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“CRITICAL MASS OF IDEAS”: A MODEL OF INCUBATION IN BRAINSTORMING

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Abstract: This paper presents the results of experiments with a computational model of group brainstorming as an environment to study the role incubation in creativity. In this model, exploration refers to the purely random search for solutions, exploitation refers to the guided search for solutions based on previous solutions found, and incubation is defined as the re-organization of the search processes used previously to find solutions with no direct output of actual solutions.. This work supports the idea that the beneficial effects of incubation in ideation depend on a number of factors, and it provides insights for understanding the complex nature of incubation and its interaction with other creativity-related processes. We suggest the concept of “critical mass of ideas” as a plausible idea to explain some of the performance of incubation and one to be investigated in future studies of creativity.

Keywords: incubation, brainstorming, multi-agent model

1. Introduction

Generating and identifying novel ideas is hard. Facilitating ideation teams to generate and identify novel ideas is probably even harder. Key insights from research and practice provide some guiding principles to facilitate creative ideation in design. For instance, research on brainstorming has yielded interesting results about the ideational productivity of interactive (individuals collaborating in teams) and nominal groups (individuals working alone), suggesting that facilitation of creative teams has a large impact in the fluency of ideas [1]. Yet, there is a lack of systematic evidence and explanations of good facilitation practices in creativity research. The creation of robust facilitation strategies for creative ideation in design is what motivates this work.

Laboratory studies of group brainstorming present considerable challenges such as the criteria to define the task or problem addressed by participants, the criteria to assess the quality of ideas, and subtle differences such as motivation and various societal dynamics that are difficult to account for. This paper presents a computational model of group ideation that enables the examination of specific variables and their interaction over time in a multi-agent simulation that can be inspected in every detail and reinitiated to understand the effects of changing a particular initial condition in the system. The results of such model may serve as guiding principles for future research and practice. In this paper we focus on modelling incubation in group brainstorming.

2. Incubation

The idea of ‘incubation’ in creativity research has been very influential. The term is usually credited to Poincare’s anecdotal account of his mathematical discoveries as characterized by the ‘four stage model’ of Wallas [2]. This model suggests that the creative process iterates through a sequence that

begins with an intense period of conscious work (preparation), followed by a period of leaving aside the task for a while (incubation), leading to a sudden flash of insight (illumination) complemented by intense and focused work on the resulting ideas (verification).

Incubation in the ‘four stage model’ suggests that the individual or team suspends the ideation process either by resting or engaging in other tasks, literally ‘sitting on the ideas’. This has been hypothesized to protect the early ideas in the subconscious, possibly providing optimal conditions for understanding and connecting them with other ideas. Dreaming has been linked to creativity due to subconscious random associations between ideas. A recent study examined the role of REM sleep on the Remote Associates Test (RAT), a test where subjects build associations between words that are seemingly unrelated. That study compared conditions of REM sleep with quiet rest and non-REM sleep, concluding that REM sleep does enhance the integration of unassociated information [3].

Studying incubation during brainstorming is inherently difficult in laboratory studies. The main approach has consisted of introducing an unannounced break half-way in the session, during which participants are asked to engage in a different task like solving puzzles unrelated to the brainstorming problem, or to rest quietly [4, 5]. After this, participants resume brainstorming and their ideation productivity is compared to control groups of no-break condition. Participants in the break conditions have been found to generate more ideas than those in a no-break condition [6]. A recent literature review found a set of potential moderators reported, including the problem type, length of the preparation period (explicit and intense ideation), and the incubation task, leading to the possible existence of multiple types of incubation [4]. Apparently, taking a break from work on a topic is differentially advantageous, and depends on the type of task undertaken during the break [7].

A study of expert and novice chess players found that incubation does not always facilitate creative problem solving, but only when the problem solvers’ mind is fixated [8]. Similarly, manipulation of the inducement of fixation as well as the presence of breaks during the session confirms that incubation has the effect of increasing the number of ideas and the number of semantic categories of these ideas only when one has become initially fixated during a brainstorming session [9]. The observed positive effects of an incubation break include reducing the usual decline in quantity and variety in the latter stages of brainstorming [10]. In conclusion, incubation is a complex construct that may have a number of effects as a function of a number of given conditions. It has been generally defined as “a stage of creative problem solving in which a problem is temporarily put aside after a period of initial work on the problem” [11]. Therefore one can expect incubation to have different effects depending on the preceding period in the ideation process.

