anales de psicología, 2014, vol. 30, nº 1 (enero), 329-336
http://dx.doi.org/10.6018/analesps.30.1.139251

ISSN edición impresa: 0212-9728. ISSN edición web (http://revistas.um.es/analesps): 1695-2294

Cognitive models of executive functions development. Methodological limitations and theoretical challenges

Florencia Stelzer[1,2], Cecilia C. Mazzoni[2,3,*] y Mauricio A. Cervigni[2,3]

1 Centro de Investigación en Procesos Básicos, Metodología y Educación, Facultad de Psicología, Universidad Nacional de Mar del Plata (UNMP)
2 Facultad de Psicología, Universidad Nacional de Rosario (UNR)
3 Instituto Rosario de Investigación en Ciencias de la Educación (IRICE-CONICET/UNR)

Título: Modelos cognitivos del desarrollo de las funciones ejecutivas. Limitaciones metodológicas y desafíos teóricos.
Resumen: Las funciones ejecutivas (EF) han sido definidas como una serie de procesos cognitivos de orden superior, que permiten el control del pensamiento, comportamiento y afectividad conforme al logro de una meta. Tales procesos presentan un desarrollo posnatal prolongado, culminando su maduración sobre el final de la adolescencia. En el presente artículo se realiza una revisión de algunos de los principales modelos del desarrollo de las EF en la infancia. El objetivo central de este trabajo es describir el estado del arte respecto de dicho tópico, identificando las principales dificultades teóricas y limitaciones metodológicas asociadas a los diferentes paradigmas propuestos. Finalmente, se señalan algunas de las soluciones sugeridas para afrontar tales dificultades, destacando que el desarrollo de una ontología de las EF podría resultar una alternativa viable para contrarrestar las mismas. Consideramos que futuras investigaciones deberían encaminar sus esfuerzos en esta dirección.
Palabras claves: Modelos cognitivos; funciones ejecutivas; desarrollo; ontología.

Abstract: Executive functions (EF) have been defined as a series of higher-order cognitive processes which allow the control of thought, behavior and affection according to the achievement of a goal. Such processes present a lengthy postnatal development which matures completely by the end of adolescence. In this article we make a review of some of the main models of EF development during childhood. The aim of this work is to describe the state of the art related to the topic, identifying the main theoretical difficulties and methodological limitations associated with the different proposed paradigms. Finally, some suggestions are given to cope with such difficulties, emphasizing that the development of an ontology of EF could be a viable alternative to counter them. We believe that future researches should guide their efforts toward the development of that ontology.
Key words: Cognitive models; executive functions; development; ontology.

Introduction

Executive functions (EF) is an umbrella term which clusters different cognitive processes that allow the control of thought, behavior and affection according to the achievement of a goal (Zelazo & Carlson, 2012). EF will facilitate individual's adaptation to his environment, enabling the generation of novel responses which could be modified along with the variations in the environment. In its origin, EF were related to frontal lobe damage (Shallice, 1988); however, today it is recognized that those cognitive processes clustered under such term depend on a complex neural network in which diverse cortical regions are involved. At the same time, the engagement of the diverse areas of the prefrontal cortex (PFC) would vary along to the cognitive process involved (Bunge & Crone, 2009; Stuss, 2011).

The first experimental studies done about EF in adults used some adapted cognitive tests available which were no originally designed with the purpose of testing patients with frontal damage. Some examples of paradigmatic tasks are the Wisconsin Card Sorting Test (WCST) (Grant & Berg, 1948), the Stroop Test (Stroop, 1935) and Tower Tasks (Tower of Hanoi and Tower of London) (Krikorian, Bartok, & Gay, 1994; Shallice, 1982). Also, other researchers developed specific tests to study the alterations associated to the PFC, being an example of such the Iowa Gambling Task (IGT) (Bechara, Damasio, Damasio, & Anderson, 1994) and the Six Elements test (Shallice & Burgess, 1991). Although frontal lobe injuries affecting the performance in tasks above mentioned, the processes and the anatomical areas involved in the performance of each of these are not yet fully clear (Bunge & Crone, 2009; Wendelken, Munakata, Baym, Souza, & Bunge, 2012; Senió w, 2012).

