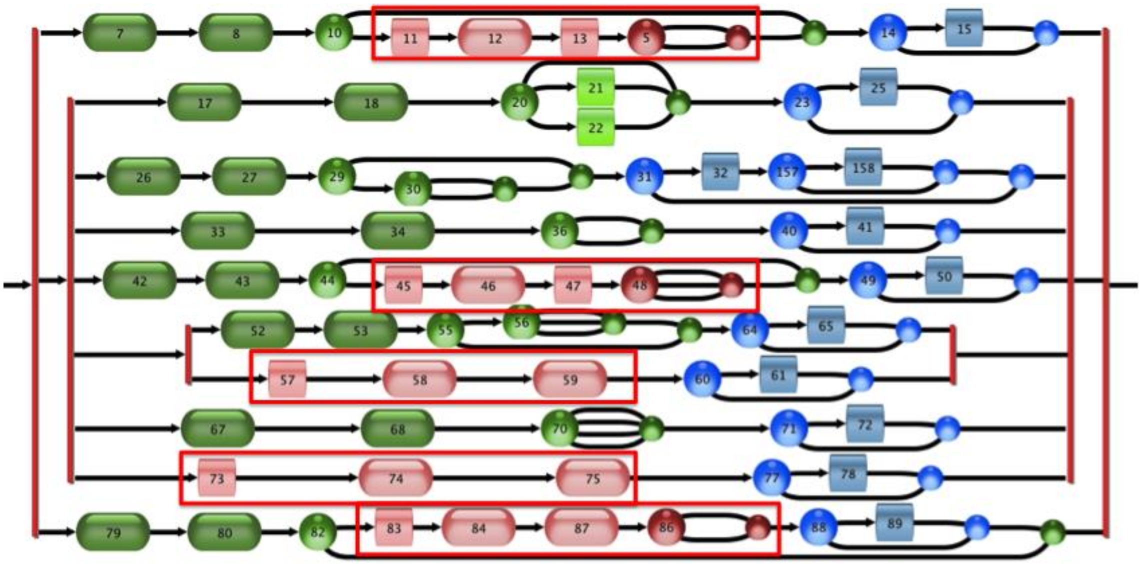
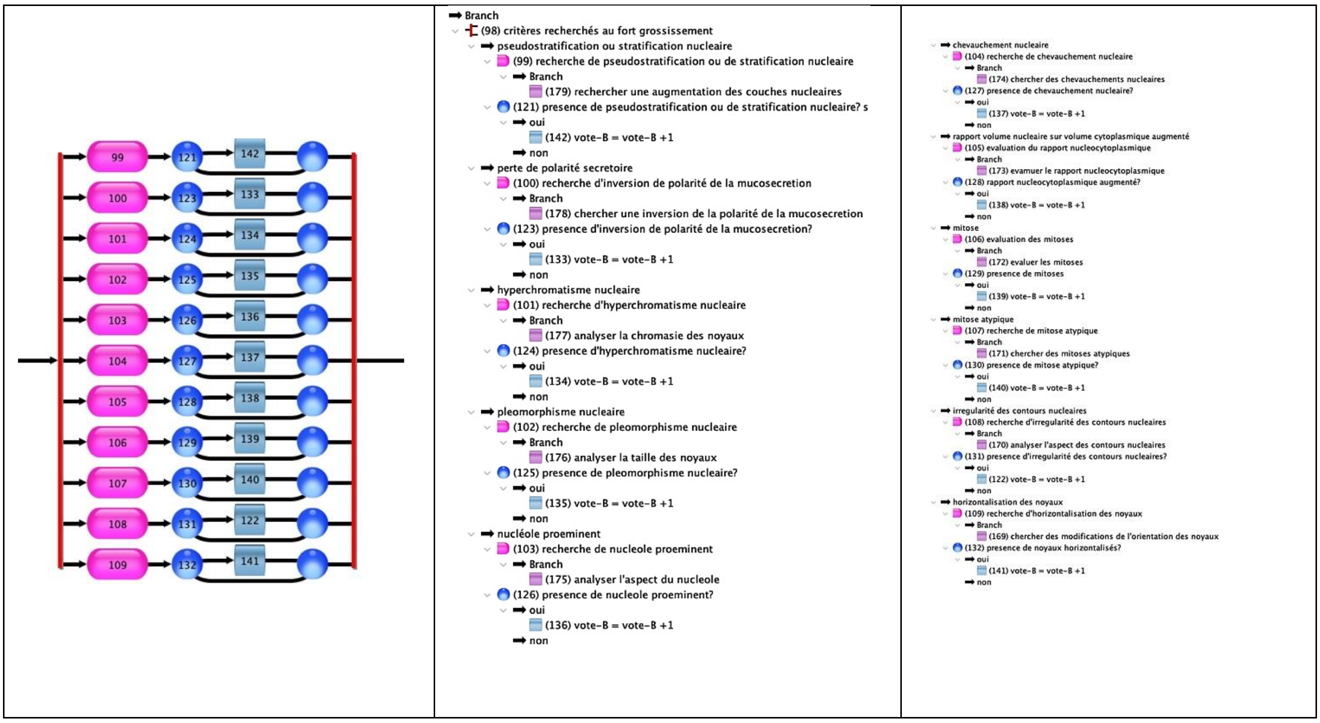


