

# Modeling artistic processes using production systems

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## Abstract

What are the problems faced by contemporary artists? By what processes do they solve these problems in real-life? This article presents preliminary results of the second phase of an ongoing project seeking to model the cognitive processes involved in a contemporary artistic practice; this project is being conducted within the *artistic creativity as situated problem solving* approach. Creativity is viewed both as a problem-solving process (Klahr & Simon, 1999) and as a situated process (Nersessian, 2004). The first phase of the project involved a field study of Canadian visual artist Isabelle Hayeur over a sixteen-month period; the second phase, which has just begun, involves the computational modeling of her artistic processes. Building on the analysis of Leclerc and Gosselin (2004), we present a partial but nonetheless substantial computer-based model of the processes involved in this artist's creative practice.

## 1. Introduction

Recently, Klahr and Simon (1999) have suggested that by using the concepts and vocabulary of human problem-solving theory (Newell & Simon, 1972) "we may be able ... to converge toward a common account of discovery in many areas of human endeavor", including the arts (p. 524). Much work have already been done to understand processes of scientific discovery with this approach (e.g., Klahr, 2000; Kulkarni & Simon, 1988; Langley, Simon, Bradshaw, & Zytkow, 1987). But, with few exceptions (e.g., Weisberg, 1993), little has been done to study artistic creativity from this perspective. What are the problems faced by artists? By what processes do they solve these? We conducted a case study to begin answering these questions.

As there have been few studies of artistic creativity as a problem-solving process, there have been even fewer efforts to model artistic creativity within that framework; most of the computational models of creativity, in recent years, have been of the creativity involved in the process of scientific discovery (e.g., Kulkarni & Simon, 1988; Langley, Simon, Bradshaw, & Zytkow, 1987; Schunn & Anderson, 1998).

## 2. Modeling artistic creativity

### *Production systems*

The results presented here represent a first effort at modeling artistic processes using *production systems*. These systems have their origin in Emil Post's (1943) study of the properties of systems based on rules (Jackson, 1999). Production systems have been adopted early on by cognitive scientists to model language, memory, and creativity (e.g., Anderson, 1976; Chomsky, 1957; Newell & Simon, 1965; Kulkarni & Simon, 1988; Schunn & Anderson, 1998). According to Anderson and Lebiere (1998), "[production systems] are the only modeling formalism capable of spanning a broad range of tasks, dealing with complex cognition, in complete detail, and with a high degree of accuracy" (p. 3). This is a bold statement, but Anderson's ACT-R theory and similar theories, like SOAR and others, provide serious evidence for it.

The production system outlined in this article was implemented using Jess<sup>11</sup> (version 6.1p6), a general-purpose rule engine, written in the JAVA programming language. Jess is a Java-implemented version of CLIPS, itself a descendant of the OPS family of production rule languages and related languages; OPS5 was the language most often used to model cognitive processes by the first generation of researchers at Carnegie Mellon (Herbert Simon, Allen Newell, and other pioneers in the study of creativity in science). The Jess language, like its ancestors, has a syntax very close to LISP, a language traditionally used in AI and in many models of human cognition.

*Isabelle Hayeur: A contemporary visual artist*

Isabelle Hayeur<sup>12</sup> is a successful professional Canadian visual artist. She works mainly with digital photography and video; her work has been shown in solo and group exhibitions nationally and internationally. A great part of her work involves producing large-scale photomontages; these often show idyllic-looking landscapes... almost idyllic, but not quite, standing at the edge of the familiar and the unknown, between the beautiful and the repulsive; these images often evoke a feeling of strangeness in the viewer. She works also with video, Net art and does site-specific projects.

At the time of writing, we have been conducting a field study of her practice and creative processes for a sixteen-month period; the study is ongoing. Multiple data types, from multiple sources, have been collected, on-site, to allow the modeling of a distributed set of cognitive activities (see Clancey, 2001). These include: interviews, photographs of work space and tools, recording of activity at the computer, and extensive field notes. All data was digitally recorded and archived (except for the field notes); total data volume amounts to about 30 gigabytes.

