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Cognitive events in a problem-solving task: a qualitative method for investigating interactivity in the 17 Animals problem

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ABSTRACT
Outside the cognitive psychologist's laboratory, problem-solving is an activity that takes place in a rich web of interactions involving people and artefacts. This interactivity is constituted by fine-grained action–perception cycles, and it allows a reasoner's comprehension of the problem to emerge from a coalition of internal and external resources. Taking an ecological approach to problem-solving, this paper introduces a qualitative method, Cognitive Event Analysis, for studying the fine-grained interactivity between a problem-solving agent and his/her environment. To demonstrate the potential of this method, it is used to study a single subject solving the so-called 17 Animals problem using a material model. The fine-grained procedure allows tracking the solution to a serendipity that was brought about because of the participant's aesthetic considerations and a change in her perceptual figure-ground configuration. While a qualitative single-case method cannot prove specific models of problem-solving, it questions prevalent mentalist models, and it generates new hypotheses on insight problem-solving, because it allows the researcher to attend to outliers and to variability on a fast and fine-grained between-measurement timescale.

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Introduction

In recent years, the field of problem-solving psychology has witnessed the upsurge of a theoretical alternative to the traditionally dominant model of cognitive science. In the traditional model, "an intelligent agent—be it animal, human, robot or space alien—can be modelled in a precise way by specifying its representations, its basic processes and its control structure" (Ohlsson, 2011, p. 37). According to this assumption, "to explain a behavior (or a regularity therein) is to specify a *program*, that is, a control structure, a set of processes and a stock of representations, that generates this behavior (or regularity)" (Ohlsson, 2011, p. 37). A cognitive psychology along these lines is named *mentalism*—"if it needs any other name than common sense," as Ohlsson (2011, p. 28) confidently adds. From this mentalist point of view, "mind is the proper subject matter of psychology" (Ohlsson, 2011, p. 25), and this "mind is a system" (Ohlsson, 2011, p. 28) that "consists of *representations*" (Ohlsson, 2011, p. 29). Gregory (1998, p. 1683) sums up this foundational assumption as follows: "the key notion of cognitive psychology since the collapse of behaviourism is that we build brain descriptions of the world of objects, which give perception and intelligent behaviour."

The alternative perspective strives "to understand how organisms make their way in the world, not how a world is made inside of organisms" (Reed, 1996, p. 11). "Making one's way in the world" is a matter of upholding homeostasis through the regulation of the organism–environment relations: "organisms are primarily sensitive to, and act so as to select and maintain desired values of, salient organism-environment relationships" (Anderson, 2014, p. 136). Given the emphasis on embodiment, ecological embeddedness and agency, the alternative has been named embodied cognition, embedded cognition, enacted cognition and ecological cognition (for an overview, see Robbins & Aydede, 2009). In line with a more general ecological approach to cognition, this paper argues for, and contributes to such an ecological approach to problem-solving, that is, the study of how cognitive

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agents reach a (more or less well-defined) goal, given some opening condition.

Traditionally, two broad classes of problems have been the focus of research on problem-solving. The first are transformation or analytic problems. For those, given the initial state specified in the problem presentation, participants transform the problem through a series of intermediate states with the repeated application of simple operators—the Tower of Hanoi (Anzai & Simon, 1979) and river-crossing problems (Knowles & Delaney, 2005) are examples of such problems. Cognitive psychologists and computer scientists are primarily interested in the processes that underpin the search for and selection of moves that trace a path of possible legal intermediate states in a well-delineated problem space. In the second class, we find so-called insight problems: for those, there are no obvious intermediate stages—nor obvious operators that can produce those stages—that map a path from initial state to goal state. In fact, such problems are designed to create an initial interpretation that results in an impasse (of sorts). These problems often take the form of riddles, for example: How can you throw a ping pong ball in such a manner that it comes to a complete stop and reverses direction without coming into contact with a physical surface (cf. Ansburg & Dominowski, 2000)? A key misleading assumption—namely a horizontal throwing motion—must be abandoned in favour of a new interpretation: the throwing motion is vertical.

While analytic and heuristic search processes prominently figure in models of transformation problem-solving (e.g., Simon & Reed, 1976), their role in insight problem-solving has been the matter of debate (Gilhooly & Fioratou, 2009; Ohlsson, 2011; Weisberg, 2015). Insight may well proceed once a problem representation has been restructured (i.e., the initial interpretation of the problem is shed for a different one), but the debate focuses on whether the restructuring is evinced through conscious analyses or the sub conscious redistribution of associative strengths among semantic elements. Fleck and Weisberg (2013) have offered an integrative framework wherein insight problem-solving can proceed from analytic and sub conscious processes; while such a synthesis does justice to a range of theoretical perspectives on insight problem-solving, it remains firmly mentalist and commits unconditionally to methodological individualism—the explanations offered for creativity and problem-solving performance only focus on processes within the individual.

Given this state of affairs, what would a more ecological take on problem-solving look like? An interesting avenue of insight problem-solving research explores the role of cues and hints (Ball & Litchfield, 2013; Kirsh, 2009). For instance, using Duncker's (1945) radiation problem,[1] participants are more likely to formulate a divide-and-conquer solution if relevant features of the diagrammatic representation—such as the healthy tissue perimeter—are animated to attract attention (Grant & Spivey, 2003, Experiment 2). Insight is also more likely if participants follow the gaze of a successful participant as he or she scans the tumour and surrounding healthy tissue, that is, observes someone's saccades that jump from the tumour to different points along and outside the healthy tissue perimeter (Litchfield & Ball, 2011). Perhaps more interesting is the finding that participants encouraged to engage in similar eye movements (movements that jump from the tumour to cardinal points along the periphery) while tracking numbers superimposed on a diagrammatic representation of the problem are more likely to discover the solution (Thomas & Lleras, 2007).

This strand of research has significantly advanced our understanding of how cues and hints can attract attention and guide the generation and evaluation of ideas (Kirsh, 2009). However, in the research on Duncker's radiation problem, participants work in a fixed environment with a static problem presentation in the shape of the diagram illustrating the tumour and surrounding healthy tissue. In such a lab environment, the nature, timing and frequency of cues are experimentally engineered, and hence participants cannot scaffold their thinking by modifying the problem presentation or any artefacts that represent the problem. Accordingly, while the cueing approach has demonstrated the importance of what the environment "offers the [agent], what it provides or furnishes, either for good or ill" (Gibson, 1979, p. 127), we worry that this line of research does not pay sufficient attention to another equally important dimension of the ecological embeddedness of cognitive agents. Thus, when an agent acts

[1]An inoperable tumour can be destroyed with a laser beam of a sufficient intensity, but at that intensity, the laser would also destroy healthy tissue. The 'solution' involves converging multiple lower intensity laser beams onto the tumour.

in the world, she/he changes the world, and perceiving these changes reveals new affordances for action. In the context of problem-solving, an ecologically embedded agent acts in ways that modify the problem presentation. Hence, real-life problem-solving, we suggest, depend on the tightly coupled action–perception cycles through which a cognitive agent explores and exploits his/her environment.

This interplay between action and perception in the dynamics between cognitive agents and their environment has in recent years been studied under the rubric of *interactivity* (Cowley & Nash, 2013; Cowley & Vallée-Tourangeau, 2013; Guthrie, Vallée-Tourangeau, Vallée-Tourangeau, & Howard, 2015; Kirsh, 2015; Steffensen, 2013; Vallée-Tourangeau, 2012, 2013; Vallée-Tourangeau, Euden, & Hearn, 2011; Vallée-Tourangeau & Payton, 2008; Vallée-Tourangeau & Vallée-Tourangeau, 2014; Villejoubert & Vallée-Tourangeau, 2011). While the concept has its roots in human–computer interaction (Kirsh, 1997), this recent literature on interactivity has shown that the fine-grained exchanges between a human agent and a computer generalise to many, if not all, aspects of human cognition. Following this generalisation, Steffensen (2013, p. 196) has defined interactivity as "sense-saturated coordination that contributes to human action." The definition pivots on coordination, because the organism, in order to stay alive, is bound to uphold far-from-equilibrium homeostasis (i.e., the ability to maintain a steady state in a dynamic context) through regulating the organism–environment relation. This regulation amounts to the coordination of material, energetic and informational processes between organism and environment. However, human beings mesh real-time coordination with sociocultural knowledge: here-and-now coordination is constrained by values and experiences ascribed to the here-and-now. In short, coordination is saturated with sense. Further, such sense-saturated coordination has an ecological function: the human access to sociocultural resources enable the species to perform actions and achieve results that were otherwise out of reach.

Thus defined, interactivity weaves a contingent spatio-temporal trajectory, constituted by the action–perception dynamics between agent and environment. The agent and the environment metamorphose into a seamless cognitive ecosystem that follows a unique cognitive trajectory, that is, a dynamical and nonlinear path that the system creates as it achieves a given cognitive result. Crucially, as the agent acts along the cognitive trajectory, the problem presentation is transformed, and that transformation creates a shifting stream of problem configurations and perceptual feedback. While these dynamics may appear as a kind of "unintentional self-cueing" (afforded by the agent's actions), we would argue that such an interpretation strengthens the implicit commitment to methodological individualism. Rather, we trace the emergent cues to the self-organising dynamics of the cognitive ecosystem: the problem configuration at one point affords, or cues, a certain course of actions, which may create an inflection point in the problem-solving trajectory. What may count as a pertinent cue for a reasoner is thus neither independent of the reasoner, nor of the spatio-temporal coordinates at which the problem is configured in a certain way. In other words, what makes a cue an effective one, one that turns into an "interesting idea" (Kirsh, 2009), is not defined in terms of its physical features independent of the reasoner's history and his/her problem-solving efforts up to that point.

An interactivity-based view on problem-solving offers a new theoretical perspective on a host of cognitive questions. Equally important, though, it points to new methodological avenues in the study of problem-solving. Since interactivity weaves a spatio-temporal trajectory, along which agents act and perceive and environmental structures cue and afford, interactivity can be observed, recorded, analysed and scrutinised. Accordingly, fine-grained observations of interactivity enable the study of cognition in terms of events where cognitive ecosystems achieve cognitive results. This methodological dimension comes to the fore in the following two sections where we first present *Cognitive Event Analysis* (CEA), an interactivity-based method for studying cognition, and second demonstrate the kinds of insights it engenders when applied to a participant solving the 17 Animals problem. Finally, in the discussion, we reflect on the insights generated by such a single-case study, on the methodological aspects of CEA, and, finally, how an interactivity-based approach contributes to an ecological understanding of problem-solving, cognition and representations.

Cognitive Event Analysis

In this section, we introduce CEA as a way of approaching the interactivity of problem-solving.

CEA is rooted in cognitive anthropology and distributed cognition (Hutchins, 1995, 2003, 2014), and closely connected with the so-called Distributed Language Approach (Cowley, 2007a, 2009, 2011, 2012; Cowley & Madsen, 2014; Steffensen, 2015). This dual origin is reflected in the method: on the one hand, it has inherited Hutchins's commitment to study distributed cognition, and on the other hand, it builds on how linguists and interaction analysts meticulously study interactional particulars. Combining these two lineages, CEA studies cognitive ecosystems via a microscopic focus on the bodily and inter-bodily dynamics of gesture, prosody, movements, etc. CEA has both been applied to naturalistic and experimental data; in the former category, one finds Steffensen's (2013) study of problem-solving in an office setting, Pedersen's (2015) study of the cognitive ecology in an emergency department, and Pedersen and Steffensen's (2014) single-case study of faecal colour categorisation. In the latter category, Cowley and Nash (2013) conducted a study of the river-crossing problem, and Steffensen (in press) has reviewed the use of CEA across settings. Further, the method is closely related to Goodwin's application of interactional methods to study cognitive phenomena, in particular colour classification and learning (Goodwin, 1994, 1997, 2000a, 2000b, 2013; Goodwin & Goodwin, 1996; Koschmann, LeBaron, Goodwin, & Feltovich, 2011), and Cowley's work on how cognition is constrained by language, prosody and inter-bodily dynamics (Cowley, 1997a, 1997b, 2004a, 2004b, 2006, 2007b, 2014; Cowley & MacDorman, 2006). Based on fine-grained observations of interactivity, CEA studies cognitive ecosystems by investigating the system's cognitive trajectory, that is, the dynamical and nonlinear path that the system creates as it achieves a given cognitive result. CEA particularly focuses on phase transitions along this trajectory. A given configuration of transition points constitute an *event* in Chemero's (2000b, p. 39) sense, that is, a change "in the layout of affordances of the animal-environment system." According to Chemero's definition, an event is a change in the relation between agent and environment, where an agent acts on her environment, perceives the consequences of that action, and then enacts another change in the environment. Obviously, the perceived consequences may differ widely from the intended consequences. A single transition point (for instance, the overcoming of an impasse in an insight problem task) may be pivotal for making this event happen. Such transition points are in CEA termed *event pivots* (Steffensen, 2013). An event pivot is thus functionally defined as a transition point which is a *conditio sine qua non* for identifying a segment of a cognitive trajectory as a specific (kind of) event. As a parallel, if one understands a goal-scoring foray in soccer as an event, the various passes and dribbles may all be part of the event's trajectory, but it is the last header which defines the event as "a successful foray." Hence, that header is the event pivot, enabled by previous actions by other players.

