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## Simulating Creativity from a Systems Perspective: CRESY

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### Abstract

Psychological research on human creativity focuses primarily on individual creative performance. Assessing creative performance is, however, also a matter of expert evaluation. Few psychological studies model this aspect explicitly as a human process, let alone measure creativity longitudinally. An agent-based model was built to explore the effects contextual factors such as evaluation and temporality have on creativity. Mihaly Csikszentmihalyi's systems perspective of creativity is used as the model's framework, and stylized facts from the domain of creativity research in psychology provide the model's contents.

Theoretical experimentation with the model indicated evaluators and their selection criteria play a bearing role in constructing human creativity. This insight has major implications for designing future creativity research in psychology.

#### Keywords:

Creativity, Social Psychology, Mihaly Csikszentmihalyi, Social Systems, Cultural Evolution, Information Theory



### Introduction

- 1.1 The phenomenon of creativity captures the awareness of countless experts in psychological science (Cropley et al. 2010; Glover et al. 2010; Kaufman & Sternberg 2006, 2010; Mumford 2011; Piirto 2004; Runco 1997, 2007; Runco & Pritzker 2011; Sawyer 2006; Sternberg 1999b; Sternberg et al. 2004; Zhou & Shalley 2007). Wehner, Csikszentmihalyi and Magyari-Beck (1991) investigated approaches used in research on creativity to assess how the construct is studied. Using their own taxonomy, they classified scientific work according to its examined social level (individual, group, organization or culture), aspect (trait, process or product) and methodology (quantitative or qualitative; empirical or theoretical). Particularly in the domain of psychology, their results indicated a strong focus on individual traits. Here, *traits* refer to any stable individual attributes, for instance personality traits (Feist 1999; McCrae 1987; Ochse 1990; Schuler & Görlich 2006), behavioral patterns (Stokes 1999, 2001, 2007) or cognitive styles (Dewett & Williams 2007; Kirton 1976; Kwang et al. 2005; Mednick 1962). Kahl, Hermes da Fonseca & Witte (2009) conducted a near-replication of Wehner et al.'s (1991) work and produced very similar results: Almost 20 years later, creativity researchers in the domain of psychology still place the most emphasis on studying individuals and their traits. This also holds for neighboring disciplines such as education and social sciences.

#### Assessing creativity in psychological science

- 1.2 There is more to creativity than just individuals and their traits, however. This assumption also applies to studies conducted in psychological science. The following, brief outline of creativity research in psychology elaborates on this, and it exposes a trace of a social system inherent in creativity assessments.
- 1.3 Psychological research on creativity commonly encompasses the administration of *non-algorithmic tasks* to study participants who work individually on them. A non-algorithmic task is characterized by its "open-endedness", that is, there is no one right solution and principally endless solutions may be generated by the experimental unit (individual, group, etc.). A classic example is the *alternative uses task*, for instance, "name all the uses for a brick" (Guilford 1967). Contemporary studies contain more realistic tasks with regard to their commonly recruited student samples: "Name ways your university/faculty/cafe/tergia can be improved" (Adarves-Yorno et al. 2006; Nijstad et al. 2003; Paulus & Brown 2003; Rietzschel et al. 2006, 2010). Besides the verbal examples mentioned here, figural non-algorithmic tasks are available (Ward et al. 1999).
- 1.4 After participants generate solutions to administered tasks, their work is evaluated by judges. A method of scientific control, these raters communicate neither with study participants nor with each other. Nevertheless, Loneragan et al. (2004) argue "the evaluative process itself may be a highly creative, or generative, undertaking" (p. 231). Silvia (2008) admits "...judges are a source of variability, so they are more appropriately understood as a facet in the research design" (p. 141). Generally, the evaluators involved in creativity studies are categorized as being a) selves or others and b) experts or non-experts (regarding the task at hand). Furthermore, *their* specific task is to respond to participants' manifest solutions with a predefined measuring instrument. Although diverse methods to measure creativity exist (Amabile 1982, 1996; Kaufman et al. 2008; Kozbelt & Serafini 2009; Loneragan et al. 2004; Rietzschel et al. 2010; Runco et al. 1994; Silvia 2008; Sternberg 1999a), most converge in their use of the criteria *novelty* and *appropriateness* to indicate the creativity of specific manifest behavior (Amabile & Mueller 2007; Lubart 1999; Metzger 1986; Preiser 2006; Schuler & Görlich 2006; Styhre 2006; Ward et al. 1999; Zysno & Bosse 2009). Shalley & Zhou (2007, p. 6) noted "novel ideas are those that are unique compared to other ideas currently available" and "useful or appropriate ideas are those that have the potential to add value in either short or long term". Similarly, Lubart (1999, p. 339) stated novel work is "distinct from previous work" and "appropriate work satisfies the problem constraints, is useful or fulfills a need".
- 1.5 It should be noted that several synonyms for these two qualities reoccur in literature on creativity research. For instance, novelty is interchanged with originality, newness, unexpectedness, freshness, uniqueness (Couger et al. 1989; Sternberg 1999a). Appropriateness is alternately described with words such as usefulness, utility, value, adaptiveness and practicality (ibid). Both terms do not seem to have been explicitly discriminated from their respective synonyms yet. Instead, implicit scientific agreement appears to prevail regarding the issue that both subsets of terms refer to the same latent dimensions of creativity – most commonly labeled novelty and appropriateness. In common research practice, both attributes are conceived as independent of each other and aggregated with equal weighting (Amabile & Mueller 2007; Schuler & Görlich 2006).
- 1.6 Summarizing, a definition, or rather operationalization, of creativity in psychological research is given under the following conditions: a) The task at hand is

heuristic rather than algorithmic; b) any particular response to the task is considered creative if it is judged to be both novel and appropriate; c) judges make their ratings independently and without prior training, that is, they are prompted to use their personal, subjective definition of what is novel and appropriate; d) judges are designated experts, even if their domain-specific knowledge is not identical. They need not have created themselves, but require enough experience in the domain to have developed a personal sense for what is novel and appropriate; e) interrater reliability must be sufficiently high to establish creativity has been validly assessed.

- 1.7 This brief outline of creativity research in psychology indicates there is another sample inherent in every study on creativity: the evaluators. Admittedly, researchers have started to acknowledge the variance evaluators may produce in measuring creativity (Haller et al. 2011; Herman & Reiter-Palmon 2011; Randel et al. 2011; Silvia 2011; Westmeyer 1998, 2009). Nevertheless, the two samples – study participants and evaluators – fall short of constituting a social system as they interact neither directly nor indirectly: Participants' creativity is usually measured just once and they do not receive feedback from evaluators. This implies evaluators' impact on constructing what psychologists measure as creativity remains obscure.

Defining an alternative view of creativity

- 1.8 How would the contribution psychological science makes to creativity research change if participants were assessed more than once, and were affected by evaluators' judgments as well as their peers? The systems perspective of creativity developed by Csikszentmihalyi (1999) illustrates such aspects, postulating they play a key part in the emergence of creativity as a social construct. His view is briefly outlined in the following.
- 1.9 According to Csikszentmihalyi's (1988, 1999) systems perspective, an individual creator is surrounded by an environment consisting of a field and a domain. Whereas the field represents a part of society, and therefore human beings, the domain represents a part of the individual's and the field's culture. It is a symbolic system containing information such as ideas, physical objects, behaviors, styles, values. Essentially, the dynamic between individual creator, field and domain functions in the following manner: An individual creates something novel, and the novelty must be accepted, or socially validated, by the evaluating field in order to be included in the domain, which serves as a frame of reference to both creators and evaluators (Figure 1). Creator(s) and their field do not necessarily have access to exactly the same elements in the domain. Furthermore, the domain's contents change as creators and their field make changes to it. Csikszentmihalyi (1999) asserted that creativity can only be determined by studying the interaction between creators, their fields and corresponding domains.

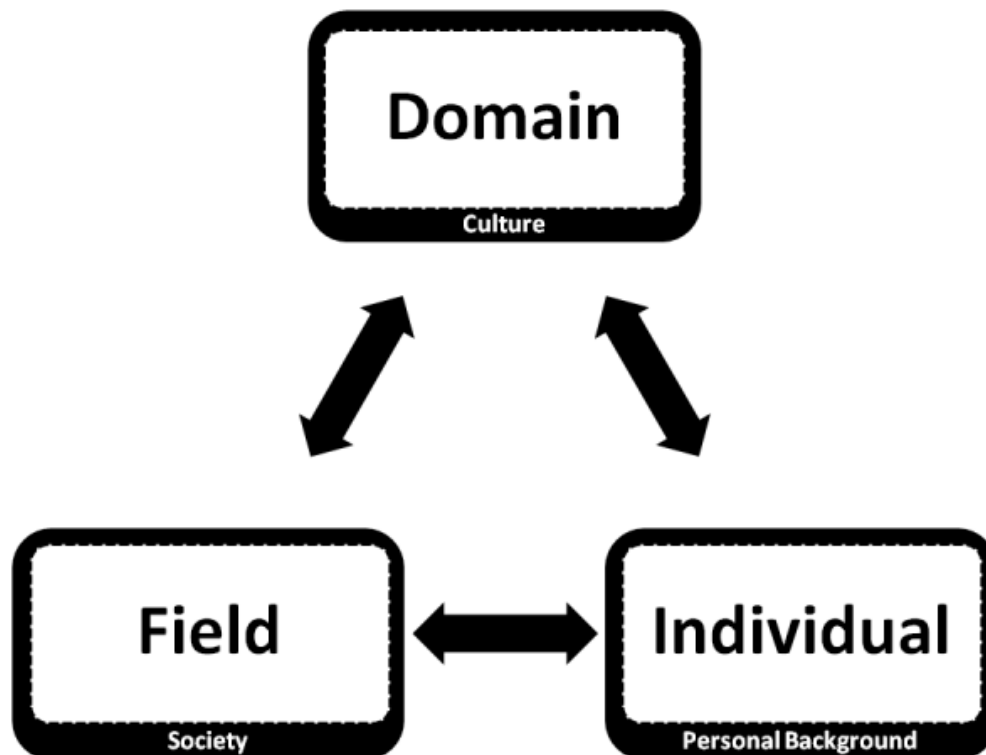


Figure 1. Graphical replication of Csikszentmihalyi's (1999) systems perspective of creativity

- 1.10 The dynamics of individuals creating, a field evaluating and their domain changing establishes a way to imagine psychological studies of creativity as a process. Moreover, the perspective resembles the evolutionary mechanism of variation, selection and retention (VSR; see Rigney 2001). Described concisely, an artifact is produced by a creator in the variation phase. The selection phase describes how an evaluator – simply put – accepts or rejects the artifact, either allowing it to persist or reducing its chance of continuance. In the retention phase, selected artifacts are preserved in some information system (e.g., culture, domain) to be reused in later variation and selection phases (see Figure 2 for a summary). Even though verbal and figural descriptions coerce VSR models to a linear form, these processes do not necessarily occur in this fashion in practice (Baldus 2002; Csikszentmihalyi 1988; Gabora & Kaufman 2010).