Here, the analysis will focus on the interview data. Eight semi-structured interviews were conducted over a six-month period, at the artist's studio (Leclerc & Gosselin, 2003). Interviews were 30 to 60 minutes long; these were digitally recorded and transcribed verbatim. Then, they were organized, stored, and analyzed using the Atlas.ti computer package. The analysis consisted of coding the interviews in terms of the *problem spaces, goals, operators* (i.e., concepts of human problem-solving theory, Newell & Simon, 1972) mentioned in the interviews and, from these, extracting a set of rules pertaining to the diverse problem spaces - problems, tasks, and so on - involved in this artist's work and practice.

*ACE: A model of real-life artistic creativity<sup>13</sup>*

We chose to model Isabelle Hayeur's artistic processes in terms of four main entities : (1) agents, (2) goals, (3) knowledge, and (4) environment. Goals and knowledge are typical categories involved in knowledge-based systems, or production systems (see Jackson, 1999); and, even though our main focus is on one individual, we want to allow for the explicit modeling of 'outside' processes, i.e. other agents and their respective environments. This relates to the situated, or distributed, part of our

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<sup>11</sup> Jess (trial version or licensing for either academic or commercial use) is available online from Sandia National Laboratories at: <http://herzberg.ca.sandia.gov/jess/>

<sup>12</sup> Her work, resume, artist's statement, and related projects can be found on her Web site at: <http://isabelle-hayeur.com>.

<sup>13</sup> The model is available online at: <http://mapageweb.umontreal.ca/gosselif/ACE.html>.

approach; basically, we consider artistic creativity to be a cognitively distributed, or extended, process.

What can we tell about the cognition involved in real-life artistic practice by modeling an artist in this way? Or, asked otherwise, what is the *grammar*, the set of rules that can describe, or produce, the observed - in our case, creative - behavior? As a partial answer, we offer the next few pages.

#### *Problem spaces of Isabelle Hayeur's creative processes*

It is traditional in the human problem-solving theory literature to distinguish sets of problem spaces, search spaces, in which a problem solver operates in order to resolve a particular problem or accomplish a task (see, for example, the two-space model of scientific discovery, first proposed by Klahr & Dunbar, 1988; this model presents scientific discovery as a process involving dual search in an Hypothesis space and an Experiment space). We previously came to the conclusion that Isabelle Hayeur's artistic activities are operating in two main problem spaces, an Artistic practice space (A) and a Career space (C) (Leclerc & Gosselin, 2004). A third space, the Economic space (E), also plays a role, a comparatively minor one. Our model's name, ACE, is the juxtaposition of the letters standing for the three search spaces involved in Isabelle Hayeur's creative process.

How Isabelle Hayeur resolves the problems of being an artist, of producing art works and of attaining a certain level of professional success all happens in these - A, C, and E - search spaces. The combined size of these search spaces is vast (compared, for example, to the cognitive space involved in the solving of a simple arithmetic problem, or some other common cognitive psychology task). Thus, a model of such spaces cannot be fine-grained; what matters most here is not detail and precision but the ecological validity of the model and its ability to give us a bird's eye view of a real-life artistic practice.

#### *ACE: An example run -- I*

Here is a sample run of ACE. Initial conditions were set to match Isabelle Hayeur's actual state. Some of these initial conditions correspond to unchanging variables in the subject, for the duration of the research project (i.e., in the course of our study, these have never been found to vary):

- (agent (name IH) (status artist))
- (goal (agent IH) (task being-an-artist--doing-that-my-entire-life))
- (goal (agent IH) (task art-must-remain-a-calling-remain-research))
- (goal (agent IH) (task taking-my-work-as-an-artist-seriously))

In first-order predicate logic, these facts state that IH (i.e., Isabelle Hayeur) is an artist, and that she has the following goals: to be an artist for her entire life, that art must remain a calling, and that she wants to take her work as an artist seriously. These facts were asserted - put in the production system's working memory - at the beginning of the simulation, went unchanged throughout a run of the program and, further, went unchanged from one run of the simulation to the other.

