Multi-Dimensional Creativity: Approaches to Computational Modeling

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Abstract

This paper presents a multi-dimensional perspective for the study of creativity and formulates a framework for computational creativity that consists of 1) Culture; 2) Society; 3) Groups; 4) Individual, and 5) Brain. This framework enables the definition of functional relationships among these scales, and captures the effects of time within each scale. Its relevance and usefulness are shown firstly by classifying recent studies of computational creativity, and secondly by illustrating multi-dimensional approaches to the computational study of creativity. The paper closes offering modeling guidelines and principles for the computational studies of creativity.

I. Introduction

How do scholars of creativity frame their research questions? One way of answering this is by looking at their disciplinary affiliations; this will suggest the methods they trust, the variables and indicators chosen in their fields to develop, test and refine theories about creativity, and even how they define the complex construct of creativity. Whilst every field has yet to develop prevalent definitions, its study spans across multiple domains and areas of knowledge. Only in recent years, the research programs include the study of "creative brains" (Fink et al 2009), "creative cognition" (Kleibeuker et al 2013), "creative personality" (Qian et al 2010), "creative teams" (Gloor et al 2012), "creative organizations" (Mathisen et al 2012), "creative occupations" (Lee and Drever 2012), "creative cities" (Evans 2009), "creative industries" (Hotho and Champion 2012), "creative countries" (Cai 2012), and "creative eras" (Marshal 2009) –to name a few.

Rather than pursuing a specific definition or seeing creativity as a binary property, we consider that *creativeness* is a relative value ascribed by weak-to-strong levels of agreement or consensus to persons, processes, outcomes, etc. with the judgment ranging from non-creative or routine to transformative or disruptive creativity (Gero 1990; Kaufman and Beghetto 2009). This ascription of values (novelty, utility, expectation, etc.) occurs in a system where creators and evaluators interact often at different scales and times, therefore this paper regards creativity as a multi-level construct eminently situational.

Computational creativity is a relatively recent and promising research approach that complements the current methods, techniques and traditions to understand and support creativity. Its origins in Artificial Intelligence (AI) help explain its emphasis on the modeling of individual processes, and its reliance on external evaluations of performance and outcomes. In the AI paradigm, the system architecture consists of *autonomous* individuals or agents interacting with an external environment and generating solutions that are assessed by human judges in terms of their quality and similarity to human solutions (Russell and Norvig 2005). Alternative ways of applying computational methods to the study of creativity are developed in this paper.

A multi-dimensional perspective for the study of creativity is presented here via a framework for computational creativity. The aims of this work include: to enable new ways of thinking about creativity from different disciplines, to support communication between research traditions, and to start mapping the units of analysis, variables and interactions across scales and time. The paper is organized as follows: Section 2 introduces key concepts and draws from the theoretical bases of this approach; Section 3 presents our framework and explains its main structural and functional aspects. Section 4 applies this framework to classify recent studies of computational creativity and illustrates multi-dimensional modeling approaches. Section 5 closes the paper presenting modeling guidelines and implications for connecting computational methods to other research methods for the study of creativity.

II. Background

A social-psychology approach to creativity began to illustrate the interaction between individual and external factors (Hennessey 2003). More recently, cultural-psychology creativity seeks to extend that work by shifting the architecture from a view of individual behavior "conditioned" by social factors and towards a more integrated view where interdependent relationships co-constitute a complex creative system (Glăveanu 2010).

Integrating scientific disciplines goes back to Comte's hierarchy of sciences according to the scale and complexity of theoretical tools (Mayer and Lang 2011). The role of cultural mediation in the development of cognitive functions has its origins in the tradition of cultural psychology since Vygotsky (Moran and John-Steiner 2003). Ecological models of creative problem solving integrate cognitive, personality, and situational factors (Isaksen et al 1993). Views of creativity as a social construct have been formulated elsewhere (Sawyer 2010; Westmeyer 2009).

Multilevel models that capture the interactions between psychological, social and cultural factors enable two complementary research directions. On the one hand, holistic explanations are possible by going up in the hierarchy drawing upon higher levels that moderate lower effects. On the other hand, reductionist explanations go down in the hierarchy to inspect lower-level factors that account for high-level phenomena (Koestler and Smythies 1969). For example, accounting for cultural constructs can be essential to understand individual attitudes to altruism (Sheldon et al). Likewise, the characterization of individual cognitive styles helps explain and manage group conflict (Kim et al 2012).