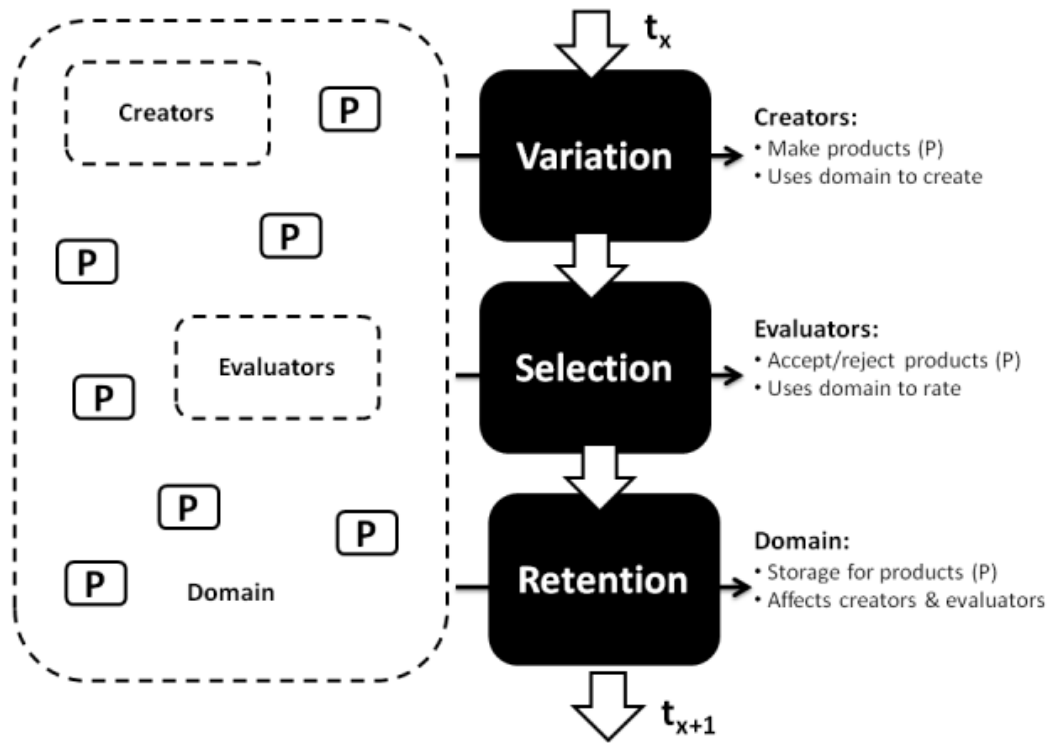


Figure 2. Subsystems (creators, evaluators and domain) and their processes (variation, selection and retention)

- 1.11 The unit of variation and selection is the single artifact or its comprising parts<sup>[1]</sup>. Artifacts are inherited by creators and evaluators when they acknowledge and retain them (Buss 2004). A domain's contents are therefore perceived, processed, (re)produced, assessed and disseminated. They accumulate and only extinguish if they are collectively overlooked, forgotten or deselected. The domain changes relative to how creators and evaluators behave, and creators and evaluators change depending on what information is available in the domain they create (Dasgupta 2004; Gabora & Kaufman 2010). The domain is therefore a dynamic entity characterized by change and growth, but it is not unrestricted. It coevolves with constraints set by its environment (Bryson 2009), namely in the systems perspective of creativity presented here, creators and evaluators. Moreover, evaluators are explicit restrictors because their main purpose in the system is to filter variations, even if they do so with differential rigor. Implicit restrictions occur, for instance, by coincidence (e.g., which variations are discovered, imitation errors; Gabora & Kaufman 2010) and due to internal psychological mechanisms (e.g., how information is processed, how behavior is exhibited; Buss 2004) regarding creators and evaluators alike. It should be emphasized that creators and evaluators actively participate in the generation of creativity. Even if they cannot predict their domain's contents, they can change them by performing their specific roles in the system, that is, by creating and attributing meaning.
- 1.12 Admittedly, caution needs to be taken when using biological evolutionary terms to describe cultural evolution (Baldus 2002; Chattoe 1998; Gabora 2004; Kronfeldner 2007, 2010), the latter similar to the systems perspective of creativity described here. However, analogical thinking does facilitate comprehension among advocates of diverse concepts of creativity (cp. Campbell 1960; Csikszentmihalyi 1988, 1999; Ford & Kuenzi 2007; Ochse 1990; Simonton 2003). Kronfeldner (2009) suggests using evolutionary analogies to aid thinking and communication between fields, and to leave the details to the specific fields. VSR theorizing also lends itself as an intermediary language to translate conceptual ideas of creativity into a more linear description for scientific exploration. It facilitates the designation of moments in time to manipulate and others to measure.

Purpose of this research

- 1.13 The purpose of this research is to explore what there is to learn about how creativity is studied in psychological science by using Csikszentmihalyi's (1999) systems perspective as a framework for an agent-based model. As described above, psychological studies on creativity commonly stop with one assessment

of the variation process. By using Csikszentmihalyi's (1999) model as a framework, selection and retention processes as well as their potential effects on variation can be theoretically explored. The next section describes the simulation model in detail.

## Simulation model

- 2.1 The agent-based model presented here is called CRESY (*CREativity from a SYstems perspective*) and was constructed with NetLogo 4.1 (Wilensky 1999). This section contains an abbreviated version of its ODD protocol (Grimm et al. 2006, 2010) as a model description. The entire simulation model (NetLogo file) and supplementary material (full ODD protocol, model verification, experiment documentation, data analyses, etc.) can be downloaded from the CoMSES Computational Model Library (OpenABM website)<sup>[2]</sup>.

Purpose

- 2.2 CRESY simulates creativity as an emergent phenomenon resulting from variation, selection and retention processes (Csikszentmihalyi 1988, 1999; Ford & Kuenzi 2007; Kahl 2009; Rigney 2001). In particular, it demonstrates the effects creators and evaluators have on emerging artifact domains. It was built based on stylized facts from the domain of creativity research in psychology in order to reflect common research practice there (Figure 3).

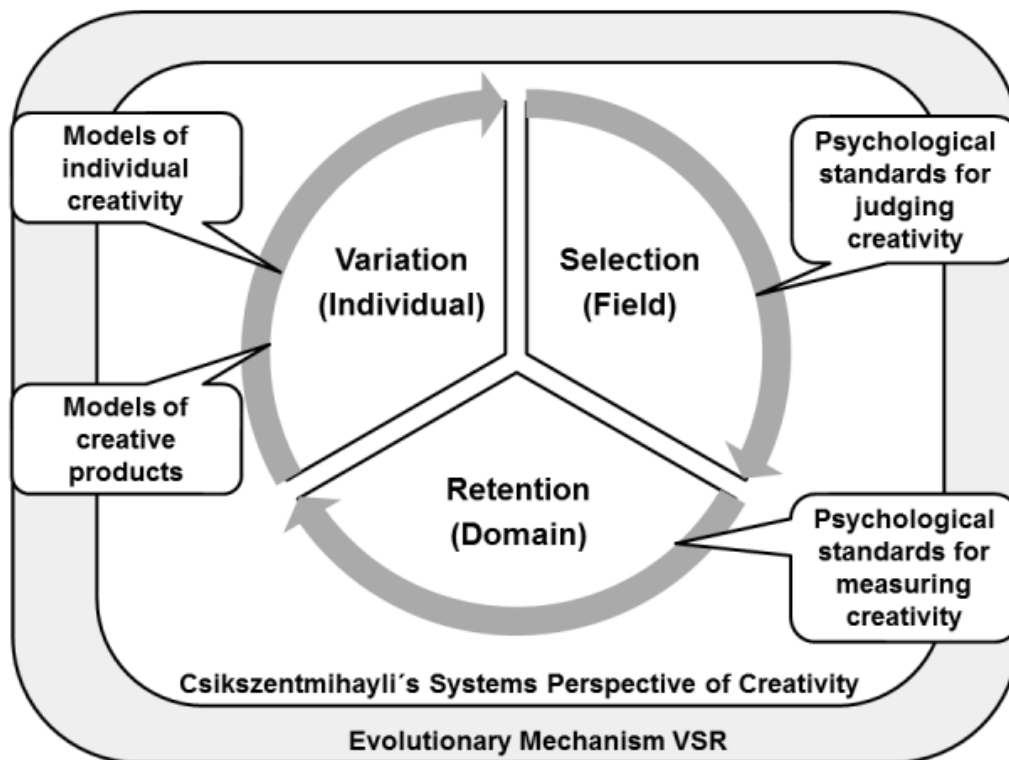
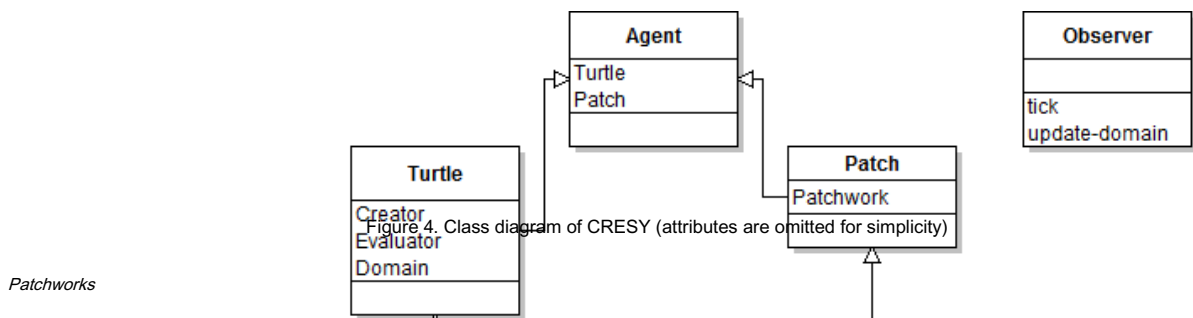


Figure 3. Basic concepts and models used in CRESY

- 2.3 An abstract model, CRESY was specifically designed for theoretical exploration and hypotheses generation (Dörner 1994; Esser & Troitzsch 1991; Ostrom 1988; Troitzsch 2013; Ueckert 1983; Witte 1991). It constitutes a form of research called *theory-based exploration*, in which models, concepts, stylized facts and observations are used as input to build a tentative model explored via computer simulation particularly in order to generate new hypotheses and recommendations as output (Bortz & Döring 2002, Ch. 6; Kahl 2012, Ch. 4; Sugden 2000). In contrast to explanatory research, the objective of exploratory research is to build theory instead of testing it. In relating this method to the model's target, Sternberg (2006) noted creativity research is currently advancing not via its answers, but via its questions.