Part of the initial conditions for a run of the model also consists of variables that may change from one simulation run to the other. These represent changing conditions in Isabelle Hayeur's own state, the state of her goals and knowledge, and in the state of her environment (these may also include the changing state of other agents). For this run of the simulation, they were:

- (agent (name IH) (variable artistic-production-unpaid))
- (agent (name IH) (variable photographic-production))
- (agent (name IH) (variable very-active-professional-life))
- (goal (agent Isabelle) (task sending-my-work-projects-to-artists-centers) (project IDC))
- (knowledge (agent IH) (variable what-I-have-to-do--to-be-an-artist))
- (environment (agent Isabelle) (variable cannot-make-a-living-from-art-alone))
- (environment (agent Isabelle) (variable opportunity-to-work-in-your-own-domain))
- (environment (agent Isabelle) (variable printing-large-scale-photographs))

An advantage of production systems, and first-order logic predicates, is that code such as this can be read - by humans - directly; accordingly, the above stated facts mean that Isabelle Hayeur's artistic production is initially unpaid for, that she has a photographic production, has a very active professional life, and so on. All of these facts are put in working memory at the start of the simulation, may change during the simulation, and serve to activate the *production rules* that constitute the model of Isabelle Hayeur's artistic process; in turn, the production rules may change the content of working memory - these facts - as the simulation runs. (Production systems are based on production rules; these rules take the form of "IF-THEN" rules, stating if an action - behavioral or cognitive - is to be taken, under which conditions, and specifically what type of action is to be undertaken.)

Here is a test run of ACE. We provide a list of the main rules fired in the course of the simulation, starting from the initial conditions.

Table 1

## A sample run of ACE

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MAKING-TIME-FOR-PRACTICE-AND-CAREER---putting-all-my-time-in-artistic-work-and-my-artist's-dossiers-[AC]<sup>14</sup>  
 MAKING-TIME-FOR-PRACTICE-AND-CAREER---half-my-time-in-putting-together-my-artist's-dossiers-[AC]  
 ...  
 BEING-AN-ARTIST-MY-ENTIRE-LIFE---doing-what-I-have-to-do-[AC]  
 ...  
 DISSEMINATION---making-the-project-move-forward-and-finishing-it-[CA]  
 DOING-A-PROJECT---putting-time-in-the-project-[AC]  
 PUTTING-TIME-IN-A-PROJECT---picking-up-work-on-the-project-[AC]  
 ...  
 ACTIVE-PROFESSIONAL-LIFE---searching-for-bread-and-butter-jobs-[AE]  
 BREAD-AND-BUTTER-WORK---taking-what-comes-[AE]  
 ...  
 PAYING-FOR-ARTISTIC-PRODUCTION---the-artist-must-pay-for-own-production-[AE]  
 PAYING-FOR-ARTISTIC-PRODUCTION ---taking-small-jobs-in-your-domain-[AE]  
 MAKING-TIME-FOR-PRACTICE---living-with-less-[AE]  
 TAKING-SMALL-CONTRACTS---own-production-is-paid-[AE]  
 ...  
 DOING-THE-ARTIST-WORK-SERIOUSLY---doing-my-artistic-work-full-time-[A]  
 MAKING-TIME-FOR-PRACTICE---having-time-for-my-practice-[A]  
 MAKING-TIME-FOR-PRACTICE ---working-less-having-a-lower-standard-of-living-[AE]  
 WORKING-LESS---living-with-less-[AE]  
 MAKING-TIME-FOR-PRACTICE ---having-time-for-my-practice-[AE]  
 ...