Chemero's event concept is crucial for understanding the ecological embeddedness of living agents' cognitive trajectories. However, as observed by Di Paolo (2005, p. 442), it is necessary to distinguish between changes *undergone* by the agent from changes *done* by the agent. In the latter case, the cognitive event is an achievement: it is the *result* of the agent's behaviour (whether it matches the agent's intention or not). Acknowledging the fact, that cognitive trajectories are *animated* by agents in real time, allows us to understand a cognitive result (e.g., when the subject in a problem-solving experiment solves the task) as enabled by preceding behaviour. This focus on results gives rise to an important methodological principle in CEA: "the research should start from the determination of the results of behaviour and lead to the necessary constituents of the living system determining the achievement of these results" (2009 Järvilehto, 2009, p. 118). In other words, in contrast to living agents who move forwards along a cognitive trajectory, we work backwards along the same trajectory, from the cognitive result to its constituents. Paraphrasing Reed, we can say that just as cognition is all about an organism finding its way in the world, so is the cognitive result the particular way found by the organism.

The focus on cognitive results implies that the proper unit of analysis is not necessarily the individual agent. Thus, since a large class of cognitive results are not brought forth by individuals, but by teams and systems relying on technological means, the unit of analysis is the *distributed cognitive system*, which can be defined as "a system that can dynamically configure itself to bring subsystems into coordination to accomplish various functions" (Hollan, Hutchins, & Kirsh, 2000, p. 176). Having identified a cognitive result, one can in turn identify the constituents of the particular "distributed cognitive system […] that produces cognitive outputs, just as an agricultural system yields agricultural products" (Giere, 2007, p. 318).[2]

To summarise the basic assumptions of CEA, a self-organising *distributed cognitive system*, animated by at least one living agent, creates a *cognitive trajectory*, as it moves towards a *cognitive result*. Achieving a cognitive result is a *cognitive event* which depends on a specific configuration of *transition points* along the cognitive trajectory. The most salient transition points function as *event pivots*. In order to understand the cognitive system and the cognitive trajectory, we thus need to take a starting point in cognitive results and event pivots.

The methodological procedure in CEA

The data material for a CEA is a video record, not necessarily based on naturalistic data: as one of the few qualitative methods in cognitive science (Ormerod & Ball, 2010), CEA can in principle yield equally good results when applied to experimental data as long as the experimental procedure is designed such that participants can interact with a physically modifiable problem presentation. The analytical procedure consists of five consecutive steps based on the video record, as outlined in Table 1 (and exemplified with the analysis presented later in this paper).[3]

In the *cognitive event identification*, one identifies a single event–be it an instance of problem-solving, decision-making, change of attention, or the like–in the data set and selects it for further scrutiny. In identifying an event, one can either rely on *external* criteria (i.e., pre-formed scientific criteria, for instance when problem-solving researchers see a behavioural pattern as an impasse), or on *internal* criteria (i.e., performed participant-derived criteria, for instance if a subject enacts an *aha!* moment, whether she actually has overcome the impasse or not).

In the second step the *event pivot identification*, one identifies what in the first place prompted the event identification. Thus, if one has identified a problem-solving event, the very moment where the subject actually solves the problem is an obvious event pivot. Likewise, if the problem is an insight problem, overcoming the impasse may be an event pivot. Again, the soccer metaphor is useful: if the event we want to study is a goal, the pivot is the header or shot that makes the ball cross the goal line, but we could equally well decide to study how the defence organises an offside trap, defining the referee decision as the event pivot. When an event pivot is identified in the data material, the cognitive trajectory acquires a *gradient* structure: if the pivot is seen as a temporal "hotspot," there will be a "warm" *peri-pivotal zone* which is crucial for the course of the cognitive trajectory.

After the event pivot identification follows a data annotation procedure. When annotating video data, one needs to consider two interdependent questions: how does one select annotation categories? And how dense should the annotation be? The first question can be further differentiated. To begin, one needs to decide on the *domains* to be annotated: minimally, given the cognitive focus on how agents achieve cognitive results, it is compulsory to annotate participant behaviour and various functionally defined features of the cognitive task (e.g., the moves made in the river-crossing problem or the position of the disks in the Tower of Hanoi Problem). Further, one may also annotate relevant circumstantial events (e.g., experimenter probing and cueing, or by-passer activity), and it is likewise possible to embed physiological measures (heart rate, galvanic skin response, etc.) and performance measures (reaction time, etc.) in the annotation. For some domains, in particular participant behaviour, the complexity is so vast, that one needs to define a hierarchy of *levels*. Imagine a person having lunch: while on an overall level, this can be annotated as a single *activity* ("having lunch"), it is likely to be composed by several sequential *actions*: taking a bite of the bread, drinking a sip of water, taking a bite of the salad, etc. Each of these actions, in turn, consists of sequential or synchronous *acts*; thus, the manual conduct differs immensely between taking a bite of the bread (holding the bread in one hand) and taking a bite of the salad (using a fork to catch a mouthful). Participant behaviour also allows for another kind of differentiation: while the action of taking a bite of the bread depends on the coordination of several movements (manual movements, turning the head and opening/closing the mouth), the vast number of acts call for a distinguishing between different modalities (e.g., utterances, gestures, manual movements, posture, gaze, handling of objects). The

[2]The distributed cognitive system is further discussed in Steffensen (2013, pp. 201–203).
[3]Steffensen (2013, p. 200) only mentions the first and the fifth phase, while the other three are implicit in his analysis.

Table 1. CEA: five steps.

Procedure	Description	Example from the 17A case study
Cognitive event identification	Identification of a cognitive event, typically an organism-initiated change in the layout of affordances in the organism–environment system, in a video record of a naturalistic or experimental data set. The event may be defined from an observer's or a participant's point of view	The behavioural process through which P27 comes to see the 17A problem as a set theoretical problem by overcoming the impasse of seeing the problem as an arithmetic problem
Event pivot identification	Identification of the critical transition point(s) without which the cognitive event would not be this specific kind of event	The point in time where P27 observes that a pen overlap is an affordance for solving the 17A problem
Data annotation	Segmentation and annotation of (peri-pivotal) video sequence, using multiple domains and levels, with or without a constrained set of annotation values	The 13 levels listed in Table 2; the 1,291 annotations of P27's cognitive trajectory
Cognitive trajectory segmentation	Segmentation of video sequence into *functionally* and/or *behaviourally* defined phases	The seven phases of P27's trajectory: preparation, Tryout 1, impasse, breakthrough Tryout 2, validation, and expiry
Cognitive trajectory analysis	Analysis of how specific segments of the cognitive trajectory (particularly the event pivot) are enabled by preceding segment and behavioural tendencies	P27's observation that the serendipitous overlap of pens—caused by her drive to organise the workspace more aesthetically—may be part of the solution

Table 2. Coding categories.

Coding category (domain and level)		Nature of coding category	# of annotations for P27
Participant behaviour			
	Activity	Constrained category: activity types (Table 3)	22
	Activity object	Constrained category: observed objects	22
	Action	Constrained category: action types (Table 4)	147
	Action object	Constrained category: observed objects	147
	Left Hand Act	Unconstrained category: act + object	318
	Right-Hand Act	Unconstrained category: act + object	374
Zebra distribution			
	Hand-held	Constrained category: number of zebras, 0–17	123
	Zebra pile	Constrained category: number of zebras, 0–17	32
	Pen 1	Constrained category: number of zebras, 0–17	25
	Pen 2	Constrained category: number of zebras, 0–17	27
	Pen 3	Constrained category: number of zebras, 0–17	23
	Pen 4	Constrained category: number of zebras, 0–17	25
Pen structure			
	Pen structure	Binary category: the absence/presence of overlap; indication of where the overlap is	6
Total number of annotations			1,291

coding categories (3 domains and 13 levels) in our case study are shown in Table 2.

For each of the annotation categories, there will be a number of descriptors. In most cases, it is possible to establish a constrained categorisation so a domain or level has a limited number of possible descriptors. For instance, in this paper, we operate with 7 activity categories (cf. Table 3) and 17 action categories (cf. Table 4). Likewise, our two functional domains, zebra distribution and pen structure, are constrained as the annotation values are numerical. However, when it comes to the annotation of acts within different modalities, most categories will be open-ended. For instance, the annotation of utterances (i.e., a transcription) must be as diverse as the utterances themselves, and what people do with their hands can hardly be captured through an exhaustive list of acts.[4]

The second question is how dense the annotation should be. While there are no principled criteria for the annotation granularity, the analysis requires a rather fine-grained annotation level. For a comparison, Anzai and Simon (1979) "microscopic account" of a single agent solving the Tower of Hanoi task relies on 232 annotations (224 "protocol statements" interspersed by 8 experimenter statements) for a 90-min session. This gives an annotation density of 0.043 annotations per second, and since all annotations are on the same level (i.e., there is no overlapping annotations) their median annotation length is

[4]Gaze is an exception, as it is often possible to define a constrained list of gaze directions for a participant.

Table 3. Activity categories.

Activity	Object of activity	Definition
Adjust	Pen, zebras	Minor modification of an object's shape, orientation or position
Arrange	PC, pen, zebras, zebra pile	Modification of the position of an object (or a cluster of objects), in relation to the workspace or vis-à-vis other objects
Count	Zebra, finger	Enumeration of concrete or virtual objects
Fold	Pen, PC	Selection and transformation of PC into enclosure (pen)
Observe	Workspace	Non-invasive orientation to objects (or clusters of objects)
Read	Paper	Orientation to a semiotic representation of task
Relocate	Zebra	Modification of the position of an object (or a cluster of objects) which constitutes a task-defined change

23.28 s. In contrast, the analysis in this paper builds on 1,291 annotations, spread over 13 levels, for a 10-min session. This gives an annotation density on 2.152 annotations per second, which is a granularity 50 times as high as Anzai and Simon's. Our median annotation length is 6.04 s (calculated as the length of the session times number of annotation levels, divided by number of annotations), spanning from a median annotation length of 1.60 s on the most fine-grained level (right-hand movements) to 100 s on the most coarse-grained level (pen overlaps). However, annotation density may vary across the data set: while participant behaviour needs to be mapped very precisely when it comes to the specific dynamics that bring about an event pivot or a phase transition, it may be less relevant to document, say, a participant's hand movements, as she/he reads the task. It is, however, not always the case that one knows what one needs, and it is thus not always possible to define beforehand where one needs a high annotation density. It might therefore be necessary to elaborate and refine the annotation during the analysis.

Based on patterns in the annotations, one can now perform a segmentation of the cognitive trajectory, using changes in behavioural patterns as an indicator of transition points on the cognitive trajectory. If a specific configuration of annotation values only appears in a given segment of a cognitive trajectory, the start and end points of this pattern are two transition points along the cognitive trajectory. This procedure is not unlike that of Anzai and Simon (1979), who divide their protocol statements into four episodes, "corresponding to the subject's four solution attempts" (Anzai & Simon, 1979, p. 126). This episodic segmentation depends on the observation of transition points (*avant la lettre*), for instance when the subject says "If I go on like this, I won't be able to do it, so I'll start over again" (Anzai & Simon, 1979, p. 138).

CEA's final procedure is an interpretive procedure aimed at answering the question: *what were the enabling conditions for the cognitive result, and how was it achieved by the cognitive system animated by one or more living agents?* An answer to this question emerges when the event pivot is interpreted as the result of immediately preceding events that in turn are traced to events preceding these. Moving backwards along the cognitive trajectory, using the trajectory segmentation as a heuristic tool, one thus establishes one or more explanatory chains. This approach can be supplemented by tracing specific peri-pivotal actions to general behavioural patterns along the observed trajectory. While such a *behavioural tendency* may be fully unrelated to the cognitive result, iteratively occurring actions indicate an agent's animating force, which she may exploit to achieve a cognitive result. Having outlined the basic assumptions and analytical procedures of CEA, in the remainder of the paper, we demonstrate its value for problem-solving psychology.

Method

In this study, we analyse a single successful solver in a recent study on the 17 Animals problem (further discussed by Vallée-Tourangeau, Steffensen, Vallée-Tourangeau, & Makri, 2015). By tracking a specific cognitive trajectory, the analysis shows what enabled the participant to reach a solution.

Participant

The participant is P27, a 24-year-old right-handed female. A Kingston University undergraduate, she received course credit for her participation. P27 was randomly selected among the 6 successful solvers in the sample of 50 participants reported in Vallée-Tourangeau et al. (2015).

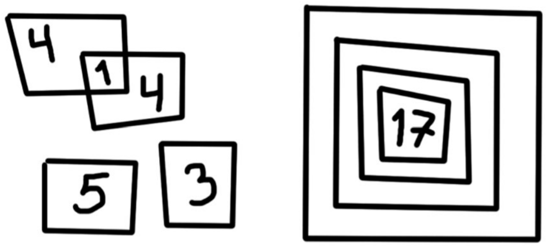

Figure 1. Two set theoretical solutions to 17A. An odd number of zebras must be placed in one or more overlapping areas.

Task

Like all 50 participants in the study, P27 was presented with the *17 Animals* problem: "Describe how to put 17 animals in 4 enclosures in such a way that there is an odd number of animals in each enclosure." 17A is disguised as an arithmetic problem, and as such, it is unsolvable since the sum of four odd numbers is an even number. To solve the problem, participants must see it as a set theoretical problem, where one or more elements can be part of more than one set. Under this condition, solving the problem is clearly unproblematic; possible solutions are shown in Figure 1.

Materials

Like all other participants under this condition, P27 was presented with a pile of pipe cleaners (henceforth, PCs) of varying length (app. 10–15 cm long), some of which are being reused from prior participants, as well as 17 figurines shaped like zebras (app. 3 × 2 × 1.5 cm; Figure 2). The PCs were material artefacts with which enclosures could be constructed, and zebras were stand-ins for the animals in the task formulation. Given the artefacts employed in this study, we use the terms *zebra* and *pen* as referents to the general categories of *animals* and *enclosures* in the remainder of this paper.