Entities, state variables and scales

- 2.4 CRESY encompasses the following entities: patchworks, creators, evaluators and a domain (Figure 4). The systems perspective of creativity outlined in the *Introduction* was used as the model's framework, and auxiliary theory from the domain of creativity research in psychology was used to formalize the entities in a more concrete and face valid way. This renders the model structurally more realistic and comparable to research practice in psychological science (Gilbert 2008; Meyer 2011).



- 2.5 Patchworks abstractly represent artifacts creators produce and evaluators rate, for instance, ideas (Paulus & Brown 2003), paintings (DiPaola & Gabora 2009), movements (Leijnen & Gabora 2010), behavior strategies (Edmonds 1999) or other cultural artifacts (Picascia & Paolucci 2010). Technically, patchworks are represented by stationary agents ("patches") in NetLogo and they appear as RGB colors. RGB colors were chosen as artifacts because they represent an operationalization of stylized facts about creative products prevalent in creativity research in psychological science: a) They represent manifest behavior; b) the three individual RGB values represent disparate elements combined to form something new (Casti 2010; Sawyer 2006; Schuler & Görlich 2006; Sternberg & Lubart 1999; Ward et al. 1999). The production of patchworks becomes visible in NetLogo's View when creators combine three independently selected values and "paint" them on a nearby patch. Moreover, patchworks are the means by which creators and evaluators communicate. Both agentsets do not interact directly; they gain knowledge of the domain (i.e., other creators' and evaluators' behavior) by processing patchworks locally. This feature is comparable to situations in which creators do not know each other personally, but know each other's work (Dennis & Williams 2003; Müller 2009; Runco et al. 1994; van den Besselaar & Leydesdorff 2009), and it is very common in creativity research (Kozbelt & Serafin 2009). It is also directly comparable to the way products are rated by judges in creativity research. Raters usually do not have contact with study participants. They judge the artifacts independently and anonymously (Bechtoldt et al. 2010; Kaufman et al. 2008; Lonergan et al. 2004; Rietzschel et al. 2006; Silvia 2008). See Table 1 for patchwork state variables and scales.

Table 1: Patchwork state variables and scales

Name	Brief description	Value
<i>pcolor</i>	List of RGB values (24 bit).	[r g b]
<i>plabel</i>	<i>domSize</i> category for <i>pcolor</i> .	Integer, [0, <i>domSize</i> -1]
<i>pDom</i>	List of RGB values reduced to domain variable <i>domSize</i> (6, 9 or 12 bit).	[r g b]
<i>pR, pG, pB</i>	Patch's current respective red, green and blue values.	Integer, [0,255]
<i>madeBy</i>	Who made patchwork? Environment (means a patch's color has not changed yet by any creator. It is still the color it randomly received when the world was initiated) or creator type.	{Env, Cx, C1, C2, C3}
<i>whosNext</i>	Holds <i>who</i> value of creator or evaluator potentially to next move on patch. Belongs to movement and evaluation procedures.	Integer, [1, number- creators] OR [1, number- evaluators]
<i>justMade</i>	Indicates whether patchwork was made during current step.	Boolean
<i>toDo</i>	Indicates whether evaluator still needs to judge patchwork.	Boolean
<i>hue</i>	Indicates whether patchwork's RGB color is warm or cool.	{warm,cool}
<i>currentEvals</i>	List of evaluators current scores for given patchwork.	List with {0,1}
<i>cScore</i>	Patchwork's cumulative creativity score. If a patchwork has never been rated before, its cScore is set to -1 by default and excluded from output variable analyses.	Integer, [0,1]
<i>PcScoreList</i>	Current domain evaluation list of <i>cScores</i> .	List of length <i>domSize</i> values of [0,1]

#### Creators

- 2.6 Creators are represented by mobile agents ("turtles") in NetLogo. There are four different types ( *Cx*, *C1*, *C2*, *C3*), and they differ in the way they make patchworks (i.e., solve a heuristic task). Accordingly, creators vary in the way they combine three digits to form an RGB color (see *Submodels*). Depending on their variable *imagination* they can invent elements they have never encountered before (genuine novelty). The ideas incorporated in creators' design are based on stylized facts from creativity research in psychological science (Abuhamdeh & Csikszentmihalyi 2004; Brower 2003; Campbell 1960; Cziko 1998; Dewett & Williams 2007; Gruber 1988; Kirton 1976; Kwang et al. 2005; Mednick 1962; Mumford 2011; Richards 1977; Sawyer 2006; Simonton 1998, 2002, 2003, 2004; Smith 2008; Sternberg & Lubart 1999; Stokes 1999, 2007; Ward et al. 1999; Welling 2007; for an overview see Kahl 2012, Ch. 7): a) Individuals differ in their creative behavior; b) their differences are often conceptualized as dichotomous extreme types (e.g., creative vs. not creative, adaptors vs. innovators); c) dichotomous types are nevertheless connected by a theoretical continuum, making more subtle individual differences detectable. See Table 2 for creator state variables and scales.

Table 2: Creator state variables and scales

Name	Brief description	Value
<i>label</i>	Describes (static) creator type.	{Cx,C1,C2,C3}

<i>cR</i> , <i>cG</i> , <i>cB</i>	Creator's 3 memory lists for red, green & blue values. Each a list of 256 nested lists; item 0 = <i>color value</i> ( $c_j$ ), item 1 = <i>absolute frequency</i> ( $f_j$ ) of value $c_j$ .	$[[0\ f_j][1\ f_j], \dots, [c_j\ f_j], \dots, [255\ f_{256}]]$
<i>imagination</i>	How likely creators C1, C2 & C3 will generate an r, g or b value not in their memory. Same value for all three creator types.	[0.00, 0.25]
<i>info-rate</i>	How many neighbors (4 or 8) a creator obtains info from per time step. Same for all creators.	{n4,n8}
<i>movement</i>	How creators move in the world.	{straightFd1, ahead3, allButBehind7, any8}

#### Evaluators

- 2.7 Evaluators are mobile agents ("turtles") in NetLogo and their task is to judge the patchworks creators make. They do so based on the criteria novelty and appropriateness, whereas their stringency in using these criteria varies. *Novelty* is a quality attributed to a patchwork when an evaluator perceives it to be statistically infrequent compared with other patchworks it has in its memory. *Appropriateness* is a quality attributed to a patchwork when an evaluator considers its hue to agree with the hues of its neighbors (see *Submodels*).
- 2.8 Whereas creators can make any one of  $256^3$  RGB colors, evaluators perceive them with a lesser degree of differentiation (this is based on evaluators' state variable *domSize*; Table 3). Their recognition of patchworks, therefore, is not as fine-tuned as that of creators. In evolutionary terms, they only perceive a patchwork's phenotype, whereas creators are aware of patchworks' genotypes (Chattoe 1998). The ideas incorporated in evaluators' design reflect stylized facts from research on how to rate the creativity of human behavior (Adarves-Yorno et al. 2006; Amabile 1982, 1996; Haller et al. 2011; Herman & Reiter-Palmon 2011; Kaufman et al. 2008; Kozbelt & Serafin 2009; Randel et al. 2011; Rietzschel et al. 2010; Runco et al. 1994; Silvia 2008, 2011; for an overview see Kahl 2012, Ch. 9): a) Evaluations are based on the criteria novelty and appropriateness; b) evaluators' stringency in using these criteria may differ; c) a concrete definition of creativity is given via evaluators' role in the creative process, that is, by their individual attribution of differential value to artifacts; d) evaluators make their judgments independently of each other. See Table 3 for evaluator state variables and scales.

Table 3: Evaluator state variables and scales

Name	Brief description	Value
<i>label</i>	Describes (static) evaluator type.	{En,Ea,Ena}
<i>eMem</i>	Evaluator's memory list for patchworks seen. List of <i>domSize</i> nested lists. item 0 = <i>domSize value</i> ( $c_j$ ), item 1 = <i>absolute frequency</i> ( $f_j$ ) of value $c_j$ .	$[[0\ f_j][1\ f_j], \dots, [c_j\ f_j], \dots, [n\ f_n]]$
<i>domSize</i>	Size of patchwork space, evaluators can perceive, e.g., number of RGB colors (patchworks) they can discriminate (12, 9 or 6 bit). This variable is set by the observer globally for all evaluators.	{64, 512, 4096}
<i>novelty-stringency</i>	Percentage.	Integer, [0,1]
<i>appropriateness-stringency</i>	Percentage.	Integer, [0,1]
<i>info-rate</i>	How many neighbors (4 or 8) an evaluator obtains info from per time step. Same for all.	{n4, n8}
<i>movement</i>	How evaluators move in the world.	{straightFd1, ahead3, allButBehind7, any8}

#### Domain

- 2.9 According to the systems perspective of creativity, the domain is an evolving system of information (Csikszentmihalyi 1999). In CRESY, information refers to patchworks as well as information about them such as their RGB values and creativity ratings. Ultimately, the domain is characterized in CRESY by output variables (Table 5). However, the patchwork information required to characterize the domain with these output variables is recorded in NetLogo by one invisible agent ("turtle"), for simplicity called a domain. See Table 4 for these domain state variables and scales.

Table 4: Domain state variables and scales

Name	Brief description	Value
<i>evalList</i>	List of <i>domSize</i> nested lists containing all evaluations ever made for particular patchwork. Note 0 = not creative, 1 = creative.	{0,1}
<i>cScoreList</i>	List of length <i>domSize</i> containing current creativity scores for patchworks. A patchwork's <i>cScore</i> is set to -1 by default if it has never been evaluated before. Default values are not processed.	Integer, [0,1]
<i>justRated</i>	List of <i>number-creators</i> nested lists containing the creativity evaluations evaluator made in current step.	Integer, [0,1]
<i>justRatedTable</i>	List of length <i>number-creators</i> *2 containing summed and squared creativity scores from <i>justRated</i> .	= 0

#### Process overview and scheduling

- 2.10 CRESY consists of seven subsequent processes occurring in one simulation step: *obtain-info*, *make-patchwork*, *rate-patchwork*, *move*, *forget-some-info*, *tick*, *update-domain*. Their scheduling is linear, i.e. their order occurs in the exact order they are listed in the sequence diagram in Figure 5. The agentsets running the commands in each process do so serially, but in a random order on the basis of NetLogo's *ask* command. The state variables were updated asynchronously. Time was modeled discretely.