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Displayed here are ‘threads’ of activity simulating parallel, or interweaved, threads of activity in Isabelle Hayeur’s life and art-related activities. Each thread begins with a top-level goal; in this run, we have six top-level goals: (1) making time for my practice and career, (2) being an artist my entire life, (3) disseminating the artistic work, (4) having an active professional life, (5) paying for the artistic production, and (6) doing the artistic work seriously. Overall, these threads give us a view of some of the most important goals and activities occupying this artist. Furthermore, we see how each thread involves the application of a certain set of rules to reach these high-level goals.

One thread in Table 1, for example, begins with the rule “DOING-THE-ARTIST-WORK-SERIOUSLY---doing-my-artistic-work-full-time”; this rule states that if one wants

<sup>14</sup> Letters in square brackets (e.g., [AC] ) , after a rule’s name, indicate in which of the three search spaces (A, C, E) the rule operates. Note that many rules bridge activity between different search spaces.

to do the artist's work seriously, one must do this work full-time. In order to achieve its goal, this rule calls on the next rule in the thread, "MAKING-TIME-FOR-PRACTICE---having-time-for-my-practice". The same goes on for the rules that follow in the thread; each one is activated in turn, until the initial goal is reached. As we can see, each thread constitutes an operator - a set of rules - working to achieve certain particular goals.

*ACE: An example run -- II*

What would happen if Isabelle Hayeur did not value her artistic practice time, did not associate artistic practice time with the quality of the artistic work produced, or did not have as a goal to produce quality work? A possible answer to these questions appeared in a recent test run of ACE, when we mistakenly modified the production system. This test run was particularly surprising; it showed the behavior exhibited by the trace below.

Table 2

The artist's 'bread-and-butter' loop

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PAYING-FOR-ARTISTIC-PRODUCTION---the-artist-must-pay-for-own-production-[AE]  
 PAYING-FOR-ARTISTIC-PRODUCTION ---taking-small-jobs-in-your-domain-[AE]  
     TAKING-SMALL-CONTRACTS---own-production-paid-[AE]]  
     TAKING-SMALL-CONTRACTS---contract-completed-[AE]  
     TAKING-SMALL-CONTRACTS---own-production-paid-[AE]]  
     TAKING-SMALL-CONTRACTS---contract-completed-[AE]  
 ...

---

In this run, the model is caught in a loop; it does not take appropriate action to augment financial resources by any other means than by getting small jobs, doing these, and finding other similar jobs, and so on. The rules active here and the initial conditions conspire, so to speak, to prevent the model from applying other operators for finding financial resources. This loop also prevents the ACE model from pursuing other types of goals - namely, artistic and career goals.

What happened to make the ACE model behave this way? The rules of the production system were the same, the initial conditions were almost exactly the same. We had just made one small change, we had added a simple fact:

(environment (agent IH) (variable small-job-completed))

This fact took advantage of an error in the following rules:

```
(defrule TAKING-SMALL-CONTRACTS---own-production-paid-[AE]

  (goal (agent ?x) (task taking-on-small-jobs))
  ?y <- (agent (name ?x) (variable own-production-unpaid))
  =>
  (retract ?y)
  (assert (agent (name ?x) (variable own-production-paid))))

(defrule TAKING-SMALL-CONTRACTS---contract-completed-[AE]
  ?y <- (agent (name IH) (variable own-production-paid))
  ?z <- (environment (agent IH) (variable small-job-completed))
  (not (environment (agent IH) (variable sufficient-grants)))
  =>
  (retract ?y)
  (retract ?z)
  (assert (agent (name IH) (variable own-production-unpaid))))
```

The added fact revealed a mistake that had remained hidden until then: we had forgotten to add a stop condition in the second rule, a condition that would take into account the additional fact (i.e., the fact asserting that a contract is completed). This rule should have included an additional condition on the ‘if’ side (i.e., the part of the rule describing the conditions under which it fires), and an additional action - the retraction of a fact - on the ‘then’ side of the rule (i.e., the part of the rule describing the action to be taken when it fires). Adding these took care of the problem (see above, in red).