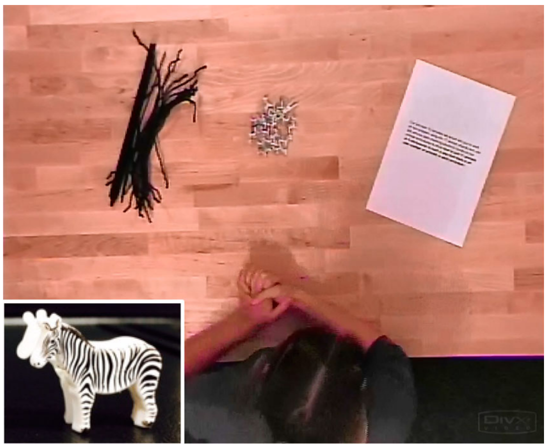

Figure 2. The layout of the experiment. From left to right, the participant has access to a pile of PCs, a pile of 17 zebra figures and a written task instruction. Bottom left, an enlarged picture of a single zebra figure (a paper clip) is inserted.

Procedure

The participants were tested individually. They were initially given a pen and piece of paper on which to sketch a solution for the 17A problem. Participants were given 3 min to do so. This initial presentation phase was designed to measure the participants' comprehension of the problem and to determine whether they conceived the problem in arithmetic terms. All did. After an interval of approximately 20 min—during which they completed a Working Memory assessment (Unsworth, Heitz, Schrock, & Engle, 2005), a Need for Cognition assessment (Cacioppo, Petty, & Feng Kao, 1984) and an Actively Open-minded Thinking assessment (Haran, Ritov, & Mellers, 2013)—participants were sat at a large rectangular work surface with PCs, 17 zebra figures and the following sheet of instructions:

> For the next 10 minutes we would like you to work on the problem using the 17 animal objects and the various pipe cleaners to construct the animal enclosures to show how to put 17 animals in 4 enclosures in such a way that there is an odd number of animals in each enclosure.

Cameras were mounted on the ceiling above the workspace and recorded the session.

Video records were coded using ELAN 4.6.2 (http://tla.mpi.nl/tools/tla-tools/elan/), developed by the Max-Planck-Institute for Psycholinguistics (Wittenburg, Brugman, Russel, Klassmann, & Sloetjes, 2006). The coding process pertained to three domains (cf. Table 2): participant behaviour, zebra distribution and pen structure. *Participant behaviour* was coded on three hierarchically embedded levels: activity, action and acts. *Zebra distribution* is a constrained category, in that the total number of zebras to distribute is 17. A zebra can either be in a participant's hand (or held by both hands), or on the table. In the latter case, they can either be in the zebra pile or in a pen. Accordingly, we coded for number of zebras (0–17) in six spatially

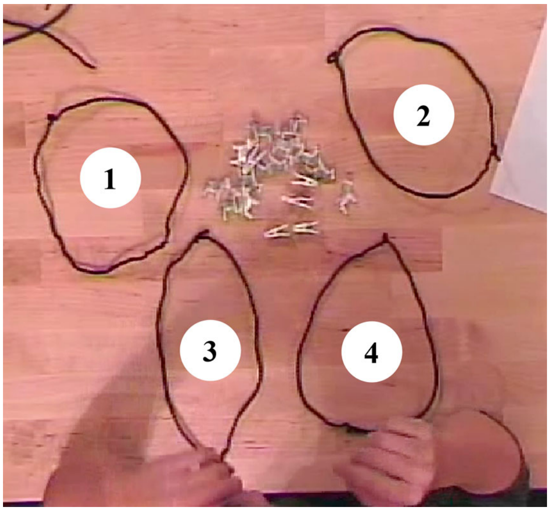

Figure 3. Default pen structure. Four pens are arranged in a 2 times two matrix. The numbers refer to the numbering of pens in this paper which for convenience corresponds to the reading direction in texts written in Latin letters, that is, from left to right, and from top to bottom. Numbers assigned to pens do not change, even if the order of pens varies during the task.

defined categories: the participants' hands, the zebra pile and Pens 1–4. The sum of zebras in these six categories is 17. The third coding domain, *pen structure*, refers to changes in the spatial layout of pens. The default layout for all participants is to place four pens next to each other, usually in a 2 times two matrix (as illustrated in Figure 3). This default pen structure is not coded, only deviations from the default, that is, when one or more overlaps between one or more pens are present.

The criterion for coding pen structure and zebra position is functional, as these two properties are necessary for determining whether a cognitive result has been achieved in 17A: only if an overlap is present can a solution be achieved, and only when a specific distribution of zebras is present, is a solution achieved.

Table 2 gives an overview of the coding categories in the three domains, indicating the total number of coding annotations for the participant analysed in this paper. Table 3 lists the coding categories for activities (and activity objects) in the coding of participant behaviour. Likewise, Table 4 lists the coding categories for actions (and action objects) in the coding of participant behaviour.

A cognitive event in 17A: the case of P27

Approaching the cognitive trajectory

Since 17A is designed to deceive participants to think of the problem as an arithmetic one, the key to understand cognitive trajectories in this particular task is to identify how participants realise that they are dealing with a set theoretical problem. From the point of view of CEA, this realisation is the primary event pivot. In the problem-solving literature, this is characterised as an insight that reflects a restructuring or representational change, either the product of unconscious processes according to proponents of the *Special Process* view (Davidson, 1995; Ohlsson, 1992) or the product of conscious analytic processes according to proponents of the *Business as Usual* view (Seifert, Meyer, Davidson, Patalano, & Yaniv, 1995). Irrespective of theoretical explanation of such changes in the cognitive trajectory, it is evident that "something happens," and that this something paves the way for a solution. We refer to this something as the *breakthrough*, here defined as a *reconfiguration of the distributed cognitive system which enables the system to achieve an acceptable solution to the problem at hand*. Whether a breakthrough depends on an insight or an analytical procedure cannot be a priori determined, because the specific patterns of interactivity that constitute such insights and analytical procedures are self-organised and open-ended.

Having defined an event pivot, we can likewise define a *secondary event pivot*. Following Murray and Byrne's (2013) distinction between *single-step* and *multiple-step* problems, 17A is a multiple-step problem in that the realisation that the problem is a set theoretical problem is not in itself a sufficient solution. Within this more adequate understanding of the problem, participants still need to achieve a correct (set theoretical) solution. We define this point at the cognitive trajectory as the secondary event pivot.[5]

Building on the annotations described in detail in the "methods/procedures" section earlier, we identify different behavioural patterns along P27's cognitive trajectory. Accordingly, we can segment it into seven phases, as indicated in Table 5.

P27 spends the first 1:52 min preparing the task. She reads the instruction and folds four pens out

[5]These two event pivots also underlie the distinction between solvers, partial solvers and non-solvers in Vallée-Tourangeau et al. (2015): a solver is a participant who achieves both the primary and the secondary event pivot; a partial solver reaches the primary event pivot, but not the secondary; and a non-solver misses both pivots. Partial solvers enact a conceptual restructuring at the primary event pivot without reaching a solution at the secondary event pivot, because they do not see how the set theoretical problem is to be solved.

Table 4. Action categories.

Action	Object(s) of action	Definition
Abort	Movement	Abrupt disruption of movement during a relocation of an object, and subsequent return to the object's first position
Adjust	Pen, zebra	Minor modification of an object's shape, orientation or position
Arrange	PC, pen, zebras, zebra pile	Modification of the position of an object (or a cluster of objects)
Close	PC	Joining of a single PC (or structure of PCs) in order to create an enclosure (pen)
Connect	PC	Joining of two or more PCs into one structure
Correct	Glasses	Minor modification of the position of a task-unrelated object
Count	Zebras, fingers	Enumeration of concrete or virtual objects
Inhibit	Move	Abrupt disruption of movement during a participant's reaching out for an object
Observe	Workspace	Non-invasive orientation to objects (or clusters of objects)
Place	Zebra	Modification of the position of an object (or a cluster of objects) which constitutes a task-defined change, and where the object's initial position is the zebra pile and the final position a pen
Read	Paper	Orientation to a semiotic representation of task
Relocate	Zebra	Modification of the position of an object (or a cluster of objects) which constitutes a task-defined change
Search	Workspace	Non-invasive orientation to objects (or clusters of objects) accompanied by multiple abrupt disruption of movements (abortions)
Take	PC	Retrieval of one or more objects from a larger grouping of similar objects
Touch	Face Hands	Establishing contact between hand(s) and task-unrelated objects, including parts of the participants body
Turn	Paper	Modification of an object's orientation on a vertical or horizontal axis
Withdraw	Hands Body	Postural change that entails an increase in distance between participant and workspace

of the available PCs. The second phase, *Tryout 1*, is the longest in the experiment: P27 engages in a single activity type (*relocating zebras*) for 3:47 min. In this phase, P27's working assumption is that she is solving an arithmetic problem. P27 first spends 24.8 s on distributing the zebras from the zebra pile into the four pens, followed by 3:22 min of shuffling the zebras from one pen to another. Having distributed all zebras and attempted to reach an arithmetic solution, P27 gives up and is evidently stuck. Thus, in a 26 s *impasse* phase, she relocates the zebras back into a pile at the middle of the

Table 5. P27's cognitive trajectory in seven phases.

Cognitive trajectory	Time	Duration	Functional definitions	Behavioural definitions
Preparation	−365,000 to −252,800	112,200 ms = 1:52 min	Reads task and folds four pens	Read + paper Fold + pen Arrange + PC Arrange + Pens 1–4 Arrange + zebra pile
Tryout 1	−252,800 to −25,900	226,900 ms = 3:47 min	Places zebras to reach *arithmetic* solution	Relocate + zebras (*into pen*)
Impasse	−25,900 to 0	25,900 ms = 0:26 min	Gets stuck; resets the task by returning zebras to pile	Relocate + zebras (*into zebra pile*) Observe + workspace Adjust + Pen 3 (*shape*)
Breakthrough (event pivot)	0 to 11,300	11,300 ms = 0:11 min	Accidentally creates *and notices* overlap between pens	Arrange + Pens 1–4
Tryout 2	11,300 to 95,000	83,700 ms = 1:24 min	Places zebras to reach *set theoretical* solution	Relocate + zebras (*into pen*)
Validation	95,000 to 101,800	6,800 ms = 0:07 min	Counts zebras to confirm that a solution has been reached	Count + zebras
Expiry	101,800 to 233,300	131,500 ms = 2:12 min	Non-task activities: adjusts zebras to make the model look "pretty"; folds PCs into figurine	Observe + workspace Adjust + zebras Observe + workspace Fold + PC-figure

Notes: Of all 14 behavioural definitions, only 1 appears in 2 different segments of the cognitive trajectory, namely *arrange Pens 1–4* which both occurs in the preparation phase and in the breakthrough. This observation emphasises the cyclical nature of P27's cognitive trajectory, as the breakthrough, so to speak, functions as a second preparation phase.

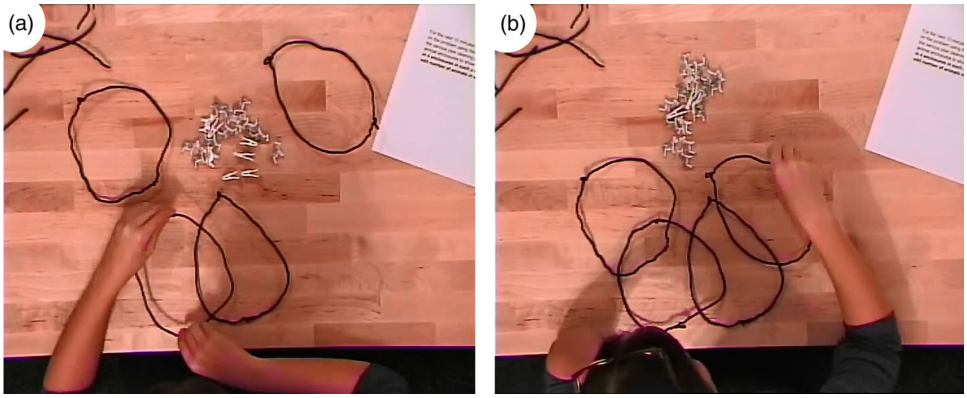

Figure 4. Overcoming the impasse. In the breakthrough phase, P27 rearranges the pens so that they overlap. The initial overlap (4a) has been generalised in order to create three overlaps.

work table which takes her 15.2 s. Having done so, she sits motionless, observing the workspace for 3.5 s before she starts fiddling with Pen 3 for 7.2 s. The activity of adjusting Pen 3 immediately leads to P27 rearranging the four pens in a neatly overlapping form, as shown in Figure 4. As this rearrangement in turn yields an acceptable solution to the task, it constitutes an 11.3 s *breakthrough* phase which, by definition, constitutes the event pivot in P27's cognitive trajectory.

After the breakthrough, we observe another tryout phase that lasts 1:24 min. However, this time she works on the assumption that the problem is a set theoretical problem where the pens may overlap. By repeating the same activity as in the first tryout phase (i.e., relocating zebras into pens), P27 now reaches a solution in Tryout 2.

In the last two phases, she first *validates* the solution by counting the number of zebras in each pen (7 s), before engaging in non-task-related behaviour (such as making the zebras stand in line) in the *expiry* phase (2:12 min). The full trajectory is visualised in Figure 5.