During the last three decades, the importance of EF integrity for human adaptation to the environment lead to an increase of researches aimed to understand the origin and development of such processes (Bernier, Carlson, Deschenes, & Matte-Gagné, 2012; Conway & Stifter, 2012; Diamond, 2001, 2002, 2013; McDermott, Westerlund, Zeanah, Nelson, & Fox, 2012; Posner, Rothbart, Sheese, & Voelker, 2012; Welsh, Pennington, & Groisser, 1991). The implementation and expansion of such studies required the establishment of adequate EF tests for its application with children. The design of those procedures was inspired partly in the existing tasks for adults, many of the tests constituting simplified versions of existing tasks (Espy, 1997; Frye, Zelazo, & Palfai, 1995; Gerstadt, Hong, & Diamond, 1994; Hughes, 1998a, 1998b; Kerr, & Zelazo, 2004; Zelazo, 2006). A broad variety of procedures was developed during this stage to be used to test children. However, the use of adult-simplified-tests in children implied difficulties when establishing the development paths of EF, producing cognitive models very different among themselves.

Beyond the variety of existing models, numerous studies agree on the importance of proper development of such processes for human adaptation to the environment (Jacobson, Williford, & Pianta, 2011; McAlister & Peterson, 2012; Rueda, Posner, & Rothbart, 2005; Wasserman, 2012). Some

*** Dirección para correspondencia [Correspondence address]:**
Cecilia Mazzoni, Instituto Rosario de Investigación en Ciencias de la Educación, Bv. 27 de Febrero 210 Bis (Ocampo y Esmeralda), Rosario, Santa Fe (2000) (Argentina). E-mail: mazzoni@irice-conicet.gov.ar

authors have linked the executive performance with: (a) the development of conscience and certain social and moral skills (Kochanska, Murray, & Harlan, 2000); (b) children's skills in mathematics and arithmetic (Blair & Razza, 2007; Bull, Espy, & Wiebe, 2008; Bull, Espy, Wiebe, Sheffield, & Nelson, 2011; Espy et al., 2004); (c) the ability to read (Swanson & Ashbaker, 2000; Swanson & Sachse-Lee, 2001; Wasserman, 2012) and the academic general performance (Latzman, Elkovitch, Young, & Clark, 2010; Thorell, Veleiro, Siu, Mohammadi, 2012; van der Sluis, 2007); (d) the development of the skills clustered under the "theory of mind" concept (Carlson, Moses, & Claxton, 2004; Hughes & Ensor, 2005); and (e) the emotional regulation (Carlson & Wang, 2007; Rothbart & Posner, 2006).

Considering the importance that executive control processes have on the individual´s adaptation to his environment, in this article we will make a review of some of the main development models of EF. Based on this review, we describe the main theoretical and methodological difficulties associated with the different models proposed, mentioning some of the possible solutions suggested addressing such obstacles. The main objective of our work is to describe the state of the art on this topic, pointing out convergences and divergences among the various authors and possible future research goals.

Some historical considerations in the study of EF

Currently, different cognitive models of EF for adults coexist (Tirapu-Ustárroz, García-Molina, Luna-Lario, Roig-Rovira, & Pelegrín-Valero, 2008a, 2008b). This fact could be based in some historic aspects of the study of frontal lobe activity since for a long time there was certain skepticism regarding the functional role of such structure (Benton, 1991, cited in Burgess et al., 2006). However, the emergence of neuroimaging technologies made possible to progressively capture with more precision the variations in the physiology and anatomy of the nervous system, showing that the PFC would be involved in the execution of diverse tasks. With the purpose of validating the use of new technologies, some researchers have used and adapted cognitive tests originated in context outside the neuropsychology in order to test patients with frontal lobe damage (*e.g.* WCST and Stroop Test) (Burges et al., 2006).

The number increase in the available tasks showed a lack of correspondence among the data given by the new technology and the frontal lobe tests (Burges, 1997; Burges et.al., 2006). This means that comparing empirical findings from diverse researches resulted contradictory and produced difficult theoretical interpretation. For example, when trying to relate cognitive specific operations to certain regions of the PFC, it was found that there was no unique correspondence relationship among both of them. At the same time, the lack of concord among the cortical areas activated by the execution of certain tasks and the theoretical construct which such tests would assess (*e.g.* working memory, controlling attention, decision making, etc.), favored the development of diverse models of EF, rooted in theoretical, empirical and methodological diverse assumptions. According to Burgess et al. (2006), the spread of the various EF models, would have developed due to the lack of correspondence among the diverse levels of explanation in the study of EF.