Was this ‘loop behavior’ just the result of a programming error? Yes it was... in that case. But the same kind of behavior could also happen in the ACE model for other reasons and, similarly, does happen to many artists caught up in a ‘bread-and-butter’, or a ‘making a living’, loop. What would it take for ACE to do that? One possibility is to change the initial conditions of the model. For example, if we took away the asserted goal of “doing the artist’s work seriously”, and also took away some “dissemination” goals, we could get similar behavior. As a result of those changes, the model would stop having the goal of “doing the artist’s work seriously” and, consequently, would devote less time to the actual artistic practice and more to the ‘economic’ activity (as in Table 2). This suggests an impact on artistic activity of the interplay between the artist’s goals and economic conditions. As a result of a few changes to the ACE model’s initial conditions, the (simulated) artist is caught up in that same loop, devoting most of its activity to ‘bread-and-butter jobs’, instead of putting more time in actual creative work. We may ask: is this loop behavior of the modified ACE model just an artifact? Or, does it reveal something more significant about the conditions of practice, and patterns of behavior, of artists? In a major sociological survey of Québec’s visual artists’ conditions of practice, Bellavance, Bernier, and Laplante (2001) report an impressive number of statistics suggesting that this is indeed the case. For example: for 20% of artists, their total income comes from activities unrelated to their artistic practice; for more than 50% of artists, only 20% or less of their income comes from

their artistic practice, and so on. It means that many, if not most, of Québec's professional visual artists live from work outside of their own practice. This is quite reminiscent of the loop behavior displayed in Table 2 (i.e., the 'bread-and-butter' loop); of course, this, and the behavior of the modified ACE model, does not reflect the patterns of behavior of Isabelle Hayeur.

*Operators from the artistic practice space*

What is it that Isabelle Hayeur's does that allows her to succeed in the middle of the difficult practice conditions that Bellavance et al. (2001) describe? In Isabelle Hayeur's case, and in contrast to the 'pathological' code responsible for the behavior shown in Table 2, one set of operators works to reduce the required financial resources necessary to produce art works, and another works to augment the financial resources available directly through her artistic activity. Other operators are also at work, ensuring her dedication to the artistic work. See Table 1 for a sample of these multi-layered operators. Below are some of the main, top-level, rules from Isabelle Hayeur's practice search space.

These rules of artistic practice, embodied in the ACE model, tell us that some of the main goals pursued by Isabelle Hayeur are: to make time for her artistic practice (and career), to be an artist for all of her life, to disseminate her work, have it be known and seen, and to do her artistic work seriously. Each rule tells us some of the actions undertaken to reach those goals. For example, to do her artistic work seriously, she must work at it full-time. This survey of her rules of practice helps explain how she may strive and succeed in the midst of Québec's and Canada's difficult socio-economical conditions of visual artists. It also gives a portrait of who Isabelle Hayeur is as an artist, of what she values as an artist and of how she is able to put into action those values.