Having thus identified the relevant event pivots, transition points and trajectory phases, we can now proceed to the two central questions in making a CEA: What were the enabling conditions of P27's achieving an acceptable solution? How did P27 solve the 17A problem? Pursuing an answer to these questions, we start from the primary event pivot. We first analyse what created the breakthrough; then we focus on a particular behavioural pattern (consisting of so-called aesthetic actions) that functions as an animating force for P27; finally, we focus on the perceptual affordances that prompt P27 to reach a successful solution.

Serendipities of change

The breakthrough phase is where P27 reinterprets the problem from being an arithmetic one to being a set theoretical one. On a material level, this reinterpretation appears as the re-organising of the four pens into the overlapping structure shown in Figure 4. The logical question implied by the observation of the overlapping structure of the pens is whether this overlap results from a plan that is projected onto the pens (Kirsh, 2010)–that is, the overlap is represented in P27's mind before being materialised on the table–or if it emerges as a result of P27's interactivity. We will examine both hypotheses in turn.

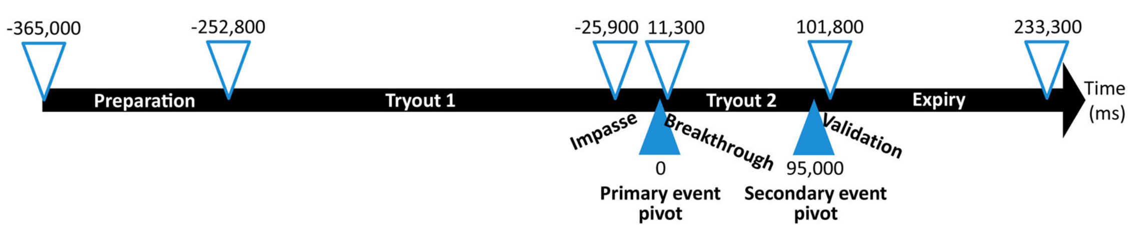

Figure 5. P27's cognitive trajectory. The whole event lasts app. 10 min. Unfilled triangles mark phase transitions; filled triangle mark phase transitions that define an event pivot.

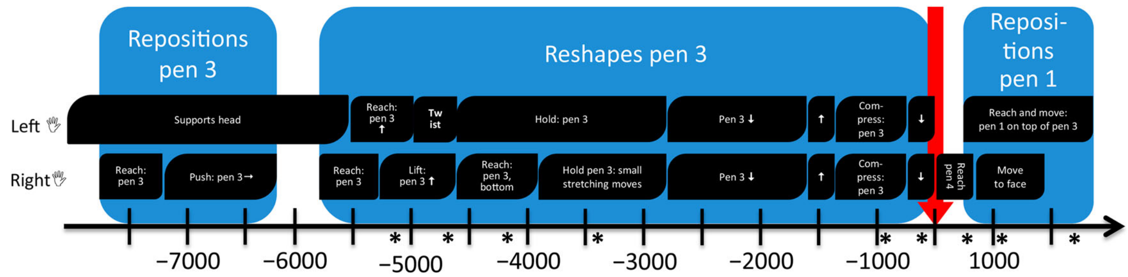

Figure 6. The peri-pivotal sequence. The two rows of black boxes show the left hand (top row) and the right hand (bottom row); arrows within these boxes indicate that the pen is being lifted or lowered. The blue boxes indicate the action; the red arrow indicates the primary event pivot.

First, if the overlaps are a result of a mental plan, then such a plan must be projected *in toto* on the environment. In that case, the projection does not depend on a series of action–perception cycles where P27 will first move one pen, see how it works, and then move another pen; rather, it will proceed as a single smooth, fluent action, since the movement would be the result of a pre-existing intention.

For the second hypothesis, if the overlaps are emergent and unplanned, we should expect three observable features of the cognitive trajectory. First, we expect that the initial (unintended) overlap is a serendipitous by-product of some other process, if nothing else is a process of trying various strategies. Second, we expect a discontinuity between the first overlap and the subsequent overlaps, as it is unlikely that P27 produces a triple overlap serendipitously. Third, we expect that P27 engages in some sort of manifest observational behaviour between the first and the subsequent overlaps, that is, there is an observable indication that she notices the overlap as an affordance for solving the problem. In other words, to test the two hypotheses, we are prompted to investigate, first, P27's pre-overlap activities and, second, indications of her observing or noticing that the initial overlap may yield a successful outcome of the task.

First, we investigate how the first overlap came into being. To do so, we focus on the *peri-pivotal* zone that paves the way for an observable cognitive breakthrough. It spans the last 7,185 ms of the impasse and the first 500 ms of the breakthrough (Figure 6).

As stated, the peri-pivotal zone follows P27's emptying the pens by piling the zebras on the table. She is clearly stuck and prepares to start all over–but does not know where to start. So rather than engaging in

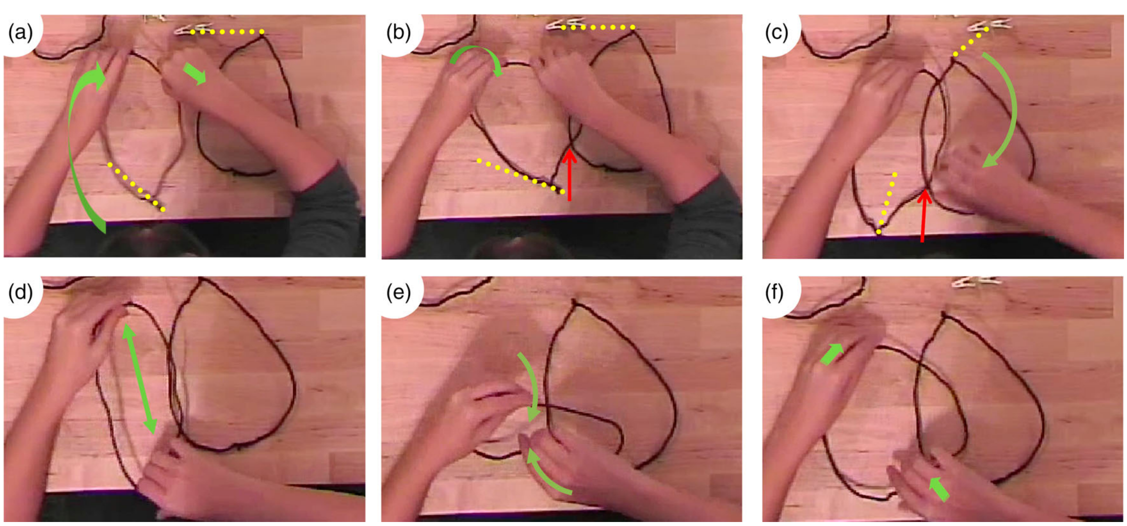

Figure 7. The peri-pivotal sequence. Green arrows indicate hand movements; red arrows indicate contact between two pens; the yellow orientation lines indicate pen movements in relation to a fixed point at the working table.

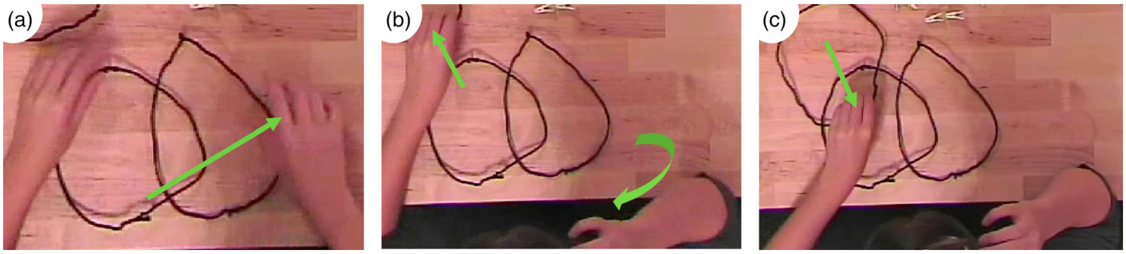

Figure 8. Inhibiting the dissolution of the overlap. Green arrows indicate hand movements.

another trial, she adjusts the layout of pens, focusing on Pen 3 which has a more oval shape. First, she repositions Pen 3, moving it approximately 1 cm to the right with her right hand (1,950 ms). Second, she reshapes Pen 3 (5,230 ms): she lifts it, twists it, stretches it, puts it down, lifts it again, compresses it and puts it down again–as shown in Figure 7.

As can be observed from Figure 7, reshaping Pen 3 has an unanticipated side effect. As P27 twists the pen with her left hand (Figure 7(a)), she causes the pen to move slightly to the right so that the rightmost periphery of the pen overlaps with Pen 4 for 240 ms. The two pens actually touch each other (as indicated by the red arrow on Figure 7(b)) and when P27 lets go of Pen 3 with her right hand, the physical energy stored in the pen (due to the left-hand twist) makes the pen slip back to the left. However, as the PCs are made of a textured material, a Velcro effect makes Pen 3 drag Pen 4 with it (Figure 7(c)). Due to this unplanned reconfiguration of the pens, P27's subsequent attempts to reshape Pen 3 (Figure 7(d) and 7(e)) are all carried out with Pen 3 positioned over Pen 4. When P27 has formed Pen 3 into a circular shape, she puts it down, but on top of Pen 4 (Figure 7(f)).

This observation indicates that the overlap is *not* a result of a pre-existing plan, but rather an emergent feature caused by P27's fiddling with Pen 3 and by the material properties of the PCs. The observation favours the non-mentalist hypothesis. But as discussed earlier, if it really is the case that P27 made the overlap by accident, we would expect to observe her noticing the overlap as an affordance for reaching a solution before generalising it to the other overlaps. Does P27 exhibit behaviour that indicates a change of attention?

Immediately after she has put down Pen 3 (Figure 7(f)), she reaches out for Pen 4 with her right hand (Figure 8(a)).

Importantly, the movement is fast (440 ms) and directed at the rightmost point of Pen 4, and during the movement her thumb points downwards. Had she continued this movement, she would have touched Pen 4 with her thumb at its rightmost place and dragged it to the right in order to reinstate the non-overlapping order of the four separate pens. But she does not. Immediately before her thumb reaches Pen 4, she aborts the movement and moves her right hand to her face (Figure 8(b)), while she uses her left hand to move Pen 1 into an overlap with Pen 3 (Figure 8(b) and 8(c)). The assumption that this 440 ms movement is in fact executed in order to dissolve the overlap is strengthened by the fact that on three previous occasions P27 dissolves such an overlap within 1–6 s (no. 1-3 in Table 6). For illustration, Figure 9 shows how the first of these sequences unfold.

Table 6. Pen overlaps in P27's cognitive trajectory.

#	Pens	Phase of cognitive trajectory	Overlap onset time	Overlap end time	Duration (ms)
1	1 and 2	Preparation phase	−318,700	−312,600	6,100
2	2 and 4	Preparation phase	−275,600	−274,300	1,300
3	2 and 4	Preparation phase	−273,250	−272,250	1,000
4	3 and 4	Impasse | Expiry	−4,175	238,475	242,650
5	1 and 3	Breakthrough | Expiry	925	238,475	237,550
6	2 and 4	Breakthrough | Expiry	4,250	238,475	234,225

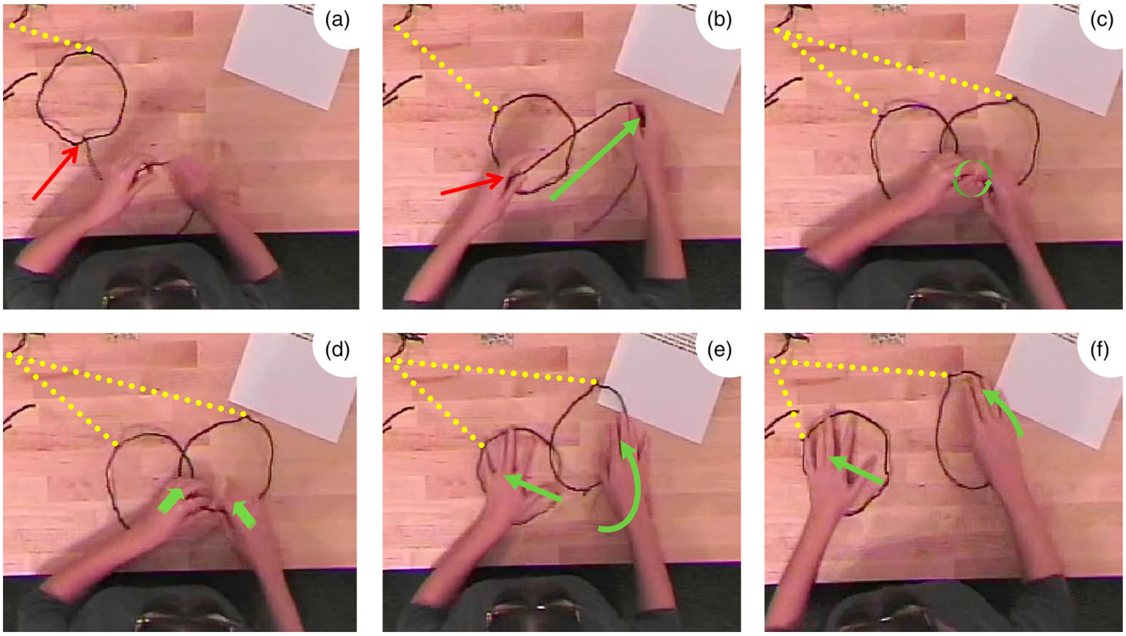

Figure 9. An early overlap in the preparation phase. Green arrows indicate hand movements; red arrows indicate contact points between two pens; the yellow orientation lines indicate pen movements in relation to a fixed point at the working table.