Further research is necessary to understand why and how interruptions during a brainstorming session improve ideation. Interruptions may enable the reorganization of information or the relation between seemingly unassociated ideas, or they may serve to recover from cognitive fatigue, or they may allow people to assimilate more complex ideas and their implications, or de-emphasize and forget dominant or commonplace ideas. In teams they may additionally be helpful to redirect or balance group dynamics, or to regain focus and recover from idea drifting. Further research is also necessary to understand moderating factors such as the nature of the brainstorming problem, the timing of the interruption during an ideation session, the nature of the task performed during the break, and the state of convergence or fixation in the stage previous to the break. The facilitation of ideation groups would greatly benefit from a better characterization of incubation, its expected effects and its appropriate timing during a brainstorming session.

3. Hypotheses

In this paper we use a computational model of group brainstorming to inspect the fundamental principles of incubation. In this model, exploration refers to the purely random search for solutions, exploitation refers to the guided search for solutions based on previous solutions found, and incubation is defined as the re-organization of the search processes used previously to find solutions with no direct output of actual solutions. The model provides quantitative and qualitative metrics of output. We use the term “ideational productivity” in this context to refer to an aggregate measure of quantity and quality of solutions generated by the model. Two hypotheses are explored in this model, the first hypothesis (H1) is that a combination of exploration and exploitation in *shapeStorming* is likely to

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produce a significant increase in ideational productivity when compared to the output of exploration alone. The second hypothesis (H2) is that incorporating incubation will carry a significant increase in ideational productivity when compared to the output of exploration and exploitation combined.

4. Experiments

The model of group ideation presented here, called *shapeStorming*, is a model of brainstorming using shape emergence. It is defined using the channels of systemic interaction specified in the IAS framework of creativity: Ideas (I), Agent (A), Society (S) [12]. Agents (A) engage in a simple exploratory designing task of two-dimensional geometric composition with emergent shape properties that constitutes the agent-idea channel (Ai). The resulting geometric representations and their topographic relations formulated as *design concepts* belong to the set of Ideas (I). Design concepts are shared by agents (Ia) and used as a basis to develop new design concepts (Aa) that are exploited or applied in the guided search of new designs (Ai') and social structures (S) determine the sharing of ideas between teammates (Si), Figure 1.

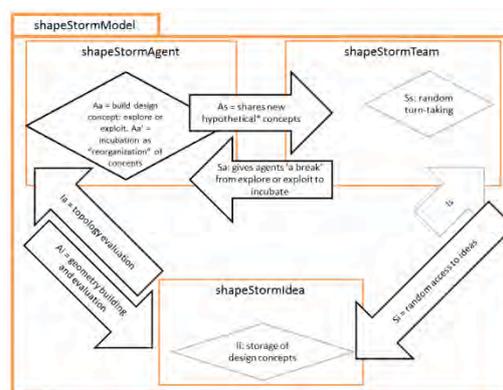


Figure 1 *shapeStorming* model based on the IAS framework of creativity [12].

The random search of geometric compositions in *shapeStorming* is called the *exploration* mode, while the guided search of geometric compositions based on the transformation of available topographic rules is called the *exploitation* mode. The construction of topographic relations from geometric representations is called the *evaluation* mode. Evaluation is a sub-process of exploration and exploitation where new candidate ideas are inspected for emergent outcomes that support new topographic rules. In *shapeStorming*, agents transition between modes in rates defined by the experimenter. The aim for agents in *shapeStorming* is to generate as many original solutions as possible, i.e., geometric and topographic compositions that are novel in the system. Every time that exploit or explore modes generate a novel combination of emergent features, the agent in *shapeStorming* evaluates the design and generates a new design concept. Further details on these strategies are provided below. This paper reports on the effects of exploration, exploitation and incubation modes on the number and quality of solutions generated by this model.

3.1. Agents, Ideas and Teams

Following the IAS framework of creativity [12], *shapeStorming* implements agent-idea interaction as a shape construction process starting from an initial set of n -number of two-dimensional shapes of m -sides that yields emergent polygons created by the intersection of lines and vertices. Six interaction processes across IAS levels are identified in [12]: agent-idea (Ai), idea-agent (Ia), agent-society (As), society-agent (Sa), idea-society (Is) and society-idea (Si). Three functions are aimed at, and are available by, targets within the same level in the IAS framework, namely agent-agent Aa, society-society Ss and idea-idea Ii [12]. In the version of *shapeStorming* discussed here, there are two variants of Ai processes: *explore* and *exploit* modes. In *explore*, agent behaviour is implemented as the random location in a two-dimensional space of m -number of connected polylines from which closed geometries of m -sides are built. Intersections are sought between all lines of the n number of geometries built. New polygons are created in *shapeStorming* by the superposition of pre-defined

shapes which leads to the identification of new vertices or nodes in the intersections of line segments and thus generates emergent polygons. This shape arithmetic task in *shapeStorming* is illustrated in Figure 2; the quality of a solution is measured by the number of emergent polygons created and the number of sides of these polygons.