Figure-7 presents the general functioning of the activity "High magnification management". Feature analysis obeys to the previous example of ESIA (Figure-4): an activity gives the instantiation of the criterion, the vote is computed in the blue part and the final result of the vote in the working context after in the ESIA.

Figure-7 Content of the Box B (activity 97) « High magnification management » in Figure-6.



The features used at high magnification are specified by the names given to arrows on left. For example, "pseudostratification ou stratification nucléaire" for the first feature. This list may be easily adapted to each expert by using the mode editing for modifying the weight of each feature or adding (or suppressing) a feature or by combining several features (e.g. presence of a feature and absence of a second feature). For example, the blue action 142 for "pseudostratification ou stratification nucléaire" gives "vote-B = vote-B + 1". All these features can be checked independently of the others in any order, but all features must be checked before to leave the ESIA for concluding on the global result of the vote (i.e. the value of vote-B once the ESIA left).

There is a consensus on (1) browsing digital slide for finding zones of interest, and a common list of features, (2) the frequent switch between low magnification (to identify a zone of interest) and zoom on features in the zone of interest according to criteria, (3) a voting system on presence or absence of features) and (4) the establishment of a common glossary. Their main difference comes from criteria exploitation (instantiation, relative weight, combination, etc.), each pathologist having a personal apprehension of features (ordering, individual importance, relationships between features, eventually the absence of a characteristic is considered as a strong argument against the disease). Flexibility is ensured by criteria evaluation after voting system in ESIA considering that a feature may be of interest or not for a pathologist. Each criterion expressing presence (or absence) of a feature is evaluated first in an activity.

Conclusion

The chronic inflammatory bowel diagnosis model, which is expressed as a contextual graph (i.e. a collective mental representation), is original under several aspects. It offers a unified view of different pathologist diagnostics, each expert model being accepted by other colleagues based on a shared glossary. Pathologists use with success glocal search based on criteria evaluation about chronic inflammatory bowel features. Finally, the voting system appears as an effective approach in decision-making that allows the flexibility required for addressing individual decision-making and adapting a collective decision-making to specific data. A direct consequence is the possibility to compare decisions of two pathologists and to determine exactly the point of bifurcation between their reasoning and the possible manner to lift the lock.

The originality of the context-based model of chronic inflammatory bowel diagnosis is due to three aspects. First, the contextual graph offers a unified view on the different ways pathologists diagnose dysplasia in a relatively ill-formalized domain. Second, glocal search is in the realm of decision-making processes when numerous contextual elements must be considered at different granularity. Third, the voting system is an effective alternative to formal approaches in decision-making that allows flexibility for adapting a collective model of decision-making to specific data, allowing personal expressions of actors' preferences, and revising on the fly result of the voting system.

All other projects developed in medicine with the use of the CxG formalism also brought interesting results. As an instance, the work of Logan-Young and Hoffman has had an important influence on the growth and development of breast imaging[6]. Their procedures try implicitly to build different context-specific models, and correspond rather at "best practices" for a large class of patients. The contextual graph representing this expertise model in a structured representation of experts' experience (with about 400 items in the contextual graph). The situation is similar to Hierarchical Task Analysis[10] in Cognitive Psychology.

Conflicts of Interest Statement:

None

Funding Statement:

None

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