Despite the disciplinary divides between psychology, anthropology and sociology, a phenomenon such as creativity requires a cross-disciplinary perspective that includes the interplay between levels of causality (Sternberg and Grigorenko 2001). In contrast to other research methods, computational creativity has the potential to embark on such cross-disciplinary modeling.

Contemporary personality research is a relevant example as it provides empirical support for the *irreducibility* postulate: i.e., "no scientific discipline is likely to subsume the others, all are needed" (Sheldon 2004). In the field of personality and well-being, multilevel approaches show the complex interactions and effects among factors located within and between levels of organization -from cultural to social, personality, cognition and neural processes (West et al 2010). Such integrated and interdisciplinary models account for moderator relationships between levels of organization.

The Multilevel Personality in Context (MPIC) (Sheldon et al 2011) and the Cognitive-Affect Personality System (CAPS) (Mischel and Shoda 1995) are two examples of how multiple levels of analysis can be integrated for a more reliable and complete understanding of complex human behavior –such as creativity. The MPIC model specifies the following levels: Culture, Social relations, and four levels of Personality: Self-Narratives, Goals/Motives, Traits/Dispositions, and Needs/Universals (Sheldon et al 2011). Reviewers of the MPIC model further suggest the addition of situations to account for contextual factors beyond the bio-psychosocial (Mayer and Lang 2011).

In computational creativity, Indurkhya (2012) identifies the interplay between system levels by framing the following dilemma: when non-conscious or unintentional processes generate artifacts deemed as creative by an audience (i.e., works of art by a person diagnosed with schizophrenia or the ubiquitous cases of unexpected successful products), "where is the creativity?". A similar point can be made when considering the attribution of creativity to designs by Nature (McGrew 2012). Understanding the interplay between generative and evaluative processes of creativity has the potential to transcend such apparent paradox where at a given level it may seem like "there is nothing distinctive […] that we can label as creative" (Indurkhya 2012).

Maher (2012) frames the need for evaluation criteria that are independent of the generative process. Jordanus (2011) suggests a standardized approach to evaluation where key components are identified, clear metrics are defined and tests are implemented. The work presented in this paper is aligned to these aims and puts forward a structural and functional framework for an integrated cross-disciplinary study of computational creativity.

III. Multi-Dimensional Creativity

The Multi-Dimensional Creativity (MDC) framework builds on the Idea-Agent-Society (IAS) triad of creative systems: epistemological, individual and social (Sosa et al 2009). IAS synthesizes constructs from five influential theories related to creativity and innovation, i.e.: exemplars, proponents, and communities (Thomas Kuhn); innovations, entrepreneurs and markets (Joseph Schumpeter); noosphere, strong spirit and culture (Edgar Morin); domain, individual and field (Mihalyi Csikszentmihalyi); and logic, genius and zeitgeist (Dean Simonton).

MDC goes beyond the mapping of systemic dimensions and enables the definition of temporal and functional relationships in five scales of analysis: 1) Culture; 2) Society; 3) Group; 4) Individual; and 5) Brain. These relationships can be defined in computational studies as independent or interdependent, i.e., the former represent processes that occur only within a single scale in isolation, whilst the latter represent processes that are connected between scales. For example, a range of cognitive functions can be studied in a computational system, some of which can be assumed to emerge from explicit lower-level neural processes, others that are defined only within the cognitive level, and a third type that lead to higher-level personality or group processes. Figure 1 depicts the organization of the MDC framework with scales represented by overlapping circles to explicitly avoid the implication of more common concentric arrangements that higher-level factors are simply the aggregation of smaller units.