As P27 is folding Pen 2 in the preparation phase, the loose end of one of the PCs "catches" Pen 1 (Figure 9(a)). Pen 1 is therefore moved into P27's working space as she pulls Pen 2 in preparation for connecting the two PCs (Figure 9(b)). Throughout the 6.1 s of closing the pen, the two pens visibly overlap (Figure 9(c)), and when she puts down Pen 2, it is placed on top of Pen 1 (Figure 9(d)). As this was unintended, she immediately dissolves the overlap by dragging Pen 1 to the left and Pen 2 to the right (Figure 9(e) and 9(f)).

The first four overlaps are strikingly similar: a weak Velcro effect makes the two PCs end up in entangled states with visible overlaps. All four times P27 moves the hand in order to disentangle them. But the crucial difference is that only in the first three instances does she carry out the movement, while in the fourth instance she inhibits the action, as described earlier. What is more, not only does she inhibit dissolving the overlap, at the same time she makes an additional overlap (#5 in Table 6), as her left hand reaches for Pen 1 which she lifts and places on top of Pen 3 (Figure 8(c)). Furthermore, 1.2 s later P27 moves Pen 2 into an overlapping position with Pen 4 (#6 in Table 6). Accordingly, 7.5 s after the breakthrough, she has now established the layout of pens that allow her to reach a solution—and indeed, 88 s later, the problem is solved.

Summarising the analysis of the peri-pivotal sequence, we can conclude that the hypothesis that the solution was the result of a pre-conceived plan is highly unlikely, as we have observed three features that characterise a serendipity: first the accidental overlap, second the manifest noticing it and third the generalisation of the overlap to the other pens. The most likely conclusion is that the solution was achieved through P27's interactivity with the material artefacts.

Functional aesthetics

We have seen that the breakthrough emerged as an interaction between (a) P27's engaging in non-task behaviour (i.e., reshaping Pen 3); (b) her ability to notice the overlap as an affordance for solving the problem and (c) the Velcro properties of the PCs. These three features all converge in the peri-pivotal sequence that paves the way for P27's cognitive breakthrough, but each has a distinct history that can be further traced in order to investigate the specific cognitive trajectory. However, we will leave the materiality of the PCs out of consideration in this context since it is invariant throughout the cognitive trajectory.[6] Rather we focus on P27's *action–perception cycle*: her actions in the artificial lab environment and her picking up affordances from the layout of the workspace. In this section, we focus on P27's actions, and in the next section, we turn to the perceptual dynamics.

Having established that the breakthrough was enabled by P27's reshaping Pen 3, we can ask *why* she reshaped it. It is noteworthy that this action has no task-related function whatsoever, since the shape of a pen does not affect its "overlappability." In particular, as this behaviour occurs before the breakthrough, P27 is still assuming that she is dealing with an arithmetic task, and from an arithmetic point of view, the four enclosures could just as well be solid containers or painted squares: attending to the physical appearance of these are functionally void. We argue that this behaviour is prompted by P27's need to homogenise the different visual appearances of the pens: Pen 1 is circular; Pen 2 and Pen 4 are egg-shaped and Pen 3 sticks out as an oblong oval (Figure 4). These differences can be traced to the time spent on folding the four pens. Thus, P27 spends approximately 50% more time on folding each of Pen 1 and Pen 4 than she spends on Pen 2 and Pen 3, and both the two quickly folded pens calls for additional action later in the cognitive trajectory: 2.2 s after being folded, Pen 2 disintegrates due to a poorly performed fold, and P27 needs to reconnect the two PCs. Pen 3, however, has kept its odd appearance throughout Tryout 1 and to this point of the cognitive trajectory.

However, for P27 to pay attention to this difference in appearance, it is not sufficient that there is a visible difference; to reshape the pen, she must be moved to *act* upon the observed differences. She must identify the current state as less fit than an anticipated future state, not according to a task-defined criterion, but according to a non-task related criterion. That criterion, we hypothesise, is *aesthetics*: what prompts P27 to reshape the pen is a *general* tendency to impose an aesthetic order onto the physical layout of her surroundings which, in the relatively constrained context of the laboratory, means the working space of PCs and zebras. To account for this dimension of P27's cognitive trajectory, we define an *aesthetic action* as an action that (a) transforms the physical layout of the environment in order to make it more ordered, and (b) has no task-related, cognitive function.

To identify an action as aesthetic in this sense requires, first, that no task-related (or otherwise) explanation for the specific behaviour can be identified. Second, the action must be traceable to a *general* aesthetic inclination that functions as a behavioural determinant throughout the problem-solving process. Were it a one-off, we would only have an observer-dependent criterion to determine whether the layout achieved was more or less ordered for the participant. As for the first requirement, we have already argued that P27 has no task-related motifs for reshaping Pen 3 in the peri-pivotal sequence. It is difficult to see what else P27 could gain by turning the oblong oval into a circle. Thus, this action is a good candidate for an aesthetic action. The second requirement can be met in two ways: one can test a given participant's level of aesthetics, similar to how working memory and other cognitive functions can be tested; however, none were applied to the participants in the current study. Alternatively, one can observe if such aesthetic drives surface elsewhere in the cognitive trajectory. If it is generally the case that a participant engages in behaviours that are not manifestly task-related and that brings about more ordered states in the visual appearance of the workspace (also in cases where it does not fuel the cognitive trajectory), then it suggests that aesthetics is precisely such a behavioural drive. In the case of P27, we observe six instances of aesthetic actions, as outlined in Table 7.

The first aesthetic action occurs at the very end of the first tryout phase (5:38 into the trajectory). P27 has for 3:30 min shuffled around with zebras, performing a total of 33 moves, and now she is stuck. She sits motionless for a 15.7 s, passively observing the workspace. Then, just as she is about to resume moving the zebras, she inhibits her action and rather engages in the aesthetic activity of adjusting Pens 3 and 4, ever so slightly (Figure 10).

Table 7. Aesthetic actions in P27's cognitive trajectory.

#	Type	Beginning time	Duration (ms)	Description
1	Aesthetic	−26,632	875	P27 slightly adjusts the position of Pen 3 and Pen 4
2	Aesthetic	−7,050	7,050	P27 reshapes Pen 3 and places it in an overlap with Pen 4
3	Aesthetic	7,675	1,850	P27 attempts to smoothen a sharp bend in Pen 2
4	Aesthetic	9,525	1,925	P27 makes a minimal adjustment of Pen 1's position
5	Aesthetic	122,100	33,525	P27 adjusts all zebras in the pens to achieve a more ordered arrangement
6	Aesthetic	170,000	68,075	P27 takes two PCs and folds a three-dimensional figure

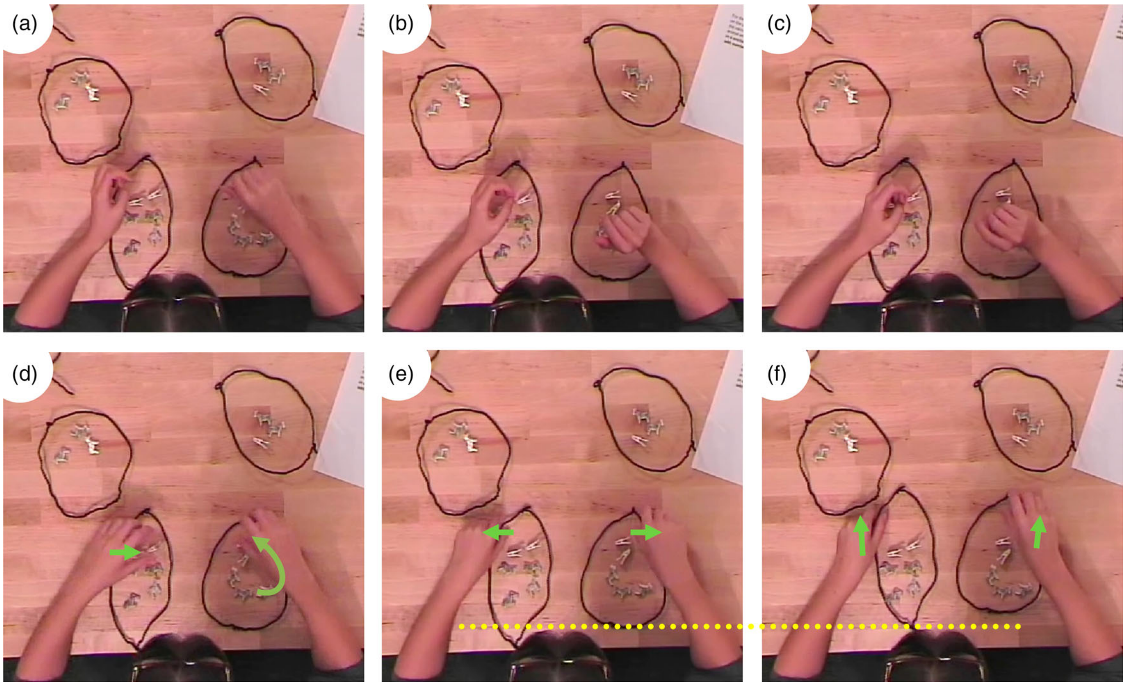

Figure 10. Aesthetic actions at the end of Tryout 1. P27 has just relocated the last zebra (in Pen 4), and now sits motionless for 15.7 s. The lapse between 10a and 10b is 8.5 s, and from 10b to 1°c is 6.6 s. 1.6 s later, P27 seems to resume her activity of moving the zebras, as she reaches for a zebra, at least with her left hand, possibly also with her right hand (10d). However, she aborts this movement by moving her hands outwards (10e) where she grasps the two pens and moves both slightly upwards (10f). Green arrows indicate hand movements; the yellow orientation lines indicate pen movements in relation to a fixed line across at the working table.

The second incident is the serendipitous creation of the overlap already analysed in the previous section. The third and fourth incidents occur immediately before the transition between the breakthrough and the second tryout (6:12 min into the cognitive trajectory). Here, P27 has arranged the four pens in overlaps, and she is now ready to engage in another try at relocating the zebras in order to solve the task. But 6 s before she grasps the first zebra (which defines the beginning of Tryout 2), she attempts to smoothen the rather sharp bend on Pen 2, just as she makes a minimal, almost unnoticeable adjustment of Pen 1's position. None of these actions has any visible outcome, let alone any impact on the cognitive trajectory.

The last two occurrences of aesthetic actions are found in the expiry phase. By definition, at this stage, P27 cannot engage in task-related activities (an already-solved task is hardly a task), and for this reason, we should expect to find many aesthetic actions in the expiry phase. And in fact, for 74% of this phase, P27 engages in aesthetic actions.[7] The sixth aesthetic action is rather trivial: for the last minute or so of the recording, P27 takes two PCs and starts folding a non-figurative figure. More significant is the fifth aesthetic action. Having validated the solution, she starts adjusting the zebras' positions in each pen. This takes her 33.5 s, and Figure 11 shows the layout of zebras before and after this adjustment. P27's aesthetic inclination is to stand all lying zebras on their hooves and align them with zebras within the same pen. Likewise, she makes groups of zebras within the same pen orient in the same direction.

In conclusion, P27's aesthetic actions function as a motor that moves her forward along her cognitive

[6]Several studies have been produced in order to investigate how material features affect problem-solving processes, most notably by comparing a "material" model-based condition with an "immaterial" pen-and-paper condition (Fioratou & Cowley, 2009; Vallée-Tourangeau, 2013; Vallée-Tourangeau et al., 2011). However, such dichotomist designs do not allow for investigating how *different* materialities–colours, textures, etc.–influence the problem-solving process.

[7]One might object that since the expiry phase in nature is task-unrelated (since the task is already solved), then all actions in this phase are aesthetic in that they are non-functional. However, to count as an aesthetic action, it is not sufficient that it is task-unrelated; it must furthermore transform the physical layout of the environment in order to make it more ordered. Thus, picking one's nose, cleaning teeth with a PC, or playing zoo with the zebras are not aesthetic actions in the sense intended here.

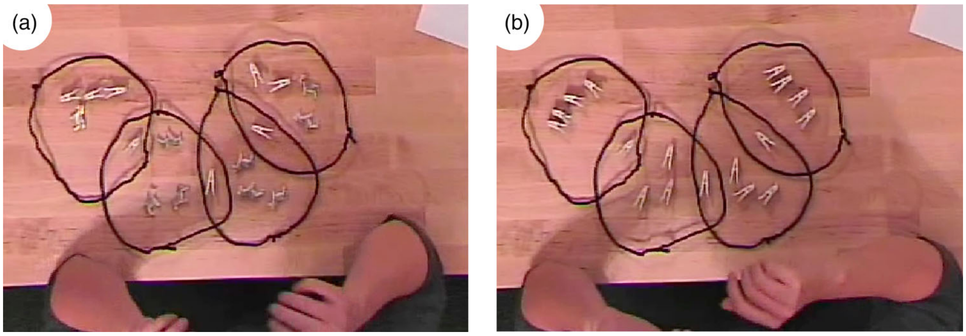

Figure 11. Aesthetic action after the validation phase. P27 has achieved and validated a solution (11a). 20 s later she adjusts the zebras' positions in the pens, so that they stand in a more ordered, symmetric pattern (11b).

trajectory. Our claim is not that aesthetics per se contributes to problem-solving, but that aesthetics lead to changes in the "lay-out of affordances" (Chemero, 2000b) that reveal task-relevant features of the environment. The question of aesthetics is further explored in the "Discussion" section.