**Table 3** Some of Isabelle Hayeur’s main A’s rules

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```

(defrule MAKING-TIME-FOR-PRACTICE-AND-CAREER---putting-all-my-time-in-artistic-work-and-
my-artist-dossiers-[AC]
  (not(agent (name Isabelle) (variable contract-small-jobs)))
  =>
  (assert (goal (agent Isabelle) (task putting-all-my-time-in-artistic-work-and-my-artist's-
dossiers))))
(defrule BEING-AN-ARTIST-MY-ENTIRE-LIFE---doing-what-I-have-to-do-[AC]
  (goal (agent Isabelle) (task being-an-artist--my-entire-life))
  (knowledge (agent Isabelle) (variable what-I-have-to-do--to-be-an-artist))
  =>
  (assert (goal (agent Isabelle) (task doing-what-I-have-to-do-to-be-an-artist))))
(defrule DISSEMINATION---making-the-project-move-forward-and-finishing-it-[CA]
  (goal (agent Isabelle) (task sending-the-work-to-artists-centers) (project ?x))
  =>
  (assert (goal (agent Isabelle) (task moving-the-project-forward-and-finishing-it)
(project ?x))))
(defrule ACTIVE-PROFESSIONAL-LIFE---searching-for-bread-and-butter-jobs-[AE]
  (agent (name Isabelle) (variable very-active-professional-life))
  =>
  (assert (agent (name Isabelle) (variable not-much-time-to-search-for-bread-and-butter-
jobs))))
(defrule DOING-THE-ARTIST-WORK-SERIOUSLY---doing-my-artistic-work-full-time-[A]
  (goal (agent ?x) (task doing-the-artist-work-seriously))
  =>
  (assert (goal (agent ?x) (task doing-the-artist-work-full-time))))

```

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For each of those top-level rules, we may also dig down further to find out how a specific operator is implemented in the artist’s activity. As an example, in Table 4, we reproduce a set of rules describing how Isabelle Hayeur achieves her goal/operator: “doing the artist’s work seriously”. This example provides a partial answer to the question of how exactly she manages to do her work seriously in real-life and shows an operator at work in a successful artistic practice.

**Table 4** An operator’s description: “Doing the artist’s work seriously”

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```

(defrule DOING-THE-ARTIST-WORK-SERIOUSLY---doing-my-artistic-work-full-time-[A]
  (goal (agent ?x) (task doing-the-artist-work-seriously))
  =>
  (assert (goal (agent ?x) (task doing-the-artist-work-full-time))))
(defrule MAKING-TIME-FOR-PRACTICE---having-time-for-my-practice-[A]
  (goal (agent ?x) (task doing-the-artist-work-full-time))
  =>
  (assert (goal (agent ?x) (task having-time-for-my-practice))))
(defrule MAKING-TIME-FOR-PRACTICE ---working-less-having-a-lower-standard-of-living-[AE]
  (goal (agent ?x) (task having-time-for-my-practice))
  =>
  (assert (goal (agent ?x) (task not-having-a-too-high-standard-of-living)))
  (assert (goal (agent ?x) (task working-less-and-less-bread-and-butter-jobs))))
(defrule WORKING-LESS---living-with-less-[AE]
  (goal (agent ?x) (task working-less-and-less-bread-and-butter-jobs))
  =>
  (assert (goal (agent ?x) (task trying-to-live-with-less-money))))
(defrule MAKING-TIME-FOR-PRACTICE---having-time-for-my-practice-[AE]
  (goal (agent ?x) (task not-having-a-too-high-standard-of-living))
  (goal (agent ?x) (task working-less-and-less-bread-and-butter-jobs))
  (goal (agent ?x) (task trying-to-live-with-less-money))
  =>
  (assert (agent (name Isabelle) (variable has-time-for-artistic-practice))))

```

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### 3. Conclusions

Part of the ACE model of Isabelle Hayeur’s artistic processes was presented in this article, mostly the A - or Artistic practice space - part of the model. We are currently extending the model to include the C, E, and also the “image-generation space”, the problem-solving space involved in the image production activity of the artist (itself part of A, but at a finer resolution than the rules presented here).

ACE is a high-level model, close to a ‘social band’ level (see Newell, 1990), model of cognition; this is why we chose to model a vast domain with relatively ‘few’, high-level, rules. Up to now, we have extracted from the interviews, observations and field notes the equivalent of about 200 rules; of these, around 60 rules have been implemented in ACE. A related model, for example, Schunn and Anderson’s model of scientific discovery processes, implemented 116 rules. Anderson and Lebiere (1998) make the distinction between *declarative knowledge* (i.e., ‘chunks’ of information)

and *procedural knowledge* (i.e., rules); whereas there can be millions of pieces of information known to a person, there is a much lesser number of rules needed or available to process this information. Anderson evaluates this number to be in the order of 10,000 to encompass everything a human being does; in restricted domains of expertise, like certain aspects of scientific discovery (or artistic creativity), there may be much less (e.g., hundreds or a few thousands).