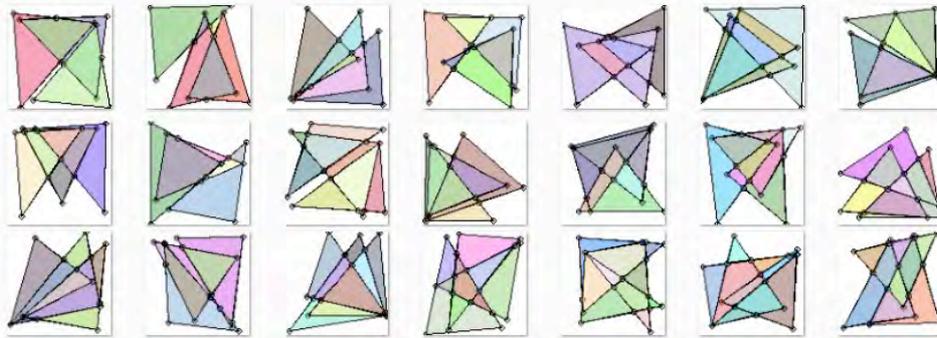


Figure 2 Shape emergence in *shapeStorming*, the output of a team of agents is assessed by the number of solutions and their quality (number of emergent shapes and sides)

In *exploit* mode, agent behaviour in *shapeStorming* is guided by topographic relations derived from previous solutions in an agent process of evaluation of emergent shapes. Evaluation characterizes the number of intersection points and their location inside, outside, in-line or in-vertex with respect to other shapes in the composition. A design concept in *shapeStorming* includes the topographic relation of shapes and the number of emergent polygons with their respective number of sides. Such a simple design task adequately models a brainstorming problem: agents are assembled in teams and take turns to generate as many different solutions as possible from an initially defined number of polyline sets. Shape exploration in *shapeStorming* can be considered potentially creative inasmuch as emergent shape semantics “exists only implicitly in the relationships of shapes, and is never explicitly input and is not represented at input time” [13].

The exploration and exploitation mechanisms used here are inspired by the classic notions of divergent or ‘horizontal’ and convergent or ‘vertical’ thinking processes [14]. During brainstorming sessions, one may assume that exploration enables the discovery of new categories or types of solutions, whilst exploitation allows for the generation of alternatives or new instances. In order to assess *shapeStorming* across a number of configurations, Table 1 presents a range of results of running four conditions: in A, the system is run for 1,000 steps with 4 agents, 2 initial shapes of 3 sides; in condition B, the same setting is run for 10,000 steps; in condition C a third initial shape is introduced and in condition D the system is run for 100,000 steps. Ideational productivity is defined here by the number of design concepts generated by agents during a simulation. We further distinguish between concepts generated in exploration mode and exploitation mode.

Table 1. Total ideation in exploration mode in different configurations of *shapeStorming*

<i>shapeStorming</i> conditions	Ideational productivity
A: 1,000 steps, 4 agents, 2 initial shapes, 3 sides	7.23
B: 10,000 steps, 4 agents, 2 initial shapes, 3 sides	9.38
C: 10,000 steps, 4 agents, 3 initial shapes, 3 sides	134.22
D: 100,000 steps, 4 agents, 2 initial shapes, 3 sides	15.35

3.1.1. Experimental settings

This paper shows results from two sets of experiments in *shapeStorming*, Experiment 1 aims to provide support for hypothesis H1 by examining the effects of exploitation mode in ideational productivity at different stages of a brainstorming session in conditions A and B as defined in Table 1. Exploration length ϕ refers to the ratio of the introduction of exploitation steps to the total simulation

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steps and is examined here from 0.0 to 1.0 in 0.05 increments. This set of experiments seeks to reveal when is exploitation more likely to give increased ideational productivity and why.