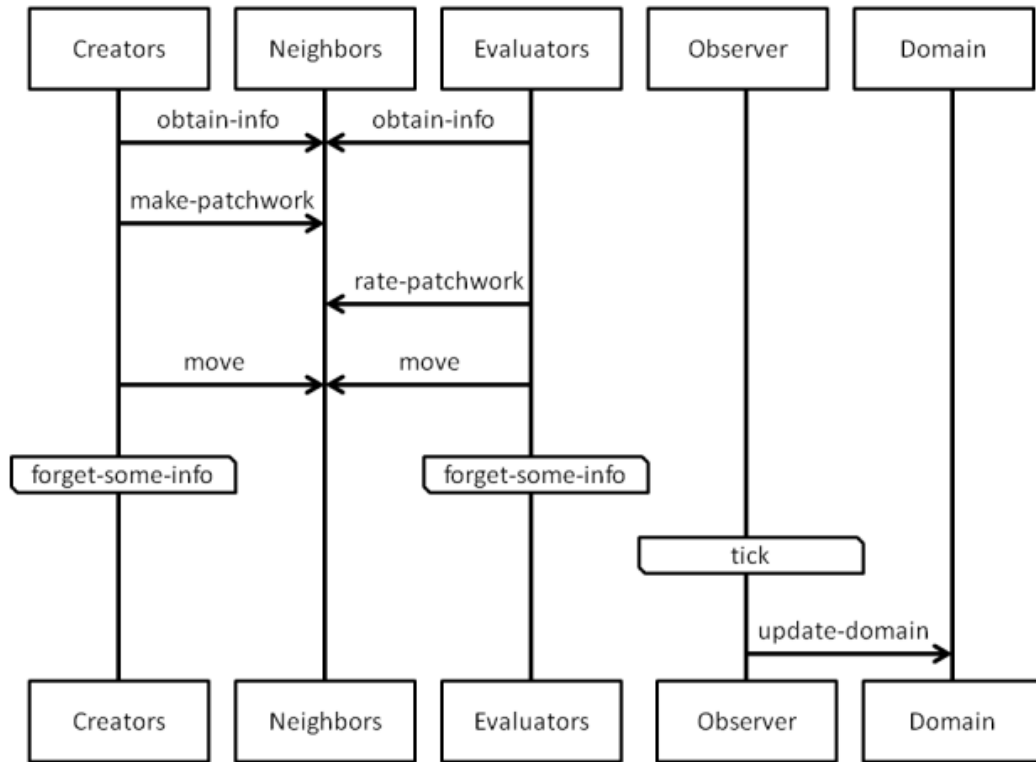


Figure 5. Sequence diagram of CRESY ("neighbors" are neighboring patches in NetLogo)

#### Submodels

2.11 This section describes all processes in CRESY.

##### *obtain-info*

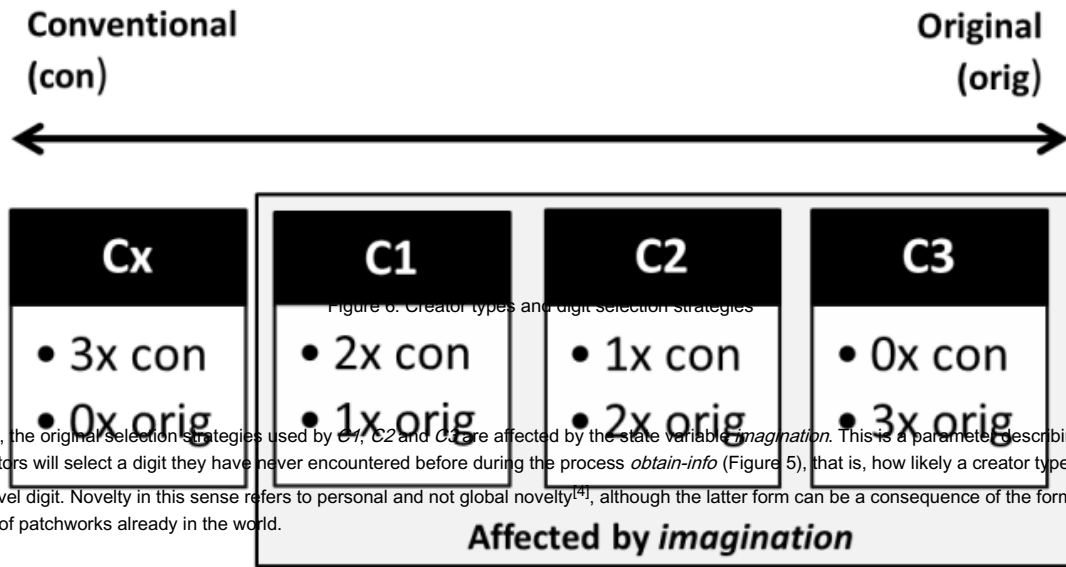
2.12 In this submodel, all creators and evaluators gather information about patchworks. They view four or eight neighboring patches according to their state variable *info-rate* (Tables 2–3).

##### *make-patchwork*

2.13 Every creator produces a patchwork (RGB color) and "paints" it on one of the eight neighboring patches with the lowest current creativity evaluation. This form of retention ensures that more favored patchworks remain in the domain longer ("survival of the fittest enough"). *make-patchwork* works differently for each creator type, but the underlying idea is the same for all: Creators combine three digits from 0-255 to produce a color. The way a creator selects these digits depends on its state variables *label* and *imagination*, and is described in the following.

##### *Conventional vs. original strategies*

2.14 A creator's *label* (*Cx*, *C1*, *C2*, *C3*) indicates its "creative type" and therefore how it retrieves individual digits from its memory lists. *Cx* is highly likely to choose digits it has most often obtained before. In everyday terms, *Cx*'s behavior is conventional, unoriginal or reliable, because it (re)produces what it "knows best". When *C3* makes a patchwork, it does so in an original or unreliable fashion<sup>[3]</sup>: All three digits it selects are highly likely to be ones it has rarely encountered before. *C1* and *C2* are hybrids of *Cx* and *C3*. *C1* selects one of the three digits in the highly original way *C3* does, and the other two in the conventional way *Cx* does. *C2* creates exactly in the opposite manner: It selects two digits in the highly original way *C3* does, and one in the conventional way *Cx* does. See Figure 6 for a visual summary.



- 2.15 Furthermore, the original selection strategies used by C1, C2 and C3 are affected by the state variable *imagination*. This is a parameter describing how likely it is these creators will select a digit they have never encountered before during the process *obtain-info* (Figure 5), that is, how likely a creator type will create a genuinely novel digit. Novelty in this sense refers to personal and not global novelty<sup>[4]</sup>, although the latter form can be a consequence of the former depending on the types of patchworks already in the world.

*Color value selection*

- 2.16 Each color value selected by a creator to form a patchwork is formally chosen in the following way: Each memory list (*cR*, *cG* and *cB*) a creator has, and therefore color dimension, is treated independently when a patchwork is made. The first step in selecting a digit (0-255) from a color dimension (red, blue or green) is to calculate the relative frequencies of all digits in one dimension (memory list). Here is an example for *one* color dimension. The relative frequency for each digit (0-255) of this color dimension is calculated as stated in Equation 1 (Figure 7).

$$p_{i,con} := \frac{f_i}{N}$$

$f_i$  is the absolute frequency of digit  $i$ .

$N$  is the total number of digits a creator has in its memory list.

$p_{i,con}$  stands for the relative frequency of digit  $i$  for *conventional* selection.

Figure 7. Equation 1 describes the relative frequency for each digit (0-255) of one color dimension (for one specific creator)

- 2.17 Relative frequencies calculated as described in Equation 1 (Figure 7) are the basis for selecting a digit with the conventional selection strategy. In implementing the original selection strategy, these frequencies are transformed twice. In the first transformation, they are inverted and normalized as shown in Equation 2 (Figure 8).

$$p_{i,con} \rightarrow p_{i,orig}^* = \begin{cases} \frac{1-p_{i,con}}{N-1} & \text{if } p_{i,con} > 0 \\ 0 & \text{if } p_{i,con} = 0 \end{cases}$$

Figure 8. Equation 2 describes how the relative frequencies for all digits (0-255) of one color dimension (for one specific creator) are transformed when the original selection strategy is used

- 2.18 Equation 2 (Figure 8) qualitatively means that a creator using the original ( $p_{i,orig}^*$ ) strategy will most likely select those values it has seldom seen before compared with those it has. However, this transformation does not ensure that a creator will produce a color value it has never seen before. This is what the second transformation does. It incorporates the state variable *imagination* (*IMG*) as described in Equation 3 (Figure 9).

$$p_{i,orig} = \begin{cases} (1-IMG) * p_{i,orig}^* & \text{if } p_{i,orig}^* > 0 \\ \frac{IMG}{K} & \text{if } p_{i,orig}^* = 0 \end{cases}$$

*IMG* is the value for *imagination* (creator state variable).

$K$  is the number of  $p_{i,con}$  which are equal to zero.

Figure 9. Equation 3 describes how the variable *imagination* is incorporated in the *original* selection strategy

- 2.19 *IMG* (*imagination*, Equation 3 in Figure 9) is the probability for a creator to choose a digit it has never seen before. This probability is assigned with equal weight to the digits which have zero frequencies in a creator's respective memory list. Before a digit is chosen for a patchwork, the frequencies of all digits of the respective color dimension (memory list) are either calculated as relative frequencies (Equation 1 in Figure 7; conventional selection strategy) or calculated according to Equation 2 in Figure 8 (original selection strategy). In both cases, digit selection is finally realized by cumulative distribution sampling (Figure 10). The entire process of calculating frequencies or probabilities and cumulative distribution sampling (Figures 7–10) occurs three times every time a creator makes a patchwork, namely once for each color dimension R, G and B.