Based on these and other considerations, we believe that we are not too remote from the completion of this portion of the project. Further work will involve expanding and validating the model. This will be done by working in collaboration with the artist in the manner usually done when building knowledge-based systems in AI; we are, in fact, considering the artist as an expert and working with her to produce a model reflecting her practice. Further work will also involve testing this model, testing various predictions made by the model, comparing these with the actual behavior of the artist. Testing the model will also involve the kind of experimentation we have done with the model in this paper, but on a larger scale.

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### ***References***

- Anderson, J. R. (1976). *Language, memory, and thought*. Hillsdale, NJ: Erlbaum.
- Anderson, J. R., & Lebiere, C. (Eds.) (1998). *The atomic components of thought*. Mahwah, NJ: Erlbaum.
- Bellavance, G., Bernier, L., & Laplante, B. (2001). *Les conditions de pratique des artistes en arts visuels: Rapport d'enquête, phase 1*. Montréal, Canada: INRS Urbanisation, culture et société.
- Chomsky, N. (1957). *Syntactic structures*. The Hague : Mouton.
- Clancey, W. J. (2001). Field science ethnography: Methods for systematic observation on an expedition. *Field Methods*, 13, 223-243.
- Jackson, P. (1999). *Introduction to expert systems* (3rd ed.). Harlow, England: Addison-Wesley.
- Klahr, D. (2000). *Exploring science: The cognition and development of discovery processes*. Cambridge, MA: MIT Press.
- Klahr, D., & Dunbar, K. (1988). Dual space search in scientific reasoning. *Cognitive Science*, 12, 1-55.
- Klahr, D., & Simon, H. A. (1999). Studies of scientific discovery: Complementary approaches and convergent findings. *Psychological Bulletin*, 125, 524-543.
- Kulkarni, D., & Simon, H. A. (1988). The processes of scientific discovery: The strategy of experimentation. *Cognitive Science*, 12, 139-175.

- Langley, P., Simon, H. A., Bradshaw, G. L., & Zytkow, J. M. (1987). *Scientific discovery: Computational explorations of the creative processes*. Cambridge, MA: MIT Press.
- Leclerc, J., & Gosselin, F. (2003). [Interviews with Isabelle Hayeur]. Unpublished raw data.
- Leclerc, J., & Gosselin, F. (2004). Processes of artistic creativity: The case of Isabelle Hayeur. In K. Forbus, D. Gentner, & T. Regier (Eds.), *Proceedings of the Twenty-Sixth Annual Conference of the Cognitive Science Society* (pp. 801-806). Mahwah, NJ: Erlbaum.
- Nersessian, N. J. (2004). Interpreting scientific and engineering practices: Integrating the cognitive, social, and cultural dimensions. In M. Gorman, R. Tweney, D. Gooding, & A. Kincannon (Eds.), *New directions in scientific and technical thinking* (pp. 17-56). Mahwah, NJ: Erlbaum.
- Newell, A. (1990). *Unified theories of cognition*. Cambridge, MA: Harvard University Press.
- Newell, A., & Simon, H. A. (1965). Limitations of the current stock of ideas for problem solving. In A. Kent & O. Taulbee (Eds.), *Conference on electronic information handling* (pp. 195-208). Washington, DC: Spartan Books.
- Newell, A., & Simon, H. A. (1972). *Human problem solving*. Englewood Cliffs, NJ: Prentice-Hall.
- Post, E. L. (1943). Formal reductions of the general combinatorial decision problem. *American Journal of Mathematics*, 65, 197-215.
- Schunn, C. D., & Anderson, J. R. (1998). Scientific discovery. In J. R. Anderson & C. Lebiere (Eds.), *The atomic components of thought* (pp. 385-427). Mahwah, NJ: Erlbaum.
- Weisberg, R. W. (1993). *Creativity: Beyond the myth of genius*. New York: Freeman.