Perceptual affordances

In the first part of this analysis of P27's cognitive trajectory, we showed how her breakthrough was serendipitous in nature, as it depended on non-task behaviour in combination with attending to the result of this behaviour. In the second part, we traced the behavioural component to P27's inclination to engage in aesthetic action, and in this third part, we investigate the dynamics of her perception and attention. In doing so, we struggle with numerous methodological problems. First, our data do not allow us to observe what P27 attends to because we did not equip the participants with eye-tracking equipment. Second, due to the single camera mounted in the ceiling, we cannot even engage in conjuring a coarse-grained picture of just what P27 looks at. However, we might occasionally deduce what she attends to, by observing changes in posture (e.g., when leaning over the paper, she probably reads the task) and in behaviour (e.g., when returning the short PC to the pile, she has probably just perceived that its size does not afford folding into a pen). In other words, because we are forced to work with "unperceivable perception," we will rely on more general behavioural observations.

The key argument in our treatment of P27's attention is that the serendipitous overlap treated earlier is not the first occurrence of overlapping pens. Therefore, something else than the overlap functions as an enabling condition for her breakthrough. Following this argument, we can more systematically compare how the pivotal overlap differs from the previous instances. These overlaps were shown in Table 6, where the pivotal overlap is #4. As argued, Table 6 shows that the last three overlap configurations are continuous: through generalisation, overlap #4 functions as an enabling condition for overlaps #5 and #6. However, this result merely shows that when an insight is achieved, it can be generalised to generate a solution. This leaves us with the more interesting question: why did this insight not occur with the first three overlaps?

First of all, we notice that these three overlaps all occur in the preparation phase. Based on P27's behaviour in the first tryout phase, it is clear that before the breakthrough she is acting as if she is working on an arithmetic problem. In other words, during the preparation phase, she is *not* looking for a solution, because she has already conceived a solution (albeit a wrong solution) which she is trying to materialise. That situation changes in the impasse: now she has lost her solution and is actively seeking out options to move forward. In the terminology of Steffensen (2013), she engages in *solution-probing*, that is, she "immethodically zigzag[s] along a cognitive trajectory […] in [her] search for something that can work as a problem solution" (Steffensen, 2013, p. 205).[8] Thus, the first three overlaps are not affordances for a solution, whereas the pivotal

[8]The current paper has shown how this process is not methodical seen from a task-defined perspective, but seen from an aesthetic perspective, her actions are rather methodical. This insight suggests that a reformulation of Steffensen's initial description of solution-probing is needed. The main point is that the "search for something" is driven by some characteristic cognitive or behavioural principle (e.g., aesthetics) that can be identified in a CEA.

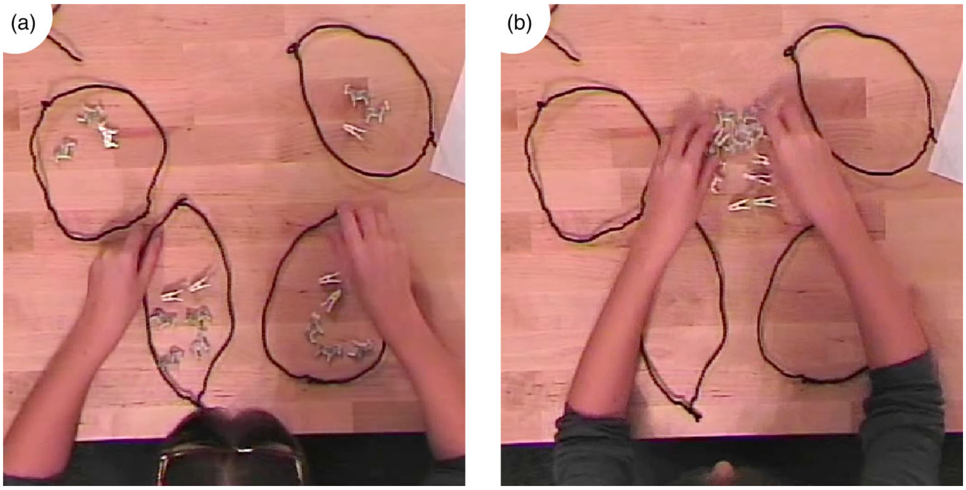

Figure 12. Figure-ground inversion in the impasse phase. Having distributed and relocated all zebras during the 3:47 min of the first tryout phase, P27 is stuck (12a). During a 15.2 s sequence, she swiftly removes all zebras from the pens, collecting them in a pile on the middle of the table (12b).

overlap is. The crucial point is that what on the one hand seems to be repetitions (the repeated creation of overlaps), on the other is "repetition without repetition" (Cowley & Nash, 2013): the behavioural pattern might be repetitious, but the perceptual and attentional embedding of the behaviour is significantly different.

Second, it is noteworthy that the pen structure is stable during both tryout phases: the only time the pen appears as an action object during the 5:11 min of tryout is the 870 ms adjustment of Pens 3 and 4 that were depicted in Figure 10. This stability suggests that during these phases, P27 relies on a perceptual figure-ground constellation where she attends to the zebras as her perceptual focus, while the pens merely function as a perceptual ground for grouping zebras. This observation casts new light on the impasse phase immediately before the serendipitous overlap. As previously stated, the impasse phase lasts 25.9 s: first, P27 relocates all zebras from the pens into a pile on the middle of the table (15.2 s), then she observes the workspace, scratching her forehead (3.5 s), and then she reshapes Pen 3 so the overlap with Pen 4 emerges (7.2 s). We have already discussed the last 7.2 s as part of the peri-pivotal sequence, but without relating it to the first part of the impasse. The initial state and the end state of these 15.2 s are shown in Figure 12.

Traditionally, the problem-solving literature interprets such behaviour as a resetting of the scene due to the participant being stuck. While definitely the case, it is not the full story. In P27's case collecting the zebras in a pile has perceptual implications, because it forces her to execute a figure-ground inversion, making the ground-so-far (i.e., the pens) her new figure. Assuming that this figure-ground inversion is an enabling condition for the aesthetic action of reshaping Pen 3 is in consonance with other findings in the literature. Thus, Vartanian et al. (Vartanian, 2009; Vartanian, Martindale, & Kwiatkowski, 2003, 2007; Vartanian, Martindale, & Matthews, 2009) have developed Martindale's (1999) hypothesis that

> In earlier phases of problem solving when the problem is relatively ill-defined, creative people are more likely to defocus attention. This tendency makes the central task more susceptible to interference by seemingly irrelevant information, some of which may provide the building blocks for solutions. […] In later stages of problem solving when creative people are verifying developed ideas, performance will benefit through the inhibition of irrelevant stimuli and added focus on the task. This narrowing of attention speeds up processing on the task. (Vartanian et al., 2007, p. 1471)

A figure-ground inversion evidently implies defocused attention, and P27's reengagement with the zebras in the second tryout phase is consonant with Vartanian et al.'s description of participants' "narrowing of attention." Changes in attention thus also work as an enabling condition for P27's successful solution in the 17 Animals task, and hence we can explain why the first three overlaps did not lead to an insight: P27 did not pay sufficient attention to the pens as a potential resource for solving the problem.

Table 8. Aesthetic actions and observation periods in P27's cognitive trajectory.

#	Type	Aesthetic action beginning time	Observation duration (ms)	Observation end time	Latency from observation to aesthetic action (ms)
1	Aesthetic	−26,625	15,700	−27,800	(1,175)
2	Aesthetic	−7,050	3,475	−7,050	0
3	Aesthetic	7,675		*No preceding observation*	
4	Aesthetic	9,525		*No preceding observation*	
5	Aesthetic	122,100	11,275	122,025	75
6	Aesthetic	170,975	15,325	170,975	0

Notes: The aesthetic actions are described in detail in Table 7. The latency before aesthetic action #1 is due to a short sequence coded as "inhibits move," that is, a sequence where P27 reaches out for a pen or a zebra, but inhibits the motion before it reaches its destination. As a continuation of the long observation phase, these 1.5 s are observational in nature, but they are not completely motionless.

Hitherto, we have discussed the aesthetic actions that fuel P27 on her cognitive trajectory and the dynamics that attune her attention to the pivotal overlap as two necessary, but separate conditions for achieving a solution. However, these two features are closely connected. As can be seen from Table 8, 4 out of 6 aesthetic actions are actually preceded by significant phases where P27 motionlessly observe the workspace.

This is noteworthy because "being stuck" is traditionally connected with being in a state of impasse. For instance, Ohlsson suggests that "behaviorally, impasses are characterized by the cessation of problem solving activity" (1992). If so, the sheer inactivity of these periods suggests that P27 is indeed stuck. For an illustrative example, Figure 10(a) and 10(c) show the longest observation phase (15.7 s) at its onset and at its end. She has hardly moved for this long period. This pattern of aesthetic actions being preceded by periods of motionless observation indicates P27's general tendency to perform aesthetic actions when she does not know what else to do. On the other hand, it is not the case that all observation periods are followed by an aesthetic actions, as is shown in Figure 13.

But significantly, all observation phases that are *not* followed by an aesthetic action occur in a tryout phase, where P27 is stuck on another level: thus, within these phases she knows (incorrectly) that she has to move a zebra to calibrate the group size, but she does not know which zebra to move where. In contrast, in the non-tryout phases, she does not know what to do altogether, since the move-a-zebra strategy has failed. Hence, it is hardly surprising that the pattern of observation-aesthetic action cluster around the main phase transitions in P27's cognitive trajectory: at the beginning of the impasse phase, just before the breakthrough and at the beginning of the expiry phase. Evidently, describing P27 as being stuck refers to an actional level, but it seems reasonable to assume that actional paralysis prompts a stronger emphasis on perception.

Summarising these insights on P27's attentional dynamics, we can conclude that the comparison between the initial overlaps and the pivotal overlap has shown that in order to perceive the overlap as an affordance for a solution, P27 first needs to realise that her initial assumption about the task does not work; second that she needs to attend to the pens, not as mere background, but as her focus of attention. Both these preconditions are met in and after the impasse phase.

Discussion

We dedicate our discussion to three topics: first, we discuss what the case of P27 has provided in terms of our understanding of problem-solving; second, we reflect on the methodological implications of

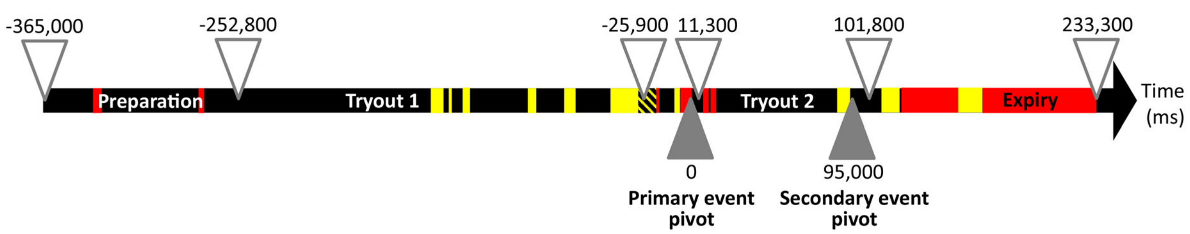

Figure 13. P27's cognitive trajectory. Aesthetic actions are marked with red; immobility phases are marked with yellow. The black and yellow area at the beginning of the impasse marks an inhibition of a movement: it is observational in nature, but is not completely motionless.

CEA; and third, we suggest a new perspective on the perennial debate between computationalists and ecological psychologists, namely on the question of the nature of representations.

Case study implications

The starting theoretical assumption of this paper is that the embodiment of the agent matters, and hence that cognition depends on agent–environment dynamics (Chemero, 2011). Consequently, in this first part of the discussion, we reflect on the three central aspects of the case study.

First, we claimed in the analysis that the specific cognitive trajectory depends on the material properties of the set-up, primarily the Velcro-like PCs, but potentially also the properties of the animal figurines. If so, the impact of different material properties can be tested experimentally. Thus, one can hypothesise that a number of material parameters determine the outcome of the experiment: pens can be formed with pieces of varying length, height, weight, rigidity and adhesiveness; they can even be formed by pre-given surfaces (e.g., disks or plates) in different shape, size, opacity and adhesiveness; likewise, animal figurines and working space can vary in size, weight, shape, etc. While such considerations allow for experimentally testing whether one material configuration prompts a higher success rate than another, it would be even more promising to investigate how success depends on, not the artefacts per se, but by the *relation* between agent and artefact. This argument parallels Anderson's (2014, pp. 172–175) discussion of how human agents measure artefacts, not in terms of weight and size, but, for instance, in terms of their *throwability*. Likewise, from an ecological point of view, we would not expect any material configuration to be superior to all others, but we would expect an optimum for *overlappability*, depending on material parameters of the pens (and the workspace) and the bodily properties of the agent.

Second, in the analysis, we traced the serendipitous creation of the overlap to P27's inclination to perform aesthetic actions. At first sight, the importance of this observation is that it illustrates the width and depth of the action repertoire from which a solution eventuates. Accordingly, one would not be surprised to find a successful participant who depended on, not aesthetic actions, but the creation of chaos, for example, by randomly shuffling pens and animals on the workspace (cf. Kirsh, 2014). After all, faced with the impasse, the important thing is to avoid doing nothing. However, we suggest reconsidering this result on a deeper level. Thus, while mentalist models focus on an idealised mapping of the representational changes necessary to reach a solution, an ecological approach further asks, what drives the cognitive agent through the territory thus mapped. Mentalist cognitive science rests on a disembodied model where a virtual agent moves through a virtual problem space. In such a model, movement (i.e., representational restructuring) is cheap: the agent needs no incentive to act, as long as the cognitive task is unresolved. In contrast, an ecological approach dismisses the assumption that the context for human action is a flat problem space, exclusively defined in terms of task-defined problem properties. Rather, it acknowledges that human agents are motivated by other drives and inclinations. For P27, aesthetics is such a drive, and it impacts on her cognitive trajectory by creating task-unrelated changes that reveal task-relevant affordances. Hence, vital aspects of the cognitive trajectory would be missed if we ignored the full ecological situation and only focused on an (observer-dependent) subset of the situation, defined by (what the cognitive psychologist sees as) "the problem."