Experiment 2 aims to provide support for hypothesis H2 by examining the effects of varying incubation against different preparation stage lengths. Incubation rate μ stands for the ratio of the time when incubation is activated to the total simulation time and it is inspected here from 0.0 to 0.50 in variable increments in conditions A and B of *shapeStorming*. Experiment 2 seeks to explain the interplay between exploration behaviour and incubation in order to understand the effect of timing of the introduction of incubation in *shapeStorming*, as well as to grasp the fundamentals behind the timing of the incubation stage in *shapeStorming*.

5. Results

Results from Experiment 1 show the effects of introducing exploitation of design concepts in *shapeStorming* at a ratio of total simulated time, from exploration length $\varphi = 0$ to 1. Since exploitation needs at least one concept to work with, even when $\varphi = 0$ we commence with agents generating one base concept. An increasing value of φ means that agent behaviour switches from exploration to exploitation at increasingly later stages of the simulation time. The effects of introducing exploitation in *shapeStorming* at different times are shown in Figure 3. In condition A, Figure 3(a), exploration-driven concepts continuously increase as a result of extending the length of exploration stage. Similarly, exploitation-driven concepts gradually decrease as a consequence of shortening the exploitation period, Figure 3(b). Overall ideational productivity in condition A increases as exploitation is delayed up to around 75% of the simulation time ($\varphi = 0.75$) when peak ideational productivity is reached. After this point, the gain of exploration-driven concepts is costly in relation to the sharp decrease of exploitation-driven concepts. Therefore, in conditions like A of short runs (1,000 steps) this advantage is relatively small (from 7.23 to 7.68 or +6% in these experiments).

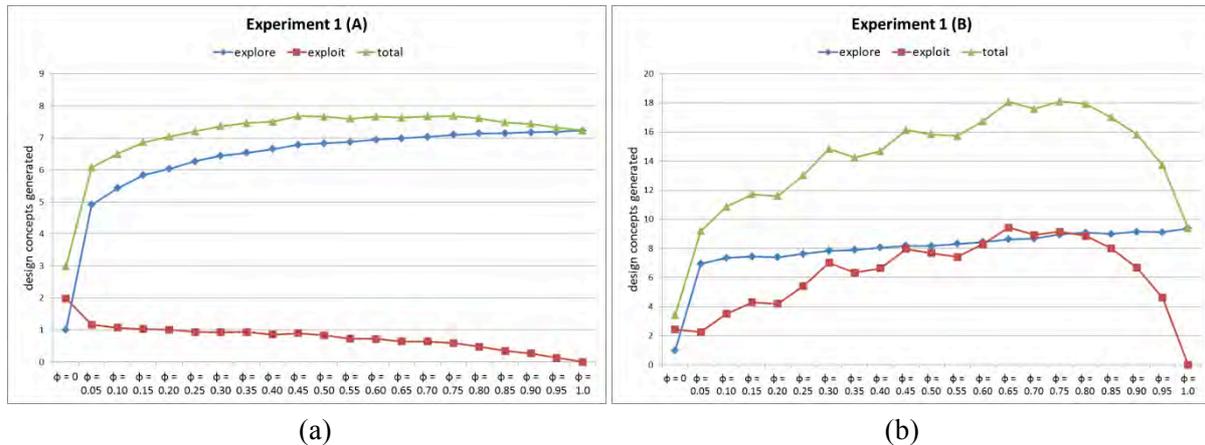


Figure 3. Experiment 1 with condition A and condition B

The advantages of exploitation are more evident in larger simulations such as condition B (10,000 steps), Figure 3(b). Here, the advantage of exploitation increases considerably (from 9.38 to 18.1 or +93%). Similar to condition A, exploration-driven concepts increase as exploitation is delayed, but in contrast to condition A, exploitation-driven concepts show a significant increase as exploitation is delayed. This could be unexpected given the results of Experiment 1(A). The reason for this can be explained by introducing the concept of *critical mass of ideas*, which explains the gain in ideational productivity due to positive feedback effects between exploitation and a sufficiently large body of ideas from exploration. In the ‘four-stage model’ of Wallas [2] this can be interpreted as verification being more productive when coupled with sufficiently rich preparation and incubation stages.

Overall ideational productivity in condition B increases as exploitation is delayed up to around 75% of the simulation time ($\varphi = 0.75$) when peak ideational productivity is reached, Figure 3(b) – a threshold similar to condition A, Figure 3(a). These results in Experiment 1 illustrate and provide a way to address the following well-known conundrum in facilitation of creative ideation sessions: building on

existing categories of ideas is a productive approach until it takes valuable time that can be invested in seeking novel categories of ideas. As discussed below, this complex interplay between exploration-driven and exploitation-driven ideation could be at the centre of the seemingly paradoxical findings that individuals working alone tend to outperform teams in creative ideation tasks. This understanding that exploitation can have positive but differentiated effects on ideational productivity depending on the ability to build on a sufficiently large mass of ideas, provides a background to examine the effects of incubation in Experiment 2.