MDC scales	Sample creativity studies
MDC-1: Culture	Cultural dimensions in creativity (Lubart 2010); Peer-reviewed repositories (Duflou and Verhaegen 2011); IP law (Lessig 2008); Built environment (McCoy and Evans 2002).
MDC-2: Society	Gatekeeping (Sosa and Gero 2005a); Cultural psychology (Glăveanu 2010); Creative class (Florida); Migration (Hansen and Niedomysl 2009); Social capital (Fischer et al 2004).
MDC-3: Group	Group conformity (Kaplan et al 2009); Team diversity (Bassett-Jones 2005); Group brainstorming (Sosa and Gero 2012).
MDC-4: Individual	Creative cognition (Finke et al 1996); Bilingüalism (Adesope et al 2010); Extraversion and dominance (Anderson and Kilduff 2009); Openness (Dollinger 2004);
MDC-5: Brain	Neuroanatomy (Jung et al 2010); NN models (Iyer et al 2009) Dietrich…

Table 1. Sample studies of creativity in the five scales of our multi-dimensional model of computational creativity (MDC)

MDC-1, Culture, refers to the epistemological scale of creativity and addresses questions such as "How do systems of beliefs, language or taste change over time?", "How may intellectual property law affect creativity and innovation?", or "To what extent do the physical environment and communication practices determine the levels of creativity in an organization?". Computational models at this scale can seek to grow these processes artificially by manipulating a range of initial factors and conditions, or they may build artificial creators that draw from or are inspired by real-world knowledge bases and corpora. MDC-1 studies include: culture and technology evolution, organizational culture, language and semiotics, economic impacts, taste and traditions, public policy, mass media, intellectual property, cross-cultural comparisons, and creative environments.

MDC-2, Society, refers to the aggregate or macro scale of human agency. It captures processes that account for the influence of –or seek to grow effects on– demographics, networks, migration, social influence and authority, roles and occupations, class structure, social capital, crowdsourcing, market segmentation, reputation and popularity, ethnic diversity, gender and aging, diffusion of innovations, crowd behavior.

MDC-3, Group, refers to creativity phenomena that occurs at the scale of small to large groups of humans. This includes ideation sessions, team dynamics, communities of practice, family and peer support, co-creation, artist collectives, art commission, brainstorming, change management and leadership, deliberation, collaboration/competition strategies, workplace practices, groupthink, game theory, adopter categories.

MDC-4, Individual, is arguably the most common scale of study of creativity and it spans cognitive science and psychology research. Beyond 'creative cognition' (intuition, insight, incubation, problem framing and solving, concept formation, representation, fixation, association, analogy, divergent thinking, abductive reasoning), processes on this scale also include personality types, motivation, curiosity, extroversion, mental health, addictions, emotions, risk aversion, well-being and lifestyle, habit, expertise, perception, biases, heuristics, etc.

Finally, MDC-5, Brain, includes all creativity processes at the neural scale including neuroanatomy (brain asymmetry), neuromodulation (risk, arousal, novelty), brain stimulation, as well as neural network (NN) modeling of creative reasoning.

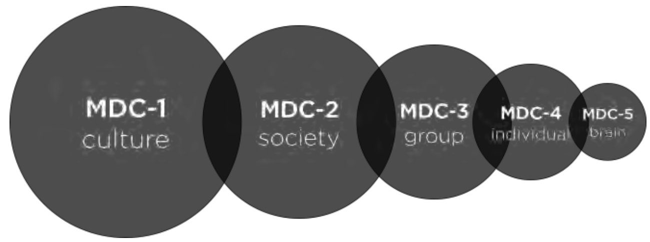

Figure 1. Overlapping circles indicate that MDC scales are more than the aggregation or subsumption of lower scales; scale-specific factors exist that are not decomposable to smaller units.

The MDC framework accounts for multiple scales of creativity, each of which has been traditionally addressed in isolation as shown by the existing research programs in Table 1 and mentioned throughout this paper. MDC links these scales together and enables researchers to explore top-down and bottom-up connections between these scales, as well as to distinguish time-based patterns within each scale.

Time in MDC

The MDC framework includes a temporal dimension that applies across scales. Time is considered by the length and stability of the interactions, ranging from a few seconds as in studies of creativity and brain activity to millennia as in studies of creativity in human evolution. In MDC-1, short-term processes of interest range from rapid changes such as those observed in the fashion industry (Mora 2006) to the modelling of transient fads (Krapivsky et al 2010). Mid-term processes of MDC-1 include geographical analyses of innovation and entrepreneurship (Lee et al 2004; Phan et al 2010), culture's influence on creativity (Bhawuk 2003), and the cultural assessment of creative ideas (Hempel and Sue-Chan 2010). Long-term processes in MDC-1 include archeological studies of the origins of human innovation and creativity (Elias 2012), and historical studies of culture and creativity (Marshall 2009; Tan 1997; Kuhn 2012).