Explanation levels in the study of EF

Burgess et al. (2006) postulated that in the study of EF three levels of explanation could be established: (a) a construct level, (b) an operation level, and, finally (c) a function level. The construct level is characterized for giving explanations postulating cognitive hypothetical resources, which existence would be inferred through the analysis of diverse research results (Burgess et al., 2006). Working memory is a paradigmatic example of the construct level explanation. Its existence was inferred mainly based on the analysis of the observed variations in the tasks which imply the capacity of remembering various types of information and manipulating them. This level of explanation gives a theoretical frame which eases experiment design.

On another hand, the level of operations would refer to those individual components of the cognition which would not be directly observable but could be inferred from the analysis of the results of diverse tasks and the observed variations in certain dependent variables (Burges et al., 2006). Examples of the associated operations of working memory construct would be the maintenance and manipulation of the information in the mind. Moreover, the variations in the number of errors of a task and changes in cerebral blood flow, etc., would be the observable indicators from which the operations are inferred.

Finally, the level of functions would refer to the behavioral observable manifestations which could be the result of a series of operations. The same could be simple (*e.g.* to describe a previously heard story) or complex (*e.g.* to prepare a cake) (Burges et al., 2006).

Burgess (1997) has suggested that the construct level explanations have reigned in the field of EF study. However, a significant part of the classical tasks (*e.g.* WCST, TOL, IGT, etc.) from which such theorizations have developed would imply demands from different operations. This means that tasks which might assess identical construct would present intrinsic different demands at the operation level. Thereby, when trying to establish the validity of theoretical construct contradictory results have emerged. Such displacement between the theoretical construct level and the operational level of the executive processes has had important consequences in the development of different cognitive models of EF. This mismatch has facilitated the application of very different EF models.

EF cognitive models in adults

Since EF constitute a term which lacks conceptual and operational definition of absolute consensus, establishing a classification of the various cognitive models of EF is a difficult task which is subject to some criticism. This fact is based in the diversity underlying its conceptual, empirical and methodological basis. However, a large number of authors has classified different models according to the characteristics of the postulated structure for such construct (Garon, Bryson, & Smith, 2008; Tirapú- Ustárroz et al., 2008a, 2008b). In the first place, there would exist a group of models which have considered EF as a unit comparable to the General Intelligence Factor, in the conceptual level (Baddeley, 1992; Duncan, Burgess, & Emslie, 1995; Duncan, Johnson, Swales, & Freer, 1997; Norman & Shallice, 1986; Shallice, 1988). An example of this trend would be represented by the assertion of Denckla and Reiss (1997) which postulates that EF would shape a cognitive module made by a series of effectors elements such as inhibition, working memory and organizational strategies necessary to structure a response. Second, a number of other models are characterized by postulate that behind the term EF different cognitive processes group independently of each other. This means that there would not be a central process which modulates the activity of the different sub-components (Godefroy, Cabaret, Petit-Chenal, Pruvo, & Rousseaux, 1999; Salthouse, Atkinson, & Berish, 2003; Stuss, 2011). Finally, in the third place, there could be a group of models which would postulate that EF constitutes a unitary construct but with partially dissociable components (Miyake et al., 2000).

EF cognitive models in infants

Like in the cases of EF models proposed for adults, the developmental models of these processes, have considered three possible structures for such construct. Firstly, some researchers have postulated that EF would present a unified structure (Munakata, 2001; Posner & Rothbart, 2007; Zelazo & Frye, 1998; Zelazo & Muller, 2002). Secondly, other authors have considered that EF would imply a dissociated components structure (Diamond, 2006, 2013). Finally, some researchers have considered an integrated vision of the previous two approaches postulating that EF would have a unitary structure but with partially dissociable components (Huizinga, Dolan, & Van der Molen, 2006; Letho, Juujarvi, Kooistra, & Pulkkinen, 2003).

Models of EF development as a unitary construct

An example of a unified model is the EF structure proposed by Munakata (2001, 2004). This author has postulated that behavior regulation implied in EF would be the result of the interrelationship among the latent and active memory traces. The active traces are characterized by its link to the attention processes and working memory, while the latent memory traces are associated to the habits and the capacity of long term memory. The latent memory systems would expand during the early postnatal development. On the contrary, the active memory system would develop slowly during childhood. Both types of representation systems interact in such way that when a conflict appears between them an active representation would be necessary to supersede the latent representation (Munakata & McClelland, 2003).