Experiment 2 introduces incubation in *shapeStorming* to inspect the timing between exploration, incubation and exploitation stages. The results from Experiment 2 also suggest that there may be a relationship between incubation rates and increased ideational productivity. For these purposes, the exploration lengths ϕ and the incubation rates μ are varied. A sampling of μ from 0 to 0.50 are tested across all ϕ 's from 0 to 1 in 0.10 increments. The results, Table 2, indicate that by introducing incubation in condition A of *shapeStorming*, the gain in ideational productivity is significant.

Table 2 Peak ideational productivities of incubation rates μ across exploration lengths ϕ

incubation rate μ	exploration length ϕ	peak ideational productivity
$\mu = 0$	$\phi = 0.75$	7.68
$\mu = 0.01$	$\phi = 0.20$	15.35
$\mu = 0.02$	$\phi = 0.20$	16.17
$\mu = 0.03$	$\phi = 0.20$	16.42
$\mu = 0.04$	$\phi = 0.20$	16.53
$\mu = 0.05$	$\phi = 0.20$	16.88
$\mu = 0.10$	$\phi = 0.20$	16.5
$\mu = 0.30$	$\phi = 0.10$	15.5
$\mu = 0.50$	$\phi = 0.10$	14.07

Peak ideational productivity in condition A is achieved with a low incubation rate $\mu = 0.05$, that is, agents engaging in incubate mode only 5% of the total simulation time. This increase is a substantial 220%, from the 7.68 solutions generated in exploration-to-exploitation modes as shown in Experiment 1(A) to 16.88 when incubation is included in Experiment 2(A). By traversing the exploration length ϕ range from 0 to 1 in 0.1 increments, we find that the timing for incubation that produces peak ideational productivity in *shapeStorming* is when agents engage in exploration for a 20% of the total simulation time. Figure 4(a) shows the impact of incubation rate $\mu = 0.05$ for the range of exploration lengths ϕ from 0 to 1.

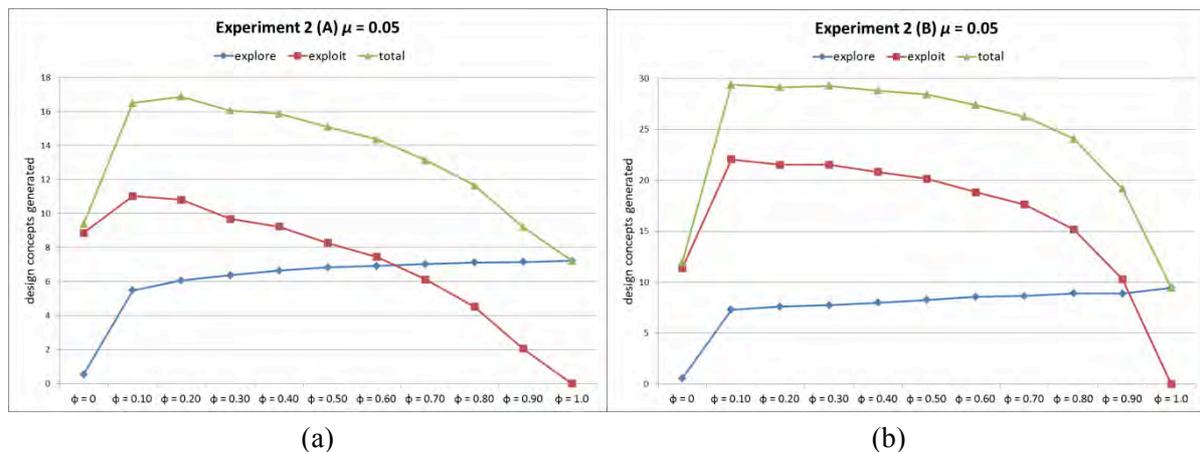


Figure 4. Experiment 2 with condition A and condition B, incubation rate $\mu = 0.05$

This indicates that exploitation in *shapeStorming* is most productive when a combination of sufficient design concepts have been generated –both real concepts produced by exploration and possible

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concepts produced by incubation. After this threshold defined by 5% incubation plus 20% exploration in condition A of *shapeStorming*, it seems that agents waste their turns engaging in less productive incubation or exploration modes, when the larger gains come from focusing on exploitation. Experiment 2 reinforces the notion of *critical mass of ideas* discussed above, and the significant role of incubation in amplifying the value of exploitation, as well as in moving the inflection point from $\phi = 0.75$ in Experiment 1(A) to $\phi = 0.20$ in Experiment 2(A).