1. All  $p_{i,con}$  (respectively  $p_{i,orig}^*$ ) are added from the digit categories (0-255), and equal 1:  $p_{i,con} = \sum_{i=0}^{255} p_{i,con}$

2. Then a value  $p_{rand}$  is chosen from 0-1 out of a uniform distribution.

3. The first digit  $i$  for which  $\sum_{j=0}^i p_{j,con} > p_{rand}$  is selected as the digit to use to make a patchwork.

Figure 10. Cumulative distribution sampling in the submodel *make-patchwork*

*rate-patchwork*

- 2.20 Evaluators rate patchworks according to perceived novelty and/or appropriateness. They can be one of three types: *En* (judges only novelty), *Ea* (judges only appropriateness) or *Ena* (judges both criteria). An evaluator's judgment results in one dichotomous creativity score (*cScore*) for a particular patchwork: *0 = not creative*, *1 = creative*. Evaluators judging patchworks based on their perceived novelty do so according to the variable threshold *novelty-stringency*, and those judging appropriateness are influenced by the variable threshold *appropriateness-stringency*. Both thresholds are set in NetLogo globally. The pseudo code in Figure 11 describes how the different evaluator types make their judgments. Evaluator type *Ena* must judge a patchwork's novelty as given (1) and its appropriateness as given (1) in order to rate the entire patchwork as creative (1).

```

; How En and Ena assess a patchwork's novelty:
LET p = relative frequency of current patchwork in my memory
IF p <= novelty-stringency
  THEN SET novelty = 1 ; novel
  ELSE SET novelty = 0 ; not novel
; How Ea and Ena assess a patchwork's appropriateness:
LET h = patchwork's hue ; warm vs. cool
LET viewed = 6 randomly selected neighbors
LET c = number of viewed with hue = h
SET c = c / 6
IF c >= appropriateness-stringency
  THEN SET appropriateness = 1 ; appropriate
  ELSE SET appropriateness = 0 ; not appropriate
; How a patchwork's creativity score is set:
IF type = En THEN SET cScore = novelty
IF type = Ea THEN SET cScore = appropriateness
IF type = Ena THEN IF (novelty + appropriateness) = 2
  SET cScore = 1 ; creative
  ELSE SET cScore = 0 ; not creative

```

Figure 11. Pseudo code for submodel *rate-patchwork* (Grey text denotes comments, black text commands, blue text variables and their values)

#### Assessing novelty

- 2.21 The variable *novelty-stringency* ranges from 0-1 and represents a threshold according to which an evaluator decides whether a patch under current evaluation is novel or not. The patchwork's (*p*) relative frequency ( $rf_{pe}$ ) is calculated from an evaluator's (*e*) memory, and it represents the absolute number of times evaluator *e* has seen patchwork *p* normalized by the total number of patchworks it has seen before. If  $rf_{pe}$  is less than or equal to *novelty-stringency*, the patchwork is considered novel (*n* = 1), otherwise it is not (*n* = 0, Figure 11). Novelty assessment depends on an evaluator's memory; two evaluators may disagree about the same patchwork's novelty depending on what they have seen before.

#### Assessing appropriateness

- 2.22 All patchworks have a variable called *hue*, which indicates whether their color is warm or cool<sup>[5]</sup>. A patchwork is considered appropriate when its hue agrees with the hues of its neighbors. An evaluator about to judge a patchwork's appropriateness first assesses the latter's neighbors. To simulate the variability with which humans perceive their environment, an evaluator only views the hues of six randomly selected neighbors<sup>[6]</sup>, and calculates their relative frequency of the hue the patchwork under evaluation has. The relative frequency is then compared with the variable *appropriateness-stringency*, which ranges from 0-1 and represents a threshold according to which an evaluator decides whether a patchwork under current evaluation is appropriate or not. If the hue's relative frequency  $\geq$  *appropriateness-stringency*, the patchwork is considered appropriate (*a* = 1), otherwise not (*a* = 0, Figure 11).

#### move

- 2.23 Each creator and evaluator has a heading, a built-in variable indicating the direction they are facing. Their movement occurs relative to this parameter. Only one creator per patch is allowed. If all patches assessed in this process are full, creators remain on the patches they are currently standing on. Different movement strategies are available for creators and evaluators (Tables 2–3), and are set globally.

#### forget-some-info

- 2.24 A total of three pieces of information are deleted from creators' memory lists every time step. In each list, one color dimension value with a frequency larger than zero is randomly chosen, and then one is subtracted from this value's frequency counter. Color values are randomly selected per creator memory list, not per creator or total group of creators. Therefore, the loss of information due to forgetting is not systematic. In this submodel, creators' state variables *cR*, *cG*, and *cB* (Table 2) are updated. Analogous to the way creators forget, evaluators also forget three randomly selected pieces of information which are deleted from their memory *eMem* (Table 3), which is updated in this procedure.

#### tick

- 2.25 In this process, NetLogo's built-in time counter advances. Time is modelled in discrete steps.

#### update-domain

2.26 During this procedure all output variables and the interim variables used for their calculation are updated. Additionally, patchworks' *cScores* (see Table 1) are updated to reflect the evaluation status of the domain.

Independent variables

2.27 The independent variables are based on each entity in CRESY: Creators, evaluators and the domain (Figure 2 and Table 5).

Creators (*cRatio*)

2.28 The ratio of creator types (Cx:C1:C2:C3) is varied to reflect different levels of a sample's potential to produce diversity (Table 5).

Evaluators (*evalStrategy*)

2.29 *novelty-stringency* (*n*) and *appropriateness-stringency* (*a*) are varied to reflect different evaluation strategies. Five strategies were designated in CRESY: *nov* (only based on perceived novelty), *app* (only based on perceived appropriateness), *cla* (classic, i.e., based on both novelty and appropriateness), *equ* (novelty and appropriateness do not matter to evaluators), *mix* (based on novelty only, appropriateness only or on both in the classic sense. This mixture of strategies is equally distributed among evaluators; Table 5).

Domain (*predefine*)

2.30 CRESY's interface sliders *predefine-r*, *predefine-g* and *predefine-b* can be set to any number from 1-256 to predefine how diverse (colorful) the world is at the start of a simulation run (Table 5).

Dependent variables

Creativity (*crea*)

2.31 After rating a patchwork's novelty and/or appropriateness, evaluators ultimately judge its creativity by giving it a binary score (*cScore*; Table 1) of 0 (not creative) or 1 (creative). Each evaluator rates every patchwork made in the current step. So *number-creators*\**number-evaluators* creativity scores result every step, because each creator makes only one patchwork and each evaluator rates every one. Subsequently, a total creativity assessment for all patchworks made in the current step is calculated and expressed in the variable *crea*. For each patchwork *j* currently evaluated, its number of corresponding creative evaluations ( $1s; N_{1j}$ ) is set in relation to its total number evaluations ( $N_{totalj}$ , equal to *number-evaluators*). That is the single patchworks's current creativity score ( $c_j$ ). These interim creativity scores are then averaged to obtain the patchworks' mean creativity in the current step (Equation 4 in Figure 12). *crea* is therefore a percentage indicating how creative evaluators find creators' current work on average.

$$crea = \frac{\sum_{j=1}^n c_j}{n}$$

Whereas *n* = number of patchworks made in the current step  
(equal to *number-creators*),  
and  $c_j = \frac{N_{1j}}{N_{totalj}}$  for patchwork *j*

Figure 12. Equation 4 describes how the variable *crea* (creativity) is calculated

Reliability (*rel*)

2.32 The interrater reliability of patchwork ratings is measured with Fleiss' kappa for binary data (Fleiss 1971; Bortz et al. 2008, 454–458), and ranges from 0-1. Calculating the reliability of independent judgments is an essential part of creativity assessment in psychology (Amabile 1982, 1996; Kaufman et al. 2008; Silvia 2008). The measure indicates evaluators' level of agreement regarding patchworks' creative value, and it must be sufficiently high in order to ascertain creativity has been measured at all.

2.33 Strictly, high interrater reliability only indicates judges agree on something, that is, the ratings share more variance than by chance. However, in creativity research in psychology, high interrater reliability is assumed to reflect that the construct of creativity has been assessed in a face valid way as long as judges are considered to be legitimate (e.g., all possess relevant expertise in the artifact domain). As Kaufman et al. (2008) note, the "judges' expertise provides a measure of face validity – it makes sense that experts in a domain could accurately assess performance in that domain" (p. 175).

Table 5: Independent and dependent variables

Entity	Variable name	Scale
Independent Variables		
Domain (retention)	<i>predefine</i> (p)	High: 256 Low: 1
Creators (variation)	<i>cRatio</i> (c)	High: (1:0:0:3) Low: (3:0:0:1)
Evaluators (selection)	<i>evalStrategy</i> (e)	nov: n = .25; a = .00 app: n = 1.0; a = .75 cla: n = .27; a = .75 equ: n = .50; a = .50 mix: n = .25; a = .75
Dependent Variables		
Current patchworks	<i>crea</i> (creativity)	0-1
Evaluators' ratings (of current patchworks)	<i>rel</i> (reliability)	0-1

## Research questions

- 3.1 To exemplify theory-based exploration with CRESY, the experiment reported here was conducted to answer the following questions: a) How do three independent variables representing creators (*variation*), evaluators (*selection*) and the domain (*retention*) affect the dependent variable creativity? b) Which hypotheses about creativity from a systems perspective, modelled as the interplay between variation, selection and retention processes, can be generated from the simulated data?

## Experimental design

- 3.2 The independent and dependent variables summarized in Table 5 were used in this experiment. Fully randomizing the independent variables yields a  $2 \times 2 \times 5$  design. The resulting 20 experimental conditions are summarized in Table 6.
- 3.3 The following variables were held constant: In each run, four creators and 15 evaluators were used in a  $21 \times 21$  torus (*density*). The *info-rate* was set to *n8*, meaning creators and evaluators collected information about patchworks from eight neighboring patches every step. Both agent types moved in the world based on the *any8* strategy, meaning they could move to any of the eight neighboring patches as long as they were empty. Creators' *imagination* was set to 0.05, and evaluators' state variable *domSize* was set to 512. *novelty-stringency* was set to 0.25 and *appropriateness-stringency* to 0.75 when evaluators used the *classic* strategy (Table 5). These values are an operationalization of the scientific convention that creative work must be sufficiently novel and appropriate. A total of 30 runs with 6000 steps each were collected per experimental condition<sup>[7]</sup>.