A second example which responds to a unitary perspective of EF is the paradigm developed by Posner and Rothbart (2007). Such authors have postulated that changes observed in the behaviour, thinking and affectivity regulation capacity during childhood would be rooted in the development and integration of three attentional systems. Through the use of various neuroimaging techniques, Posner et al. identified three specific neuronal networks related to the attentional functions of alerting, orienting and executive control (Posner, Sheese, Odludas, & Tong, 2006; Rueda et al., 2005). The alert network is linked to the acquisition and maintenance of the alert state. Such network is associated to the activity of the thalamic and cortical areas of norepinephrine innervation. On the other hand, the orientation network is linked to the capacity of redirecting the attention focus according to the characteristics of the stimulus being sent. The functions thereof are linked mainly to the parietal cortex activity being modulated by the cholinergic neurotransmitter system. Finally, the executive network is related to the performance in conflict tasks which involve the identification and correction of errors (Petersen & Posner, 2012). This network has been linked mainly to the activity of the anterior cingulate cortex and dorsolateral prefrontal cortex. Furthermore, this network would depend on dopaminergic neurotransmitter system. The executive network enables the resolution of conflicts through the control of other neural networks allowing the regulation of thought and affectivity.

On the other hand, a third model of EF development which would consider them as a unitary construct is one of cognitive complexity and control theory proposed by Zelazo et al. (Bunge & Zelazo, 2006; Zelazo et al., 1998; Zelazo, Frye, & Rapus, 1996). This model postulates that the executive performance of individuals is based on the capacity of representing and structuring information in organized systems of hierarchical rules. That is, the increase in the complexity of the rules that the child can develop and maintain during problems resolution, would gradually take greater control over his behavior, thought and affection. According to Zelazo et al. these changes could be possible due to the development degree in which children could show themselves consciously in the rules which they represent (*e.g.* from thinking about doing something, to the actual knowledge of knowing that they are thinking about doing something, to the point of knowing that they know and then on) (Zelazo, Muller, Frye, & Marcovitch, 2003; Marcovitch & Zelazo, 2009). In this way, the persistent behavior in specific situations would be the result of the absence of integration of incompatible rule systems, which would make room to discrepancies between what the children knows and his behaviour.

Zelazo has observed that towards the end of the preschool period, children become able to integrate systems of incompatible rules in progressively more complex hierarchical structures. The organization of such rules systems would enable them to adjust their behavior to the contingencies in the environment. On the other hand, it is worth mentioning that the author suggests a distinction between "cool" and "hot" EF (Zelazo, Qu, & Muller, 2005). Cool EF would be linked to abstract or decontextualized tasks. This means that the conditional rules relating to the implementation of those tasks would be associated with emotionally neutral stimuli. On the contrary, hot EF would be associated to control emotional and motivational processes. This type of EF would be linked to the representation of rules which imply the behavioral control in presence of rewarding or punishing stimulus.

Models of EF development as a dissociated components structure

From a different point of view, Diamond (2006) proposed that working memory, inhibition, and shifting are dissociable components that have different developmental trajectories. At the same time, some researches done by the same author would indicate that the capacity of coordination of EF components would follow a developmental curve with growing periods accented during the last half of the first year and between three to six year old (Diamond, 2001; 2002). Consistent with the vision of dissociated components of Diamond, Hughes (1998a) identified three different and independent components of EF. This author based her model in factorial analysis of the preschoolers' performance in different EF tasks. The resultant factors were labelled attentional shifting, inhibitory control and working memory.

From another methodological perspective, Senn, Espy and Kaufmann (2004) used path analysis to test the relation between simple and complex EF in preschoolers. These authors found that the scoring on a working memory task and on an inhibition task were correlated, and at the same time, predicted performance on a complex problem-solving task. However, the children's performance in a shifting task was not related neither to the inhibition nor to the working memory tasks. These results could indicate that EF constitutes a construct with a dissociable components structure but mutually related.