Experiment 2(B) replicates these findings when *shapeStorming* is run with condition B for a total of 10,000 simulation steps. With $\mu = 0.05$, the exploration length ϕ range is varied from 0 to 1 in 0.1 increments. Compared to Experiment 1(B) where only exploration and exploitation modes are used and a mean 18.1 design solutions are generated, when incubation is incorporated in these long simulations, its impact is still considerable. Ideational productivity climbs around 160% reaching 29.38 mean solutions when $\mu = 0.05$ and $\phi = 0.10$. Incubation even in exhaustive simulation runs have a positive effect in *shapeStorming*, Figure 4(b). This indicates that the effects of incubation may be dependent on the size of the problem space addressed in ideation; as a result, incubation is likely to have higher impacts when applied in shorter sessions.

While incubation in *shapeStorming* doubles ideational productivity, it improves by two orders of magnitude the performance of the *shapeStorming* model, since it generates in only 1,000 steps (condition A) similar results than those in 100,000 steps without incubation (condition D).

6. Introspection

The work presented in this paper confirms via a computational model of group brainstorming the notion that incubation has a positive effect on ideation. It also suggests that the beneficial effects of incubation in ideation depend on a number of factors, and it provides insights for understanding the complex nature of incubation and its interaction with other creativity-related processes.

Our model shows that the combination of guided and random search may be only marginally better than purely random search in short runs, but its advantage increases as simulated time is extended. This points to a close interaction between exploratory and informed search processes over time. A process of ‘building upon ideas’ is more productive when it is activated after a sufficiently long initial period where a larger pool of initial ideas has been generated. According to our model, a significant increase can be obtained through exploitation even with a marginally larger pool of ideas previously generated by exploration. We refer to this as the “critical mass of ideas” (CMI), the principle that a sufficiently rich body or repository of initial ideas is a pre-condition for combinatory processes to generate a high number and variety of creative ideas.

A seemingly paradoxical outcome in creativity research is that the same number of individuals is likely to generate more and better ideas when working in isolation than when interacting in brainstorming sessions as a team [1]. Although such results are consistent, no definite explanation has been offered until now, particularly since common sense suggests that interacting ideators have a higher potential to combine and build upon their ideas. The principle of “critical mass of ideas” (CMI) may provide a simple working mechanism for these results: in teams, group dynamics may prevent the formation of a sufficiently large body of initial ideas that others can build upon. In contrast, when working in isolation, individuals self-control the transition between exploratory and guided search. It is possible that teams may overcome this limitation by implementing an adequate facilitation technique that enables the formation of a critical mass of individual ideas that can be subsequently combined and improved by other teammates.

The second experiment presented in this paper demonstrates in a simple model of creative computational behaviour and a highly constrained domain representation, that even very low rates of incubation may carry a radical increase in the number of ideas generated in a brainstorming session. With very short incubation periods of only 5% of the total simulation length, when the incubation mode is activated around 1/5th through the simulation, it seems to produce the peak results in our model. This captures Edison’s famous dictum that creativity consists of marginal levels of inspiration accompanied by an overwhelming majority of hard work (“Creativity is 1% inspiration and 99% perspiration”). Apparently, incubation represents a cost-effective way of manipulating ideas that were previously generated and they also serve as a pool of possible ideas that can be used later to generate

novel ideas. When incubation is activated at the right time and for the right length of time, it seems to catalyse the combined search processes of exploration and exploitation by reaching the highest point of ideation significantly sooner than in equivalent runs without incubation. In other words, when incubation is activated, less randomness may be required in order to generate a sufficiently large pool of initial ideas upon which new solutions can be built. Incubation may thus serve as a type of ‘shortcut’, with the highest advantages seen in shorter time periods.

The notion that a small pool of ideas is unlikely to spark sufficient synergy to reach “the critical mass needed to overcome the overhead associated with (team) interaction” was proposed previously in a different context [15]. Here it is suggested that CMI may be useful in understanding differences in ideational productivity between nominal and interacting groups [1], as well as the observed effect that “longer preparation periods give rise to larger incubation effects” [4]. Our computational model suggests that CMI is a valuable theoretical construct worth analysing in future studies.

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