Table 6: Experimental design

Domain																			
										<i>predefine-r/-g/-b (p)</i>									
1										256									
Creators																			
<i>cRatio (c)</i>																			
3:0:0:1					1:0:0:3					3:0:0:1					1:0:0:3				
Evaluators																			
<i>evalStrategy (e)</i>																			
nov	app	cla	equ	mix	nov	app	cla	equ	mix	nov	app	cla	equ	mix	nov	app	cla	equ	mix
<i>novelty-stringency</i>																			
.25	1.0	.25	.50	.25	.25	1.0	.25	.50	.25	.25	1.0	.25	.50	.25	.25	1.0	.25	.50	.25
<i>appropriateness-stringency</i>																			
.00	.75	.75	.50	.75	.00	.75	.75	.50	.75	.00	.75	.75	.50	.75	.00	.75	.75	.50	.75
Experimental Condition																			
01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20

## Results

- 3.4 The experiment was analyzed with R (Version 2.13.0). The data were analyzed in the following steps: a) reliability calculation, b) graphical diagnostics, c) dependent variable aggregation, d) analyses of variances.

### Reliability

- 3.5 Almost perfect reliability was reached in nearly every condition ( $M = .94-.99$ ). The only exceptions are conditions 5, 10, 15 and 20 in which the mean reliability is moderate ( $M = .45-.67$ ; Landis & Koch 1977). These conditions share a common factor: All have *evalStrategy* set to *mix*, meaning evaluators are not using the same strategy to judge patchworks. *predefine* and *cRatio* are completely varied among these four conditions (see Table 6). This result is expectable, as evaluators' judgments are based on different thresholds. The fact that evaluators agree so well in all other conditions indicates face and construct validity regarding the dependent variable creativity (*crea*; Amabile 1982; Kaufman et al. 2008)<sup>[8]</sup>.

### Graphical diagnostics

- 3.6 Line and violin plots (Hintze & Nelson 1998) were made to visually assess patchwork creativity (*crea*). Line plots depict the average run, violin plots the entire data per experimental condition. The line plots in Figure 13 indicate the following: Experimental conditions 01, 06, 11 and 16 exhibit average creativity levels of  $m_{crea} = 1.00$ . All other experimental conditions exhibit average creativity levels varying from approximately  $m_{crea} = 0.5 - 0.8$ . The violin plots in Figure 14 show this difference more explicitly<sup>[9]</sup>: Conditions 01, 06, 11 and 16 have the highest medians for creativity (roughly  $md_{crea} = 1.00$ ) as well as minute interquartile ranges. All other conditions exhibit medians varying from approximately  $md_{crea} = 0.4 - 0.8$ , as well as comparably larger interquartile ranges. Conditions 01, 06, 11 and 16 have a common independent variable value (*evalStrategy* = *nov*; Table 6). The differences between these four conditions and all others means patchwork creativity is, on average, rated the highest in experimental conditions in which only patchwork novelty is assessed (01, 06, 11, 16).

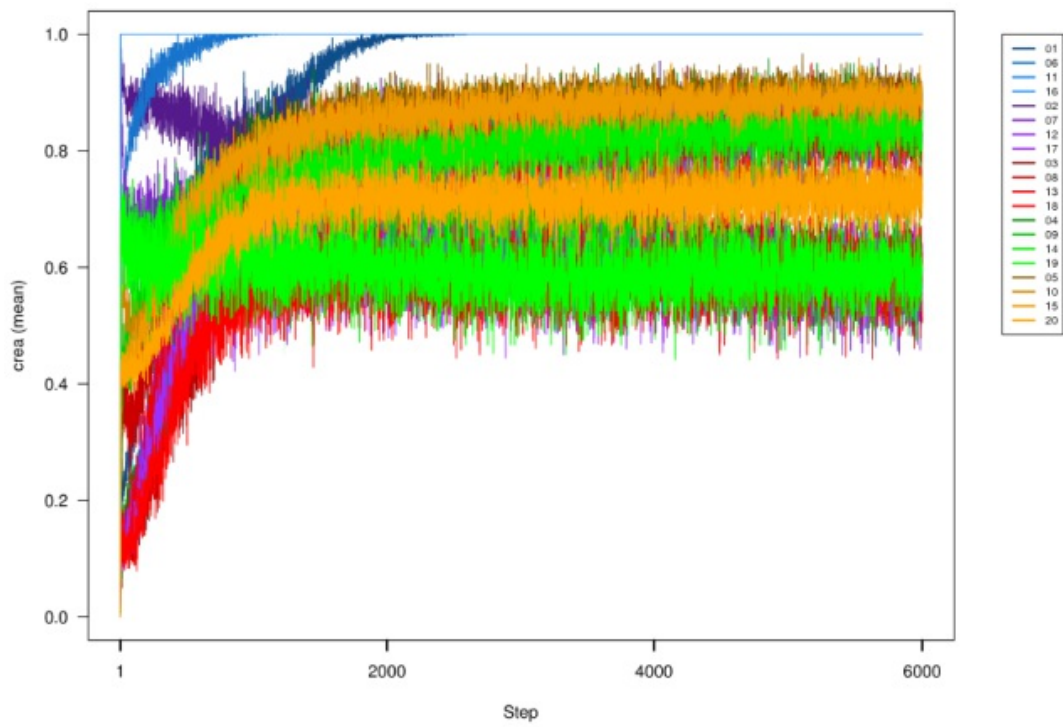


Figure 13. Average run per experimental condition for *crea* (patchwork creativity)

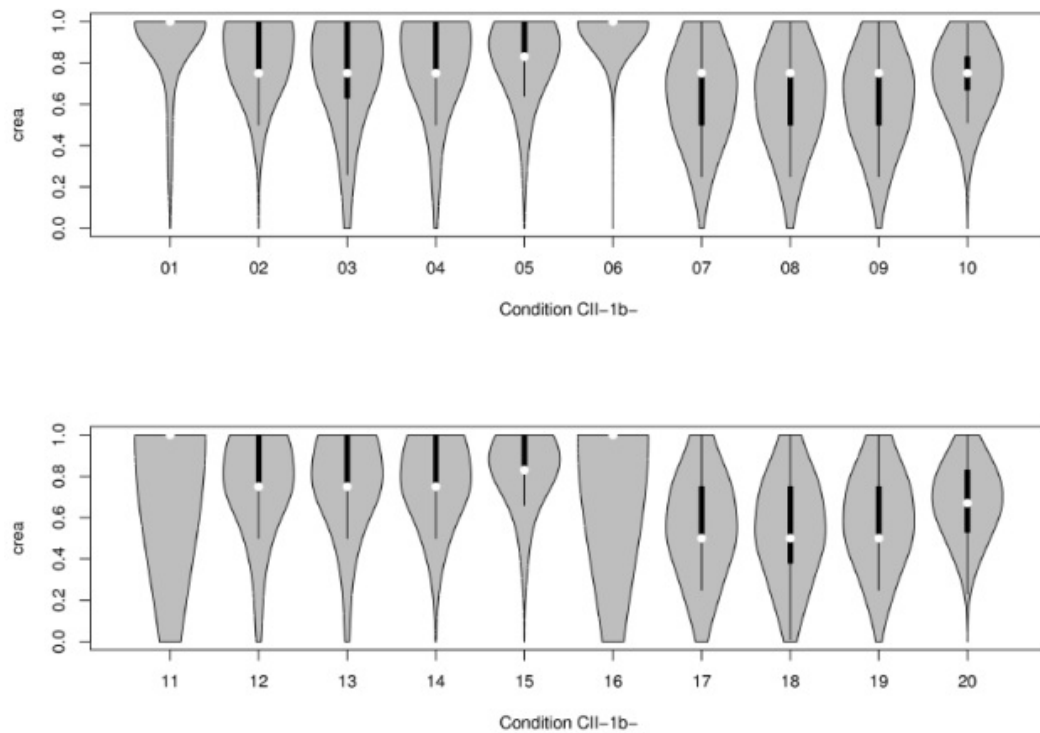


Figure 14. Violin plots showing *crea* (patchwork creativity) for each experimental condition

#### Dependent variable aggregation

3.7 The dependent variable *crea* (patchwork creativity) was measured in every step (6000) of every run (30) in each experimental condition (20). Two measures, the mode and the coefficient of variation (CV), were calculated per run to describe these time series. The former is an indicator of a run's average location, the

latter an indicator of a run's variability. This aggregation allows the comparison of experimental conditions based on centrality and stability of the dependent variable creativity (*crea*) in subsequent analyses of variances.

Analyses of variances

3.8 The modes and CVs calculated for *crea* were separately tested in three-way independent analyses of variances with the factors *cRatio* (*c*, variation), *evalStrategy* (*e*, selection) and *predefine* (*p*, retention). The results are summarized in Tables 7–8. Figures 15–16 display the interaction plots. The effect size generalized omega squared (Olejnik & Algina 2003) was additionally calculated for each effect. The following was done to create a frame of reference to select effects for interpretation: Firstly, all violin and interaction plots were compared, and based on inspection certain effects were preselected for interpretation. Secondly, all effect sizes were ranked (Tables 7–8). Thirdly, the effects preselected based on the plots were compared with the effect size ranks. The preselected effects indicated that only effects with a value = 0.82 for generalized omega squared would be considered meaningful enough to interpret as making a notable difference. These effects happen to be those ranked first in the ANOVAs. The only exception is the second-order interaction  $p \times c \times e$  in the ANOVA for *crea* modes, although the effect sizes for the individual factors are comparably higher (Table 7). This procedure permits an overview of the kind of effect sizes reachable given the type of simulation data at hand, something which externally set thresholds do not account for. It also constitutes an internal, pragmatic threshold to detect differences considered meaningful or large enough to render interpretation for theory-based exploration worthwhile.

Table 7: Three-way independent analysis of variance for *crea* modes

Source	df	F	p	Generalized Omega <sup>2</sup>
predefine (p)	1	683.81	< .0001	0.53(3) <sup>2</sup>
cRatio (c)	1	1089.25	< .0001	0.64(2)
evalStrategy (e)	4	1101.27	< .0001	0.88(1)
p × c	1	317.04	< .0001	0.35(4)
p × e	4	69.57	< .0001	0.31(6)
c × e	4	78.87	< .0001	0.34(5)
p × c × e	4	25.33	< .0001	0.14(7)
Residuals	580	(0.00192) <sup>1</sup>		

<sup>1</sup> The value in parentheses is the mean square error.  
<sup>2</sup> The numbers in parentheses are the ranks of the effect sizes.