Models of EF development as an integrated structure with partially dissociable components

Currently, some authors have suggested, in relationship with the EF model for adults proposed by Miyake et al. (2000), that EF have a unitary structure but with partially dissociable components. An example of this type of model was proposed by Letho et al. (2003) who applied exploratory and confirmatory factor analyses (*CFA*) to three to eight year old children's EF performance. These authors found that the different EF measurements provided an inter-correlated and partially dissociable three factor model. In the same way that Miyake`s model, these factors were denominated working memory, shifting and inhibition. The results of such researches would support the vision that EF would have a unitary structure with partially independent components.

At the same time, Huizinga et al. (2006) test the consistency of the different EF factors throughout the development, applying *CFA* to the executive performance of children and adolescents between seven and twenty one year old. Even though two latent variables could be extracted from the tasks aimed to asses working memory and shifting, this did not occurred with those tasks oriented to asses inhibition, which were no charged within a common factor. The contraposition of these results with the findings of Letho et al. (2003) could be originated in the wide age range considered by Huizinga et al. (2006). All together, the findings of Huizinga et al. (2006) and Letho et al. (2003) would support the proposition of Miyake et al. (2001) of a dissociable structure with partially inter-correlated components of EF. However, the different results observed among the work of Letho et al. (2003) and Huizinga et al. (2006) would evidence that the independence degree and the unity of EF components could change along the development.

Regarding this point, Wiebe, Espy and Charak (2008) found that variations in the performance of three to six year old children in tasks used to assess working memory and inhibition constructs could be explained by a single factor. Subsequent studies with preschool children would be consistent with these results (Hughes, Ensor, Wilson, & Graham 2010; Wiebe et al., 2011). Taken together, the findings of these researches indicate that during the preschool period variations in performance in several tests of EF could be explained by only one factor, while in older children EF adopt a partially dissociated structure with related components, such Miyake (2001) observed in adults.

Theoretical and methodological difficulties in the establishment of EF developmental models

The EF developmental models previously considered are rooted in empirical, theoretical and methodological diverse bases. For example, the cognitive complexity and control model proposed by Zelazo et al. (1998) would be based mainly in the analysis of children's performance in experimental variations of the Dimensional Change Card Sort (DCCS) task. On the other hand, Posner et al.'s attention model lies mainly in the articulation between different levels of neural networks activity (genetics, molecular, physiologic and anatomic) and the performance of specific attention tasks (Posner et al., 2006; Posner, Rothbart, Sheese, Voelker, 2012; Rueda, Rothbart, McAndliss, Saccomanno, & Posner, 2005). From another perspective, the EF model proposed by Munakata (2001, 2004) would be based mainly in the modeling of neural networks activity associated to EF. In contraposition, the structure proposed by Diamond (2002; 2006; 2013) would lie in an empirical view based in the analysis of children´s performance in different EF tasks. To summarize, the tasks, procedures, data analysis and theoretical basis under which each model was formed, differ significantly among them.

In addition to the above, partly conflicting results found between Lehto et al. (2003) and Huiziniga et al. (2006), may be founded on the methodological difficulties which *CFA* presents when it is applied to the data set from a wide range age sample. First, to avoid ceiling effects in EF assesment, complex tasks are used, which generally demands different operations (*e.g.* WCST, TOL, etc.). However, in order to simplify, researchers use to classify these tasks by an only cognitive construct. Nevertheless, there is no absolute consensus among the different authors regarding the corresponding construct-task. For example, the WCST has been considered by some authors as an inhibition task and by others as a shifting task (Diamond, 2013; Garon et al., 2008); TOL has been identified by different researchers as an inhibition, working memory or planning task (Berg & Byrd, 2002; Huizinga et al., 2006; Welsh, Satterlee-Cartmell, & Stine, 1999); the Stroop test has been described as an inhibition or an attention control task (Diamond, 2013; Espy & Bull, 2005; Franco-de-Lima, Pinheiro-Travaini, Salgado-Azoni, & Ciasca, 2012; Gonzalez, Fuentes, Carranza, & Estevez, 2001).

Also, in the development models which hope to discriminate the diverse EF components, the observed development paths would be influenced by the type of task used to obtain the diverse latent factors. Regarding this fact, task complexity (number of operations required for its resolution), type of performance recorded (*e.g.* errors by trials versus total errors in a task), type of requested answer (motor response versus verbal response) and type of conflict implied in each task (inference control versus motor inhibition), could jeopardize the paths of the observed development. This fact should lead researchers to be cautious when reaching conclusions regarding the diverse components' developmental paths obtained through factor analysis (Best & Miller, 2010).