In MDC-2, the shortest timescale includes events such as creativity in online collaboration and unconventional self-coordinated rapid responses to contingencies (Tosato and Bodi 2012; Webb and Chevreau 2006; Crespo et al 2007). Social processes that span weeks to months in their planning and execution include: word-of-mouth communication, and innovative bottom-up structures such as social movements in politics, sports, and festivals (Godes and Mayzlin 2004; Shepard 2012). More stable social relationships relevant to creativity grow over years and can extend through centuries and beyond, such as schools, awards and creative guilds; studies of population genetics, human behavioral ecology and evolutionary psychology also illustrate long-term social phenomena related to creativity (Mahmood 2008; Kijkuit and Van Den Ende 2007; Scott 2006; Becker 1997; Sunstein 2003).

In MDC-3, ephemeral interactions occur in settings such as ideation sessions, conversation analysis and improvisation (Paulus and Nijstad 2003; Sawyer 2003; Björkman 2004; Lemons 2005). More stable events include project teamwork and conflict, workplace dynamics, creativity and leadership, creative performance over time, and classroom creativity (Chen 2006; Nemeth et al 2004; James et al 2004; Shalley and Gilson 2004; Tierney and Farmer 2011; Saracho 2012; Starko 2009). Long-term structures in MDC-3 may span for decades and longer, such as in the role of social networks and career development (Jones 2010; Ohly et al 2010).

In MDC-4, the research methods tend to focus on laboratory settings where particular cognitive mechanisms are targeted, and may extend to include effects that last days or weeks, i.e., periods of incubation and *a-ha* moments of insight (Smith et al 1995; Gero 2011; Storm and Angello 2010; Hennessey and Amabile 1998; Gilhooly et al 2012). Personal traits and processes that span over several years include formal education, ageing, childhood and mental health (Simonton 2012; Vygotsky 1990; Duffy 2006; Basu et al 2011; Zhang and Niu 2013; Noori et al 2012). Lastly, MDC-4 life-long phenomena such as giftedness, career trajectories and biographies represent the long-term dimension in this category (Sak 2004; Gardner 2011; Syed 2010).

Lastly, in MDC-5 brain activity is analyzed over short periods from seconds to minutes (Aziz-Zadeh et al 2013, Kowatari et al 2009; Green et al 2012; Dietrich and Kanso 2010). More persistent processes include the effects of brain magnetic stimulation, drugs, sleep and dementia, as well as brain plasticity (Snyder et al 2012; Fink et al 2010; Rosenthal and Westreich 2010; Maquet and Ruby 2004; Miller and Hou 2004; Otte 2001). Long-term brain phenomena include the evolution of the brain, the relation between brain development and language, and the neurobiology of nonhuman animal creativity (DeFelipe 2011; Christiansen and Chater 2008; Kaufman et al 2013).

MDC Modeling

MDC is a cross-disciplinary framework that aims to guide computational studies of creativity, although it is applicable to other research approaches. Cross-scale and time-based interactions open up a triple set of opportunities:

- MDC allows reductionistic studies of generative processes, i.e., what neural mechanisms enable the individual cognitive processes and the team interactions necessary to create solutions including a small ratio of new and useful ones (*A* arrow, Figure 2); how group dynamics, societal and cultural norms shape change agency and change resistance (*B* arrow, Figure 2).
- MDC also supports holistic analysis across scales, i.e., how individuals and societies anticipate new ideas to evolve their culture or create new sub-cultures (*C* arrow, Figure 2); the links between brain evolution and language (*D* arrow, Figure 2).
- MDC also enables longitudinal studies within scales, i.e., how sudden events may lead to long-term cultural changes, workplace policies or social movements (*E* arrow, Figure 2); how a short-lived experience may affect an individual's creative career (*F* arrow, Figure 2).

The MDC framework accommodates various research traditions, approaches and units of analysis. Figure 2 depicts the MDC framework with scales on the vertical axis and time on the horizontal axis. The arrows show the type of cross-scale and time-based interactions that MDC supports.