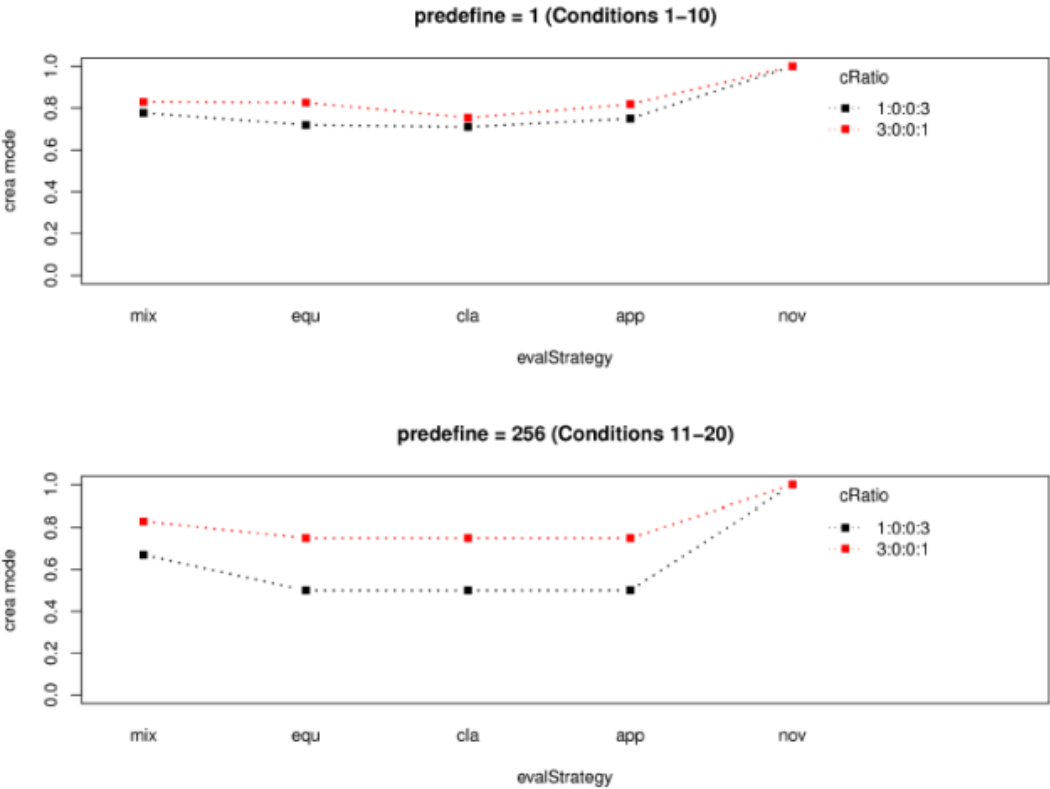
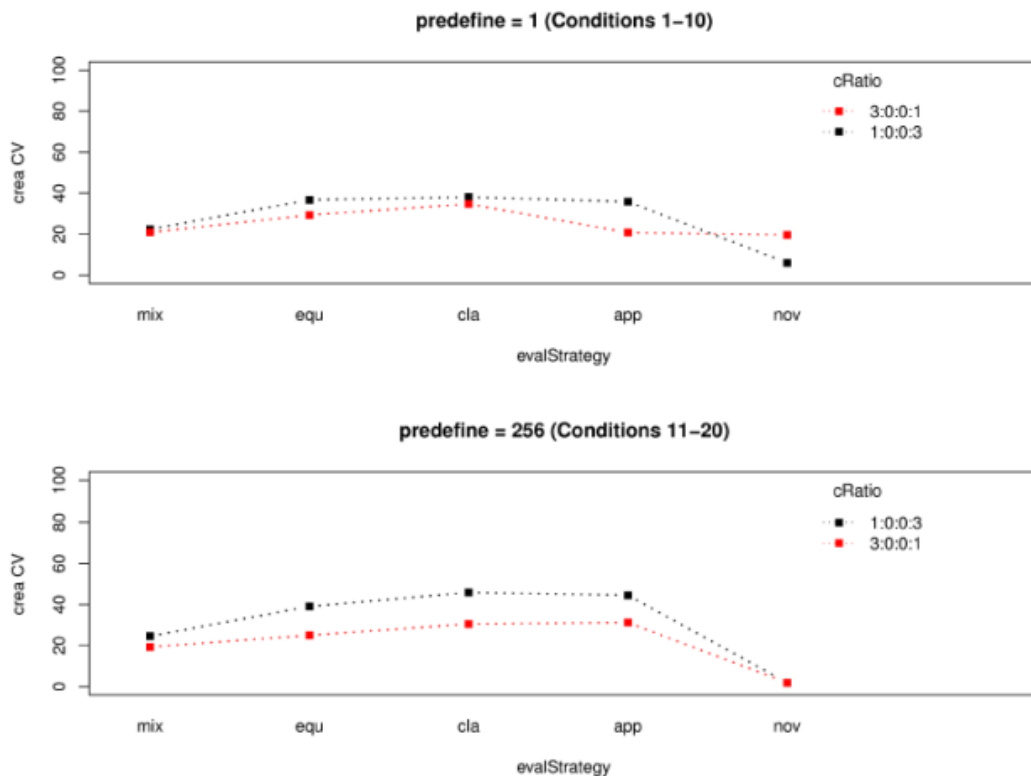


Figure 15. First-order interaction plots for *crea* modesTable 8: Three-way independent analysis of variance for *crea* CVs

Source	<i>df</i>	<i>F</i>	<i>p</i>	Generalized <i>Omega</i> <sup>2</sup>
predefine ( <i>p</i> )	1	0.70	0.79	0.00(7) <sup>2</sup>
cRatio ( <i>c</i> )	1	591.60	< .0001	0.50(4)
evalStrategy ( <i>e</i> )	4	1826.33	< .0001	0.92(1)
<i>p</i> × <i>c</i>	1	182.87	< .0001	0.23(5)
<i>p</i> × <i>e</i>	4	168.76	< .0001	0.53(3)
<i>c</i> × <i>e</i>	4	211.86	< .0001	0.56(2)
<i>p</i> × <i>c</i> × <i>e</i>	4	30.43	< .0001	0.16(6)
Residuals	580	(9.6) <sup>1</sup>		

<sup>1</sup> The value in parentheses is the mean square error.

<sup>2</sup> The numbers in parentheses are the ranks of the effect sizes.

Figure 16. First-order interaction plots for *crea* CVs (coefficients of variation)

#### Creativity (*crea*) modes

- 3.9 The following effects are considered meaningful based on the interaction plots (Figure 15) and the effect sizes (Table 7). Main effect *e* (generalized omega squared = 0.88): The common level of creativity (*crea mode*) is notably higher in conditions in which only patchwork novelty (*e* = "nov") is judged. It is equal to one in those conditions. Average creativity does not notably differ between conditions with the other evaluation strategies. This coincides with the information depicted in Figures 13–14. Second-order interaction *p* × *c* × *e* (generalized omega squared = 0.14); main effect *c* (generalized omega squared = 0.64); main effect *p* (generalized omega squared = 0.53): Average creativity is notably lower in conditions in which diversity is most expected (*c* = 1:0:0:3 and *p* = 256).

Otherwise, it is worth remarking that a) the two sample types do not noticeably differ and b) patchworks made by the least original sample type ( $c = 3:0:0:1$ ) are generally considered slightly more creative. Apart from the interaction between  $p = 256$  and  $c = 1:0:0:3$ , the different types of domains do not notably influence creativity levels.

*Creativity (crea) coefficients of variation (CVs)*

- 3.10 The following effect is considered meaningful based on the interaction plots (Figure 16) and the effect sizes (Table 8). Main effect  $e$  (generalized omega squared = 0.92): The instability of creativity judgments (*crea CVs*) is noticeably lower in conditions in which only patchwork novelty ( $e = \text{"nov"}$ ) is evaluated. Otherwise, the instability is similar across the remaining conditions. This coincides with the information depicted in the violin plots in Figure 14.



## Discussion

### Discussion of the results

- 4.1 High reliability levels indicate creativity was validly measured in terms of face and construct validity (Amabile 1982; Kaufman et al. 2008). The evaluators have the greatest effect on average creativity levels. Neither creators, evaluators nor the domain substantially affect the stability of these levels over time

### *Theoretical implications*

#### *The field and the domain render models of individual creativity incomplete*

- 4.2 The experimental results qualitatively indicate contextual factors systematically affect creativity. Specifically, the following circumstances apply when the field evaluates appropriateness: In homogeneous domains, that is, those with little artifact diversity, creators cannot be discriminated based on the creativity of their artifacts. In heterogeneous domains, "conventional" creators surpass "original" creators regarding the creativity of their artifacts. The former implies a sufficient amount of informational stimulation or availability is necessary for individual creativity to be discriminable. The latter implies that a system designed to facilitate the most change, that is, consisting of maximum domain heterogeneity and highly "original" creators, does not lead to maximum creativity levels when appropriateness is evaluated. In this case, "conventional" creators fare better by adhering to norms evaluators develop.
- 4.3 Both cases elaborated above demonstrate the fragility of models of individual creativity. As illustrated in the *Introduction*, creativity research in the domain of psychology is characterized by a strong focus on stable attributes or behavior exhibited by individual creators to detect and explain differences in creativity (Dewett & Williams 2007; Feist 1999; Kahl et al. 2009; Kirton 1976; Kwang et al. 2005; McCrae 1987; Wehner et al. 1991; Zaidel 2014). The creators in CRESY were designed to reflect this stylized fact. However, these stable differences do not cohere with respective differences in creativity when the field and the domain are explicitly modeled and varied. To understand and explain the process of creativity, therefore, contextual factors are necessary. Although his ideas have not been tested empirically, Csikszentmihalyi (1999) recognized the significance of the field *and* the domain in constructing *creators*. He specifically addressed the availability of "cultural capital" (Bourdieu 1986), and the ways significant others support an individual's creativity. This is not an argument for ignoring creators' agency in contributing to the creative production process, as he does describe their role in detail, but rather an appeal for acknowledging the relevance of social factors in cultivating individual creativity and the need for their assessment. Moreover, creativity is a *condicio sine qua non* for innovation (cp. Ahrweiler 2013; Viale 2013). Information (ideas, concepts, prototypes, etc.) produced in creative processes are precursors for innovations (cp. Schulte-Römer 2013). Understanding how the information pool evolves via socially distributed selection and retention processes is significant for providing or varying the informational basis of innovations (cp. Barrère 2013).
- 4.4 Videos 1-2 illustrate how the domain, as one contextual factor, affects artifact creativity (*crea*) and creator discriminability ( $hX.Y$ ) over time. The latter measure is known as the mutual information of two discrete variables (Attneave 1959; Bischof 1995), and ranges from 0 – 1. It refers to how well a creator type can be "predicted" or "guessed" by looking at a randomly selected color. Such an interpretation is important for discriminating the creator types from each other, therewith assessing their validity as different and stable behavioral types. Both Videos 1-2 show one run of 1000 steps. They have exactly the same settings as conditions 3 and 8 (Video 1; low domain diversity) and 13 and 18 (Video 2; high domain diversity) in the experiment reported above (Table 6). They only differ in the number of creators. Each video shows 6 creators (3  $Cx$  and 3  $C3$ ). Note in both cases and as time passes, it becomes harder to discriminate creator types from each other based on the colors they have produced. Their stable differences do not suffice to make a difference in terms of creative products.