The above consideration leads to that, when in the application of factor analysis techniques, battery tests are swapped by others, both the number of factors extracted as well as the observed developmental path can be modified. This fact implies that: (a) the number of components obtained has a probable error level originated by the type of initial variables introduced and consequently, (b) when forcing the extraction of components by this procedure, the detection of EF variations throughout the development would be affected. Regarding this point, it is important to mention that the models based on factor reduction analysis used to be generally synchronic, since they often do not consider the evolution within time. Some literature review has pointed that during the development, the emergency and the coordination of cognitive operations implied in EF would not constitute a lineal process (Garon et al., 2008). Garon et al. (2008) suggested that the processes underlying EF would mature in a hierarchical mode establishing two great developmental phases: (a) from six month old to three year old, basic operations of EF emerge and start to develop (holding information in the mind, focusing attention, simple inhibition); (b) from three year old to five year old, such abilities would mutually coordinate, reaching more complex form of regulation of behavior, thought and affectivity progressively. However, currently the components structure which could be discriminated during the different stages of EF development would not be clear (Hughes, Ensor, Wilson, & Graham 2010; Wiebe et al., 2011).

Proposed solutions

The reviews done by Garon et al. (2008) and Best and Miller (2010) would point that during development, the basic operations implied in EF would coordinate among themselves allowing the resolution of tasks with more complex demands. This means that both studies would indicate that EF development imply qualitative and quantitative changes in its different aspects. However, it is still unknown in depth the way in which such changes occur. For example, in the specific case of response inhibition it is still unknown which are the mechanisms that lead an infant to be able to move from the simple inhibition ability to more complex inhibition mechanisms which require the combination of different cognitive operations.

A possible way of extending our knowledge about EF structure during development would be to move from the mere description of EF components to the identification of the mechanisms underlying the changes occurred during development. Regarding this task, Best and Miller (2010) propose:

> (a) Use meta-analyses to examine the effects of moderating variables at different ages by including a larger age range. (b) Compare the developmental trajectories for two or more aspects of performance for clues as to whether one aspect influences another. (c) Look for correlations between a measure of neural activity and EF performance (d) Focus on the transition phase from one developmental level to the next (Best & Miller, 2010, p. 1653).

Discussion

Based on the review of the literature performed we consider that there is currently no conclusive scientific evidence attesting to the acceptance of a single model of EF development. We believe that this impossibility is inherent to the study of EF, as that term has been characterized since its emergence, by the lack of consensus on its conceptual and operational definition.

In the context of the absence of absolute agreement about what the EF construct "really is", we consider the development of an ontology of EF a viable alternative that would achieve a greater understanding in the study of the development of such processes. In this context, the term "ontology" must be understood in the sense used in bioinformatics, as an account of "what is" in a universe of scientific knowledge (Marino, 2010). That is, ontology constitutes "an explicit specification of a conceptualization" (Gruber, 1993, p. 199) based on a data carrier.

The solutions proposed by Best and Miller (2010) could be improved through the use of computer platforms that allow interoperability among the data from researches which consider diverse analysis levels. In this way, the difficulty inherent to the study of EF could be faced through the use of computer applications which allow: (a) the identification of terms used to describe EF in their different levels of explanation, (b) the scanning and comparison among them, (c) the identification and integration of the results from different researches which consider different analysis levels in EF study (molecular, genetic, cellular, functional, anatomic) (Pollack et al., 2011).

In the genetic and molecular biology, the development of an ontology has led the accumulation and comparison of data from different studies. An example is the "Ontology Gen" (Ashburner et al., 2000) which contains consistent descriptions for the cellular components, molecular and biological processes of different organisms. The explanation implied in such ontology would prevent researchers using diverse terms to refer to the same biological process or component, allowing the integration and comparison of data from different researches. In this way, the ontologies could be defined as a structured base of knowledge intended to endure the exchange and automatic reasoning based on it (Poldrack et. al., 2011).

While today some researches are leading their efforts toward this direction (Turner & Lair, 2011; Poldrack et al., 2011), the establishment of one ontology of the EF which allows the understanding of these processes is still a long term goal. We consider that future researches should guide their efforts toward the development of that ontology.

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(Article received: 12-11-2011; reviewed: 23-01-2013; accepted: 23-01-2013)