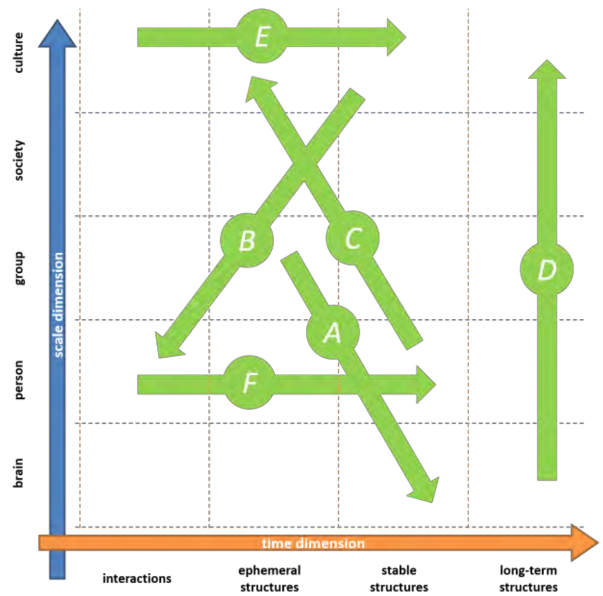

Figure 2. MDC dimensions (axes) and modeling approaches (arrows)

IV. MDC Mapping of Background Literature

This section applies the MDC framework to analyze a set of recent studies of computational creativity. All 34 full papers published in the proceedings of a recent international conference were selected for this exercise (Maher et al 2012). They were classified in one or more of the MDC scales according to their research aims and claims as stated by the author(s), as well as the target research agendas in position papers. Table 2 presents the 34 papers (rows) and their relation to the MDC scales (columns) –only the first author's surname is used for clarity.

Table 2. Classification of the ICCC'12 papers in MDC levels

Authors	MDC-1	MDC-2	MDC-3	MDC-4	MDC-5
Agustini	●			●	
Baydin	●			●	
Burnett	●	●		●	
Charnley				●	
Colton	●			●	
Eigenfeldt		●		●	
Gabora	●			●	●
Gatti	●			●	
Grace	●			●	
Hoover	●			●	●
Indurkhya	●	●		●	
Jennings				●	
Johnson	●	●		●	
Jordanus	●				
Jursic	●			●	
Keller				●	
Li				●	
Linson			●	●	
Maher	●	●	●		
Monteith	●			●	
Montfort				●	
Morris	●			●	
Noy				●	
O'Donoghue	●			●	
Ogawa	●			●	
Pérez y Pérez	●	●		●	
Rank				●	
Ritchie				●	
Smith	●			●	
Sosa			●	●	
Toivanen	●	●		●	
Veale	●			●	
Wiggins				●	
Zhu	●				

As may be expected, a vast majority of papers (more than 90%) address the individual scale MDC-4, mainly by describing generative systems that produce creative outputs which are selected by the researchers and, in some cases, evaluated by external judges. This widespread focus on the individual scale is explained by the origins of computational creativity in Artificial Intelligence, but also by the "lone genius" view of creative practice, the dominance of individual approaches to the study of creativity in cognitive, personality and biographical fields, as well as the reductionistic belief that other scales will ultimately build upon the individual dimension once it's well understood (Johnson 2012).

The most common type of paper overall (41%) reports corpus-based generative systems, i.e., where the researcher selects a set of exemplars used in various ways as the basis for the synthesis of new solutions. The range of themes and domains is varied: poetry generators that use newspaper articles as input, music generators from sample classical music and from non-musical audio signals, poster generators that modify existing designs, and recipe generators based on recipes gathered from specialized websites.

These archetypical papers can also be seen as addressing MDC-1 not because they aim to model cultural changes within the system, but because they take repositories of human culture as inputs to produce their output. Such papers account for 67% of papers dealing with the MDC-1 scale, the rest being mainly position papers that underline the importance of including the cultural dimension in computational studies. The two exceptions are Baydin et al (2012) whose algorithm is based on the concept of "memes" or units of culture and Gabora and DiPaola (2012) who specifically aim to model cultural evolution in their work.

Societal factors (MDC-2 scale) are mentioned in 20% of all papers, half of these by reporting evaluation by audiences or panels of experts. The four cases that explicitly refer to the modeling of social processes are all position papers proposing approaches and analyzing the potential benefits of accounting for the social scale of creativity in computational systems. Likewise, group creativity (MDC-3) is targeted in less than 10% of all cases, two position papers and one research paper reporting results from a computational study of group influence (Sosa and Gero 2012).