Video 1. One run of 1000 steps plotting artifact creativity (*crea*) and creator discriminability ( $hX.Y$ ). Except for domain diversity (*predefine* = 1), all settings are the same in Video 2).

Video 2. One run of 1000 steps plotting artifact creativity (*crea*) and creator discriminability (*hX.Y*). Except for domain diversity (*predefine* = 256), all settings are the same in Video 1.

*The criteria evaluators use affect creativity the most*

- 4.5 The experimental results qualitatively support the assumption that the field (evaluators) plays a decisive role in generating artifact creativity (Csikszentmihalyi 1988, 1999). However, acknowledging their existence in the process does not suffice to explain how creativity emerges. Their behavior can be differentiated according to the kind and number of criteria they use. The highest levels of creativity coincide with evaluators' use of one criterion, namely *novelty*. It is based on the relation between artifacts previously seen and the artifact to be currently judged. Notably lower creativity levels coincide with evaluators' sole use of the criterion *appropriateness*. It is based on the relation between task restrictions and how well the current artifact meets them. Moreover, using both criteria to evaluate artifacts coincides with creativity levels similar to or lower than those measured when only artifact *appropriateness* is judged. Due to the algorithms' design, it is "easier" for an artifact to be considered novel than appropriate as there are less constraints to attaining that value (Figure 11). Regardless of whether or not novelty and appropriateness are judged in this algorithmic way in practice, the implication here is that some indicators of creativity may be harder to fulfill than others, and this impacts what passes as creative.
- 4.6 To a certain degree, the trade-off between novelty and appropriateness resembles the notion of exploration and exploitation of knowledge in organizations (March 1991; see also Page 2011). What the novelty criterion rewards is the discovery of and experimentation with new knowledge. In contrast, the appropriateness criterion rewards the "refinement and extension" (March 1991, p. 85) of existing knowledge. Achieving a balance between both novelty and appropriateness is something evaluators can guide by being aware of the quality of information they want the domain to encompass, the criteria they are using, and how they weight the latter (Keller & Weibler 2014; March 1991). The creator types reflect this duality, too: The "original" creators explore the knowledge space, while the "conventional" creators exploit it (cp. Gupta et al. 2006; Kunz 2011). Which behavioral strategy is more adaptive (in terms of creativity scores for patchworks) depends on the evaluation criteria used to select their work. In more fluid, real-world settings, these criteria are constructed and therewith malleable (cp. Dexter & Kozbelt 2013; Salah & Salah 2013).

*Practical implications*

- 4.7 How do these results inform the practice of creativity research? Firstly, psychological studies on creativity commonly stop with one assessment of variation. By explicitly personifying and repeating the selection mechanism, the impact the field has on creativity can be demonstrated. The obscurity of the selection process as described in the *Introduction* would therewith be reduced, and the influence evaluators have on creators and their artifacts exposed (Haller et al. 2011; Herman & Reiter-Palmon 2011; Lonergan et al. 2004; Randel et al. 2011; Silvia 2008, 2011, Westmeyer 1998, 2009).
- 4.8 Secondly, the results recreate ideas stated in Csikszentmihalyi's (1999) qualitative model. A (recognized) variation depends on the properties of its environment just as much or even more so than on its creator (Ahrweiler 2010; Cropley & Cropley 2010; Westmeyer 1998, 2009). According to Csikszentmihalyi (1999), evaluators are the ones "who have the right to add memes to a domain" (p. 324), and "if one wishes to increase...creativity, it may be more advantageous to work at the level of the fields than at the level of individuals" (p. 327). CRESY formalizes these ideas and exhibits a way to conceive psychological studies as a complex system (Holland 2014; Mitchell 2009), or rather, a creative system (Page 2011). This implies acknowledging the agency (e.g., intelligence, intentionality, bias, foresight) evaluators have in establishing a domain, that is, their selective behavior functions as a balance between exploiting and exploring the domain.
- 4.9 Thirdly, by demonstrating the impact of social validation (selection), it raises practical questions about the validity of study design and creativity assessment:
- Who constitutes the field? (How vast is their experience with the domain? How do they recognize, for instance, appropriateness?)
  - How is the field composed? (How reliable should the field sample be? Is their variation in judgments welcome or should it be reduced?)
  - Which and how many criteria are used for creativity assessment?
  - How are they operationalized in terms of their scope / frame of reference?
  - How are they aggregated?
  - How often does evaluation take place?
  - Do creators receive feedback on their work?

*Limitations*

- 4.10 The scientific scope of this model is limited to a very specific target: creativity research within psychological science. It is based only on stylized facts from that domain. Furthermore, the model was built with the sole purpose of conducting theoretical experiments in order to reflect how creativity is and could be studied in psychology. Specifically, CRESY focuses on one particular form of variation, namely combinatorial creativity, the most widely defined kind in creativity research (e.g., Amabile 1996; Sawyer 2006; Sternberg 1999b; Sternberg et al. 2004; Zhou & Shalley 2007).
- 4.11 The interaction incorporated in CRESY is restricted to indirect social influence. On the one hand, this is consistent with the model's target, creativity research

in psychology, and its purpose, to reflect how science is conducted there. As described in the *Introduction*, study participants commonly work alone on creative tasks and their work is subsequently rated by judges evaluating independently of each other. This by no means implies creators and evaluators do not influence one another, given both parties can perceive each other's work and ratings (which is the case in CRESY). The "indirectness" of this social influence can be viewed in many other instances of real life beyond creativity research: graffiti (Müller 2009), online brainstorming (e.g., <http://www.bonspin.de/>), Amazon reviews (Chattoe-Brown 2010), fashion trends (e.g., <http://www.signature9.com/style-99>). There are creators and evaluators virtually everywhere anonymously viewing, consuming, acknowledging and therefore being influenced by artifacts of other creators they do not necessarily know personally. On the other hand, modeling social influence in an impersonal way limits this model's applicability, as it does not address phenomena inherent in interpersonal relationships (e.g., leadership-follower dynamics, sympathy, reciprocity or ingroup-outgroup bias), which may affect creativity.



## Conclusion

- 5.1 Stylized facts from the domain of creativity research in psychological science were incorporated in CRESY, an agent-based model build to describe and test a systems perspective of creativity. Systematic experimentation with the model indicated creativity is affected by contextual factors such as evaluation strategies and informational diversity, results which can be used to stimulate and refine research practice in the target domain. The current model could nevertheless benefit from assessing its applicability to other targets (external validity) and extending its architecture to include more social and informational complexity. Model extensions could include processes depicting direct social influence, creators and evaluators incorporated into one agent, or multiple artifact domains. Assessing the model's external validity could be initiated by compiling its similarities and differences to other domains, for instance peer review (Squazzoni & Gandelli 2013; Squazzoni & Takács 2011), information retrieval (Picascia & Paolucci 2010; Priem et al. 2012), art criticism (Alexander 2010; Alexander & Bowler 2014), personnel assessments (Nicholls 1972) as well as pop culture reception (Chattoe-Brown 2010), and testing whether results obtained with CRESY hold in such areas.



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## Notes

<sup>1</sup>A journal article, for instance, represents a single creative artifact. Yet perhaps just individual attributes such as its method, sample or results are retained by those acknowledging it.

<sup>2</sup><http://www.openabm.org/model/2554/version/4/view> (Note the model is called CRESY-II online. There is an earlier version of the model, which does not contain evaluators, also available: <http://www.openabm.org/model/2552/version/3/view>).

<sup>3</sup>The term unreliable actually refers to how an observer interprets *C3*'s behavior. Technically, *C3* functions reliably based on a stable behavioral rule, that is, *C3* will always select with high probability digits it has seldom encountered before. However, its behavioral outcomes (patchworks) are so diverse that it appears to behave "unreliably", because an observer cannot predict its next patchwork as easily as one made by *Cx*.

<sup>4</sup>Creativity researchers discriminate and refer to these situations as "little-c" (personal, everyday) and "Big-C" (global, historical, eminent) creativity (Boden 1999; Beghetto & Kaufman 2007).

<sup>5</sup>Hues can be depicted with a color circle of 360°. The RGB values of a patchwork are translated into their corresponding degrees on the circle. Values from 135°-314° are categorized as cool, all others as warm.

<sup>6</sup>Without this stochasticity appropriateness judgments would always be the same, as all evaluators would view the same eight neighbors and come to the same judgment according to the algorithm described here (see also Chattoe 1998).

<sup>7</sup>Parameterization for all variables held constant in this experiment (*density*, *info-rate*, *movement*, *imagination*, *domSize*) as well as for the number of runs and steps chosen was carried out in a series of experiments specifically designed to test the robustness of these parameters. The experiments, their data analyses and discussions are fully available online in this model's documentation (<http://www.openabm.org/model/2554/version/4/view>).

<sup>8</sup>An intriguing notion creativity researchers usually sidestep is whether evaluators really have to agree, as demanded via adequately high interrater reliabilities. High reliability only indicates raters agree, but as long as legitimate evaluators are the ones agreeing, creativity researchers consider it to be an appropriate indicator of face validity (Amabile 1982; Kaufman et al. 2008). The absence of high interrater reliability means, according to the discipline, creativity was not measured. One alternative explanation could be that evaluators are being creative themselves. Presently, there is a lack of work reflecting this idea and its consequences for creativity research. Evaluators' potential to stimulate change, as for example remarked by Amabile (1996) and Csikszentmihalyi (1999), could encourage scholars to focus on rater dissent and its meaning in future research.

<sup>9</sup>Violin plots are vertical boxplots with rotated kernel density plots at both left and right sides. The white dot represents the median, and the thick black line the interquartile range (IQR). The thin black lines extend to the lowest datum still within 1.5 IQR of the lower quartile and to the highest datum still within 1.5 IQR of the upper quartile.



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