Finally, in our analysis of P27's cognitive trajectory, we argued that the identification of a cue as the anchor to a cognitive event is not predicated on its physical feature independent of the problem-solving trajectory wrought through interactivity. Thus, if it was the mere physical overlap of pens that brought forth the breakthrough, P27 would have solved the problem right after she accidentally created the first overlap. There is an important lesson to be learnt about the nature of perception. As the Gestalt theorists noticed nearly a century ago, perception is not a result of sensation, but a result of how sensory stimuli are synthesised with conceptual anticipations; or in Neisser's succinct terms, "perception is basically a constructive act rather than a receptive or simply analytic one" (Neisser, 1967, p. 94), and "the mechanisms of visual imagination are continuous with those of visual perception" (Neisser, 1967, p. 95). As P27 *imagines*, as it were, a workspace laid out for solving an arithmetic task, she does not notice the affordances for solving the tacit set theoretical task. On the one hand, this observation emphasises the importance of interactivity, because it shows that we cannot make valid inferences from the configuration of artefacts, independently on how the agent (perceptually and actionally) engages with it. On the other hand, the very same observation can lead one to prefer a representational model to an interactivity-based model, because there so obviously is a discrepancy between what there is to see and what P27 actually sees. One could argue, as indeed Ohlsson (2011) does, that any such discrepancy between the external physical reality and experienced reality (or imagined experience) is a proof of representations. We will return to this question.

Methodological implications

Our starting point for a methodological reflection on CEA is the question: can qualitative methods add anything at all to a cognitive psychology built on controlled experiments and nomothetic inferences? We believe it can. But a caveat is in place: as we in this paper propose a qualitative method for doing single-case studies, we are obliged to discuss the generalisability and the danger of "hasty generalisations" (Walton, 1999) and "just so" explanations. On this question, we see ourselves as being in the same situation as Anzai and Simon (1979) when they embarked on their single-case study of the learner solving the Tower of Hanoi:

> It may be objected that a general psychological theory cannot be supported by a single case. One swallow does not make a summer, but one swallow does prove the existence of swallows. And careful dissection of even one swallow may provide a great deal of reliable information about swallow anatomy. Although the generality of the theory we have constructed remains to be tested, we undertook to model accurately the learning mechanisms that we observed in the behavior of our single human subject, modelling them in such a way that their applicability would not be limited to the specific task environment […] in which we discovered them. (Anzai & Simon, 1979, p. 136)

Like Anzai and Simon, we have not provided a general *theory* of problem-solving; the serendipitous character of problem-solving cannot be generalised; and the specific suggestions about, for instance, aesthetic actions and perceptual figure-ground inversion remain to be tested.

However, the current study does provide us with lines of inquiry beyond the insights provided by the single-case study. Thus, while cognitive psychology indeed has developed robust methods for meticulously testing hypotheses, it is strikingly silent on how to *generate* hypotheses. For instance, a search on PsycINFO gives 1,979 hits for "test(ing) or evaluat(ing) hypothesis/-es" within cognitive psychology, but only 149 hits for "generat(ing), creat (ing) or produc(ing) hypothesis/-es" within this field.[9] Since the field invests its scientific validity in experimental testing, the development of scrupulously controlled methods for generating hypotheses has been neglected. As a result, by and large, hypotheses are either deduced from extant theories or derived from anecdotal observation or philosophical speculation.

With CEA, we have provided a method that is neither anecdotal nor speculative, but a manifestly data-driven, qualitative method. Accordingly, based on the scrutiny of P27, one can investigate a number of dimensions of the 17A problem by formulating such hypotheses as: (a) due to the interactivity cycles between participant and the material layout of the problem, solution rates can be manipulated by changing the materiality of the pens (i.e., as pieces of varying length, height, weight, rigidity and adhesiveness, or as surfaces of different shape, size, opacity and adhesiveness); and (b) for each of these dimensions there is an optimum value that maximises solution rates. Further, having dismissed the assumption that the context for human action is a flat problem space, this paper also suggests the hypothesis that (c) across contexts, cognitive agents have emotional drives (including aesthetic inclinations) that prompt them to engage in specific behavioural patterns, irrespective of the concrete task. Finally, based on the proposed figure-ground inversion, we suggest the hypothesis that (d) cueing works by perturbing the agent into altering his/her perceptual dynamics, for example, through figure-ground inversion.

CEA's focus on embodied interactivity also provides experimentalists with new ways of coping with two problems that arise with experimental

[9]The search was performed on 10 December 2014, using the following two "key word" search strings in PsycINFO:

(("test hypothes*" OR "testing hypothes*") OR ("evaluate hypothes*" OR "evaluating hypothes*")) AND "cognitive psychology"

(("generate hypothes*" OR "generating hypothes*") OR ("create hypothes*" OR "creating hypothes*") OR ("produce hypothes*" OR "producing hypothes*")) AND "cognitive psychology" methods: the *outlier problem* and the *granularity problem*. According to the standard work on statistical outliers (Barnett & Lewis, 1994), an outlier is a data point inconsistent with the overall data set. Traditionally, outliers are seen as a source of data contamination that masks otherwise valid tendencies, and for this reason, they are done away with by the application of various statistical methods. However, while outliers may be caused by measurement or performance errors, they may just as well be caused by the inherent variability in the data set. Outliers that are not due to measurement or performance errors, constitute a challenge to models that eliminate inherent variability, because such models fail to explain manifest cognitive performances. Outliers may be strange, peculiar, odd or anomalous—but they still manifest behaviour and instances of cognition, and they must be described as such. If a given performance pattern can be produced by human cognition, then our cognitive theories must be able to cope with it. If our overall models do not provide an explanation, auxiliary models must be generated through meticulous description of what actually happens in the outlier cases. CEA is a method for constructing such models which can be tested through further experiments.

The granularity problem is similar to the outlier problem. Any experimental setting depends on a series of measurements that generate one or more data points for each point in time. The number of data points depends on the measurement granularity. In the extreme case, one finds explanatory models based on merely two measurements: an initial measurement (problem unsolved at t_1) and a final measurement (problem solved or unsolved at t_2). For instance, a model of cognitive extension can be based on measurements of participants solving a task X (e.g., solving the 17A problem) in condition Y (e.g., using artefacts), but not in Condition Z (e.g., using pen and paper). Obviously, such methods cannot show *how* subjects solved the problem or whether they did it in different ways or the same way. As Van Orden and colleagues point out, "one cannot resolve systematic variation on timescales faster than the pace of measurement. The timescale of data collection is too sparsely paced to accurately gauge variation on faster timescales" (Van Orden, Holden, & Turvey, 2003, p. 338). Loosely speaking, on the timescale of measurement, one can show "*that* P1 solved X"—but in order to show "*how* P1 solved X", one needs more fine-grained measurements. Evidently, this argument is valid irrespective of measurement granularity. Thus, more fine-grained measurements may show "that P1 did Q to solve X", but they do not show "*how* P1 did Q to solve X". For instance, given a less fine-grained method, we might have shown that P27 solved the 17A problem by serendipity, but not how that serendipity was brought forth.

No method can solve the granularity problem, as no method can gauge faster-than-measurement variations. But different methods have different granularities, and their measurement granularity is limited by three factors: (1) the unit of analysis: for instance, the verbal protocol of Anzai and Simon (1979) cannot show variability within a single protocol statement; (2) annotation density: for instance, coding and measurement procedures can be performed as sparsely or as densely as one is up to and (3) technical constraints: for instance, a standard video file format has a frame frequency on 24 Hz. This corresponds to a measurement interval on app. 40 ms which thus defines the measurement granularity. CEA is neither limited by pre-defined units of analysis, nor by a fixed interval density. As such it can for each *that*-observation generate substantiated *how*-observations, all the way down to a 40 ms granularity. Therefore, CEA generates observations and hypotheses that would otherwise be ignored or overseen by other methods.

In conclusion, CEA does more than supplement the well-established stock of quantitative methods in cognitive psychology. It is a method capable of testing hypotheses against single cases, and furthermore it can zoom in on cognitive events on a very fine-grained level. Depending on the research agenda, CEA can, in combination with quantitative methods, serve the purpose of generating hypotheses by scrutinising statistical outliers and fine-grained between-measurement phenomena. Or CEA can stand alone as a qualitative method on a par with extant qualitative methods, such as (coded) verbal or video protocol analyses and cognitive ethnography (Ormerod & Ball, 2010).

Theoretical implications

We dedicate this last part of the discussion to the question of how our results contribute to the perennial debate on representations. Given the premise that problem-solving follows a trajectory from a state where the agent has a problem to a later state where the problem is (dis)solved, the question is: does problem-solving require representational restructuring (Ohlsson, 2011), or can it proceed on the basis of changes in the world? We have observed how a cognitive agent acts on the world, manipulates artefacts, models aspects of reality, and rearranges physical features, but does this observable interactivity *result from*, *catalyse* or *constitute* problem-solving?

A die-hard mentalist would opt for the *result from*-interpretation, arguing that any overt behaviour must result from a pre-existing mental plan or program: "an explanation of an observed behavior of the organism is provided by a program of primitive information processes that generates this behavior" (Newell, Shaw, & Simon, 1958, p. 151). In contrast, a convinced anti-representationalist (Chemero, 2000a, 2011) would trace problem-solving to the embodied-ecological dynamics of action–perception cycles, that is, interactivity *constitutes* problem-solving. In-between, one finds the cueing-based view that representational restructuring must somehow be involved in problem-solving, and therefore interactivity only works because it *catalyses* representational changes. *Ceteris paribus*, our data are compatible with all three models, because the data *underdetermine* the three competing theories (Stanford, 2013): observational data cannot verify or falsify theoretical claims of representational and computational processes in a mental realm, because such theoretical claims are "not at all concerned with the physical structures that allow this symbolization, nor with any properties of the memories and symbols other than those it explicitly states" (Newell et al., 1958, p. 151).

Although our data and our approach were not designed to disentangle these different accounts, they may still throw some light on the controversy. We start from the observation that the criterion for determining whether a problem has been solved, does not pertain to the mental realm, since evidence of successful problem-solving is mined from the world: what is measured is physical and behavioural evidence. The claim that representational restructuring has taken place builds on the warrant that such behaviour *requires* (the enaction of) mental representations. However, proponents of representational models have the burden of proof: as they solve the problem of how an agent connects action and perception by introducing a representational realm, they are obliged to explain how this realm interacts with the behavioural realm of the agent. This challenge was posed by Gilbert Ryle half a century ago, but still unresolved:

> […] the postulated interactions between the workings of the mind and the movements of the hand are acknowledged to be completely mysterious. Enjoying neither the supposed status of the mental, nor the supposed status of the physical, these interactions cannot be expected to obey either the known laws of physics, or the still to be discovered laws of psychology. (Ryle, 1949, p. 52)

If one accepts that the burden of proof lies with the proponents of mentalism, the strategy to lift the burden is to argue that a non-representational model cannot account for all data. For instance, in the P27 case, the fact that she so persistently sticks to an arithmetic interpretation for the first ca. 7 min of the cognitive trajectory suggests that she must have some sort of a mental representation of the problem. Again, our data cannot falsify such a claim. But the same effect can be accounted for by the non-representational model that has developed in the phenomenological tradition, in particular Merleau-Ponty's (2002) concept of the *habitual body*:

> On the basis of past experience, I have learned that doorknobs are to be turned. This 'knowledge' has sedimentated into my habitual body. While learning to play the piano, or to dance, I am intensely focused on what I am doing, and subsequently, this ability to play or to dance sedimentates into an habitual disposition. (Flynn, 2011)

In a literate community, interacting with written texts (and tasks in psychological experiments) has the same habitual status as turning the doorknob, playing the piano and dancing. We enact and embody a habitually defined way of relating to such tasks, and thus our habitual body makes us follow a distinct line of action. To the mentalist, this automaticity is the proof of an internal plan, but this mentalist interpretation does not follow from empirical data, but from a deep-rooted mentalist presupposition, as discussed earlier. To exemplify, Luchins's (1942) water jug experiments show that relying on the habitual body is cognitively simpler than identifying a new method, although that new method may count as simpler to the mentalist experimenter who articulates it in an abstract problem space.

Interestingly, invoking habituality prompts us to specify the nature of the ecological position that interactivity constitutes problem-solving: this position does not imply that perception and action are connected *directly* (i.e., unmediated by intraorganismic dynamics), as such a model leaves no room for P27's attentional change and problem reinterpretation. Crucially, in the ecological model, the world is not enough: cognition depends on "the deep *complementarity* between the inner and the outer and between the neural and the bodily" (Clark, 2008, p. 153), and it thus reflects a dynamic transactional agent–environment coupling which connects *knowledge* and *performance*:

> What we do depends on (follows from, is motivated by, is shaped by, is partially explained by) what we know and think; and what we know and think depends on (follows from, is motivated by, is shaped by, is partially explained by) what we do. Knowledge and practice are in this sense intertwined and coconstructing. (Anderson, 2014, pp. 199–200)

The exact nature of the inner pole of this complementarity is a matter of debate, to be sure. But as Anderson continues, even if the inner pole is representational in nature, "it is time to admit that simply discovering a representation in a cognitive system tells us virtually nothing about the nature of the underlying architecture in which the representation plays a role" (Anderson, 2014, p. 201).