Only two papers (6% of all entries) refer somehow indirectly to the brain scale (MDC-5), in both cases by using neural network approaches for the implementation of generative systems (Gabora and DiPaola 2012, Hoover et al 2012). Elsewhere, progress is being made explicitly modeling creative neural processes (Iyer et al 2009).

The following observations can be made from this mapping exercise: a) the field of computational creativity is characterized by studies that focus on individual generative processes (MDC-4); b) most of the generative systems reported take human cultural corpora as inputs, training sets or exemplar cases; and c) less than 1 in 4 papers span more than two MDC scales –half of these being position papers suggesting future research directions. The MDC framework provides a modeling structure to address such ongoing development of the field that seeks to tackle multi-level research questions related to creativity.

More specifically, this mapping exercise of the literature using the MDC scales, supports the framing of possible modeling approaches. Here we develop a few scenarios for illustration purposes:

- Computational models that integrate group and social evaluation of creativity explicitly within the system, i.e., "automated critics" or "artificial audiences" capable of simulating the assessment criteria and patterns of human judges. Such evaluations could account for multiple decisive conditions such as agreement/disagreement, public opinion, expert endorsement, and different scales and levels of domain expertise. A sample research question for such systems is "How may a computational system automatically distinguish innovative from ordinary designs?"

- Computational models of neuro-mechanisms related to the synthesis as well as to the evaluation of creativity. Such systems could capture the connections between neural mechanics and other scales, particularly cognitive and group processes. A relevant research question is "How do basic functions such as word retrieval and short term memory moderate the generation and evaluation of creative ideas in brainstorming?"
- Computational models of personality and motivation in the synthesis as well as the evaluation of creativity, for example systems that create or evaluate artifacts based on emotional predispositions, gender and age differences, and other personality dimensions. In such models, creative behavior can be analyzed as moderated by environmental cues. Research questions such as "How do extraversion traits such as assertiveness moderate the assessment of new ideas?" can be addressed with such models.
- Accounting for the effects of time across scales can lead to computational models that help understand the conditions that make an ephemeral event or a new idea become influential in modifying a culture or a domain of practice. By modeling managerial practices and informal interactions in teams and organizations, computational models can help grow scenarios where leadership creates and sustains a culture of innovation. Generative systems that integrate time-based factors could model perseverance, anticipation, habit, and the effects of expertise and mastery.

In summary, mapping recent computational creativity studies applying MDC scales is valuable because it allows to clarify assumptions and units of analysis, connect issues, identify gaps and formulate new proposals for the advancement of the field. MDC suggests ways to transcend the current focus on individual generative systems that draw from a hand-picked set of external sources to cleverly produce new solutions which may be judged as creative by external experts and audiences. As computational models integrate multi-scale factors, they can connect to a multiplicity of ongoing research methods to support and complement alternative ways of studying creativity.

Multi-scale MDC computational modeling

This subsection offers a detailed analysis of a possible multi-scale computational approach in order to illustrate the type of questions, target processes, experimental variables and conditions, and ultimately the type of outputs and contributions to our understanding of creativity using cross-scale computational creativity in multidisciplinary research programs.

A generative system that combines individual and small-group creative processes (Paulus et al 2010) is programmed to draw from and transform a corpus that is internal to the system, i.e., repositories of baseline solutions which may be inspired by but are not directly imported from external (human) cultural references. Although this may bias MDC models toward 'minimal' or 'small scale' systems (Montfort and Fedorova 2012), such self-contained cultural systems do support the three criteria of *creative autonomy*: autonomous evaluation, autonomous change and non-randomness (Jennings 2010). With such systems, researchers can focus on explicit rules and frame their claims without arbitrarily bridging the gap between what is creative inside and outside a computational model.

Recent work on automated recipe generation illustrates such gap between computational representations (the explicit written recipes) and human interpretations (the imagined cooked version of the recipes) (Morris et al 2012). This gap explains one of the main paradoxes of early computational creativity: that automated generators are expected to impact an external domain both by drawing from real cases and being evaluated by external judges who have far more complete access to the frames of reference. MDC models avoid this irony by studying artificial individuals, groups and societies that interact to generate and evaluate new designs in reference to a shared domain that is internal to the system.

Depending on the type and level of research question, cross-scale computational studies may establish predefined and uniform processes at some levels, while setting other processes as experimental at the same or different levels. For instance, if the researchers are interested in the possible ways in which neural activation determines how different individuals cope with failure (Davis et al 2012), a system can be devised where a range of cultural, social, group and individual phenomena relevant to creativity is manipulated as control, while variations of the neural activity of individuals within certain social situations can be tweaked to capture possible causes and effects throughout the system. In such system, top-down changes can be introduced experimentally to inspect the transition levels at which social situations and neural activation in some individuals replicate target cases or rates of cultural change.

From this description, the nature of MDC models can be labelled as *weak computational creativity* according to the AI nomenclature (Al-Rifaie and Bishop 2012). In distinction to *strong* positions that seek to address the conundrum "Can computers ever be creative?", *weak* or *soft* positions explore the value of algorithmic studies of creativity in helping us to develop and empirically evaluate very specific and explicit ideas about this complex topic. As such, MDC models are not expected to provide strong evidence for new theories, or conclusive evidence to support or challenge current theoretical constructs. Their role is exploratory, their value is to aid reasoning, and they can be seen as an inductive approach to the study of creativity: MDC models demonstrate what is possible, with the advantage of explicitly representing the mechanisms and dynamics at work.

As with other types of inductive research, MDC modeling can be used to collect data systematically in an attempt to develop a theory or hypothesis. Inductive methods are valuable in new lines of enquiry where limited knowledge is insufficient to deduce testable propositions (Saunders et al 2011).

In addition to multi-scale questions, possible longitudinal studies can be analyzed based on the MDC framework where time effects within and across scales can be systematically inspected. In an early study, questionnaires were applied to a large group of children in 1958 and again in 1980 showing that a significant relationship existed between having a mentor and creative achievement (Torrance 1981). Computational studies of mentorship can implement several rules of interaction between generative agents with a focus on hierarchies of expertise in order to dissect the principles and types of knowledge transfer between individuals to minimize learning curves or to challenge conventional practices.

Studies of the link between childhood and adulthood creativity have yielded contradictory outcomes: whilst Albert (1996) suggested that creativity was typically not maintained, whilst Keegan (1996) found children's creativity to be a predictor of adult creativity. As with other factors related to creativity, answers are unlikely to be straightforward, and computational models can be enlightening to understand the type of *life events* that are more likely to nurture or suppress creativity through life stages (Casas 2003).

VI. Discussion

Blunt (2010) states that "creativity is quintessentially a neurodevelopmental phenomenon". Such views are pervasive across disciplines and traditions where creativity is studied: assumptions of what type of phenomenon is under scrutiny largely influence the questions, methods and claims. This paper has introduced a structured way of rethinking creativity from a multi-dimensional perspective.

The following principles and guidelines are provided to orient this type of modelling efforts, building on the evaluation guidelines by Jordanus (2011).

- Principle #1: Scales to be included within the model
  a) Define primary and complementary scales; whilst empirical validation may not be possible across levels, computational explorations systematically support alternative thinking in scales of interest.
  b) Identify level variables (experimental and dependent) that represent target factors and observable behaviors or patterns of interest. Background literature from several disciplines are necessary to inform the formulation of contextual conditions.
  c) Define inputs and outputs at target levels, establishing the bootstrapping strategies of the model.
- Principle #2: Processes and links between scales
  a) Establish explicit connections above/below primary levels in the model.
  b) Define irreducible factors, causal links and whether the model is being used for holistic or reductionistic purposes.
  c) Identify internal/exogenous factors to the system.
- Principle #3: Processes and links across time
  a) If relevant, establish time-based conditions, processes and variables of interest.
- Principle #4: Define system outputs
  a) Define type and range of outputs, identifying extreme points such as non-creative to creative artifacts
  b) Capture and analyze aggregate data, model tuning and refinement
- Principle #5: Evaluation metrics
  a) Validity may be achievable in some models where relevant empirical data exists at the primary level(s) of interest, but this may be inaccessible and even undesirable for exploratory models.
  b) Usefulness and relevance of such systems are ultimately defined by their aids as thinking tools, to explore hypotheses, to identify and connect issues across scales, to articulate conversations between disciplines.

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