In this paper, we have argued that interactivity is the force that weaves the emergent and transactional properties of thinking.[10] Our claim is that it is worthwhile to pursue a research agenda in problem-solving psychology where the focus is on the *relational oscillations* between habitual bodies and environments.[11] The notion of *interactivity* as "sense-saturated coordination that contributes to human action" (Steffensen, 2013, p. 196) captures these dynamics because it emphasises the oscillating relations ("coordination") between agent and environment, the habituality of these dynamics ("the sense-saturation"), and the teleological dimension of action. The main difference between Merleau-Ponty's phenomenological approach and an interactivity-based one is that the former limits habituality to the body, whereas the latter find patterns of habituality distributed all over the extended human ecology (Steffensen, 2011), including cognitive artefacts. In fact, it is such patterns of distributed habituality that makes the human agent more than a mere organismic agent, but crucially a sense-making creature that weaves performance and knowledge:

> For in the end, the human agent is both a doer and a knower, and we can accept the point that our cognitive architecture is organized such that we generally know in order to do, and still recognize that the relative importance of doing, knowing how, and knowing that will vary with the skill to be explained as well as across time and circumstance. (Anderson, 2014, p. 201)

Conclusion

An ecological, interactivity-based approach to problem-solving may pave the wave to an ecological understanding of the cognitive processes in problem-solving. In order to study problem-solving under laboratory conditions, real-world cognitive ecosystems must be scaled down, so problems are presented to participants in a manner that permits the manipulation and rearrangement of the elements configuring the problem. Eliminating interactivity for the sake of methodological rigour produces a distorted window onto problem-solving, and the resulting science is fundamentally misaligned with how humans think outside the psychologists's laboratory. The contingent spatio-temporal itinerary must be recorded and analysed to trace the genesis of insight.

A triangulation of quantitative and qualitative analyses can identify recurrent patterns of behaviour that help explain (and predict) why some participants solve a problem and others do not, and provide a rich source for generating testable hypotheses about aspects of the agents and the ecosystems within which they are embedded. An ecological science of problem-solving, supported by an analytic tool such as the CEA, is in a good position to explain insight. Ormerod and Ball (2010) argue that qualitative methods mainly supplement experimental methods because they capture otherwise elusive phenomena, such as cognitive processes over longer periods of time, situated cognition, distributed cognitive systems and technological interfaces. However, CEA does more than widen the scope of cognitive psychology; its main value comes from its focusing on "the glue of cognition" (Kirsh, 2006, p. 250), that

[10]By transactional, we mean that neither the agent nor the environment can be independently specified without considering the dynamic coupling.
[11]The rich literature on cueing is a valid example of such oscillations because it shows how environmental cues can perturb a habitual pattern of behaviour, so the cognitive agent needs to apply neural resources to engage in solution-probing (Steffensen, 2013), using material artefacts and other environmental resources.

is, fast, small-scale interactivity that couples the organism to its environment. CEA thus not merely applies to phenomena that are less adequately captured with experimental methods; it also sheds new light on this type of data by generalising across real-life and laboratory settings.

Obviously, this paper is merely the tip of the iceberg in that respect. Given its single-case design, it proves nothing; however, it may generate questions, and it may *dis*prove extant hypotheses on problem-solving. For instance, a general theory of problem-solving must be sufficiently broad to take the possibility of serendipitous manipulation into account. With CEA, we have provided a method for testing hypotheses against single cases of what agents actually do, as they engage in a given cognitive activity. While fine-grained qualitative analyses of agent–environment interactivity still has to stand the test of time, the novelty of the questions asked in this context is indicative of the potential for this approach.

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References

Anderson, M. L. (2014). *After phrenology: Neural reuse and the interactive Brain*. Cambridge: MIT Press.

Ansburg, P. I., & Dominowski, R. L. (2000). Promoting insightful problem solving. *The Journal of Creative Behavior*, *34*(1), 30–60. doi:10.1002/j.2162-6057.2000.tb01201.x

Anzai, Y., & Simon, H. A. (1979). The theory of learning by doing. *Psychological Review*, *86*(2), 124–140. doi:10.1037/0033–295X.86.2.124

Ball, L. J., & Litchfield, D. (2013). Interactivity and embodied cues in problem solving, learning and insight: Further contributions to a "theory of hints". In S. J. Cowley & F. Vallée-Tourangeau (Eds.), *Cognition beyond the Brain* (pp. 223–239). Heidelberg: Springer.

Barnett, V., & Lewis, T. (1994). *Outliers of statistical data* (3rd ed.). Chichester: John Wiley.

Cacioppo, J. T., Petty, R. E., & Feng Kao, C. (1984). The efficient assessment of need for cognition. *Journal of Personality Assessment*, *48*(3), 306–307. doi:10.1207/s15327752jpa4803_13

Chemero, A. (2000a). Anti-representationalism and the dynamical stance. *Philosophy of Science*, *67*(4), 625–647. doi:10.1086/392858

Chemero, A. (2000b). What events are. *Ecological Psychology*, *12*(1), 37–42. doi:10.1207/S15326969eco1201_3

Chemero, A. (2011). *Radical embodied cognitive science*. Cambridge: MIT Press.

Clark, A. (2008). *Supersizing the mind: Embodiment, action, and cognitive extension*. Oxford: Oxford University Press.

Cowley, S. J. (1997a). Conversation, coordination, and vertebrate communication. *Semiotica*, *115*(1–2), 27–52. doi:10.1515/semi.1997.115.1–2.27

Cowley, S. J. (1997b). Of representations and language. *Language & Communication*, *17*(4), 279–300. doi:10.1016/S0271-5309(97)00008-6

Cowley, S. J. (2004a). Contextualizing bodies: Human infants and distributed cognition. *Language Sciences*, *26*(6), 565–591. doi:10.1016/j.langsci.2004.09.005

Cowley, S. J. (2004b). Early hominins, utterance-activity, and niche construction. *Behavioral and Brain Sciences*, *27*(4), 509–510. doi:10.1017/S0140525X04290112

Cowley, S. J. (2006). Interaction promotes cognition: The rise of childish minds. *Behavioral and Brain Sciences*, *29*(3), 283–283. doi:10.1017/S0140525X06269061

Cowley, S. J. (2007a). The cognitive dynamics of distributed language. *Language Sciences*, *29*(5), 575–583. doi:10.1016/j.langsci.2007.01.002

Cowley, S. J. (2007b). How human infants deal with symbol grounding. *Interaction Studies*, *8*(1), 83–104. doi:10.1075/Is.8.1.06cow

Cowley, S. J. (2009). Distributed language and dynamics. *Pragmatics & Cognition*, *17*(3), 495–508. doi:10.1075/p&c.17.3.01cow

Cowley, S. J. (2011). *Distributed language*. Amsterdam: John Benjamins.

Cowley, S. J. (2012). Linguistic fire and human cognitive powers. *Pragmatics & Cognition*, *20*(2), 275–294. doi:10.1075/pc.20.2.05cow

Cowley, S. J. (2014). The integration problem: Interlacing language, action and perception. *Cybernetics & Human Knowing*, *21*(1–2), 53–65.

Cowley, S. J., & MacDorman, K. F. (2006). What baboons, babies and Tetris players tell us about interaction: A biosocial view of norm-based social learning. *Connection Science*, *18*(4), 363–378. doi:10.1080/09540090600879703

Cowley, S. J., & Madsen, J. K. (2014). Time and temporality: Linguistic distribution in human life-games. *Cybernetics & Human Knowing*, *21*(1–2), 172–185.

Cowley, S. J., & Nash, L. (2013). Language, interactivity and solution probing: Repetition without repetition. *Adaptive Behavior*, *21*, 187–198. doi:10.1177/1059712313482804

Cowley, S. J., & Vallée-Tourangeau, F. (2013). *Cognition beyond the brain: Computation, interactivity and human artifice*. Dordrecht: Springer.

Davidson, J. E. (1995). The suddenness of insight. In R. J. S. J. E. Davidson (Ed.), *The nature of insight* (pp. 125–155). Cambridge: The MIT Press.

Di Paolo, E. A. (2005). Autopoiesis, adaptivity, teleology, agency. *Phenomenology and the Cognitive Sciences*, *4*(4), 429–452. doi:10.1007/s11097-005-9002-y

Duncker, K.. (1945). On problem-solving. *Psychological Monographs*, *58*(5), i–113.

Fioratou, E., & Cowley, S. J. (2009). Insightful thinking cognitive dynamics and material artifacts. *Pragmatics & Cognition*, *17*(3), 549–572. doi:10.1075/p&c.17.3.04fio

Fleck, J. I., & Weisberg, R. W. (2013). Insight versus analysis: Evidence for diverse methods in problem solving. *Journal of Cognitive Psychology*, *25*(4), 436–463. doi:10.1080/20445911.2013.779248

Flynn, B. (2011). Maurice Merleau-Ponty. In E. N. Zalta (Ed.), *The Stanford Encyclopedia of philosophy* (Fall 2011 Edition ed.). Retrieved from http://plato.stanford.edu/archives/fall2011/entries/merleau-ponty/

Gibson, J. J. (1979). *The ecological approach to visual perception*. Boston: Houghton Mifflin.

Giere, R. N. (2007). Distributed cognition without distributed knowing. *Social Epistemology*, *21*(3), 313–320. doi:10.1080/02691720701674197

Gilhooly, K., & Fioratou, E. (2009). Executive functions in insight versus non-insight problem solving: An individual differences approach. *Thinking & Reasoning*, *15*(4), 355–376. doi:10.1080/13546780903178615

Goodwin, C. (1994). Professional vision. *American Anthropologist*, *96*(3), 606–633. doi:10.1525/aa.1994.96.3.02a00100

Goodwin, C. (1997). The blackness of black: Color categories as situated practice. In L. B. Resnick, R. Säljö, C. Pontecorvo, & B. Burge (Eds.), *Discourse, tools and reasoning: Essays on situated cognition* (pp. 111–140). Heidelberg: Springer.

Goodwin, C. (2000a). Action and embodiment within situated human interaction. *Journal of Pragmatics*, *32*(10), 1489–1522. doi:10.1016/S0378-2166(99)00096-X

Goodwin, C. (2000b). Practices of color classification. *Mind, Culture, and Activity*, *7*(1–2), 19–36. doi:10.1080/10749039.2000.9677646

Goodwin, C. (2013). The co-operative, transformative organization of human action and knowledge. *Journal of Pragmatics*, *46*(1), 8–23. doi:10.1016/j.pragma.2012.09.003

Goodwin, C., & Goodwin, M. H. (1996). Seeing as situated activity: Formulating planes. In Y. Engeström & D. Middleton (Eds.), *Cognition and communication at work* (pp. 61–95). Cambridge: Cambridge University Press.

Grant, E. R., & Spivey, M. J. (2003). Eye movements and problem solving guiding attention guides thought. *Psychological Science*, *14*(5), 462–466. doi:10.1111/1467-9280.02454

Gregory, R. (1998). Brainy mind. *British Medical Journal*, *317* (7174), 1693–1695.

Guthrie, L. G., Vallée-Tourangeau, F., Vallée-Tourangeau, G., & Howard, C. (2015). Learning and interactivity in solving a transformation problem. *Memory & Cognition*, 1–13. doi:10.3758/s13421-015-0504-8

Haran, U., Ritov, I., & Mellers, B. A. (2013). The role of actively open-minded thinking in information acquisition, accuracy, and calibration. *Judgment and Decision Making*, *8*(3), 188–201.

Hollan, J., Hutchins, E., & Kirsh, D. (2000). Distributed cognition: Toward a new foundation for human-computer interaction research. *ACM Transactions on Computer-Human Interaction (TOCHI)*, *7*(2), 174–196.

Hutchins, E. (1995). *Cognition in the wild*. Cambridge: The MIT press.

Hutchins, E. (2003). Cognitive ethnography. In R. Alterman & D. Kirsh (Eds.), *Proceedings of the twenty-fifth annual conference of the cognitive science society* (p. 18). Mahwah, NJ: Lawrence Earlbaum Associates.

Hutchins, E. (2014). The cultural ecosystem of human cognition. *Philosophical Psychology*, *27*(1), 34–49. doi:10.1080/09515089.2013.830548

Järvilehto, T. (2009). The theory of the organism-environment system as a basis of experimental work in psychology. *Ecological Psychology*, *21*(2), 112–120. doi:10.1080/10407410902877066

Kirsh, D. (1997). Interactivity and multimedia interfaces. *Instructional Science*, *25*(2), 79–96. doi:10.1023/A:1002915430871

Kirsh, D. (2006). Distributed cognition: A methodological note. *Pragmatics & Cognition*, *14*(2), 249–262. doi:10.1075/pc.14.2.06kir

Kirsh, D. (2009). Problem solving and situated cognition. In P. Robbins & M. Aydede (Eds.), *The Cambridge handbook of situated cognition* (pp. 264–306). Cambridge: Cambridge University Press.

Kirsh, D. (2010). Thinking with external representations. *AI & Society*, *25*(4), 441–454. doi:10.1007/s00146-010-0272-8

Kirsh, D. (2014). The importance of chance and interactivity in creativity. *Pragmatics and Cognition*, *22*(1), 5–26.

Knowles, M. E., & Delaney, P. F. (2005). Lasting reductions in illegal moves following an increase in their cost: Evidence from river-crossing problems. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *31*(4), 670–682. doi:10.1037/0278-7393.31.4.670

Koschmann, T., LeBaron, C., Goodwin, C., & Feltovich, P. (2011). "Can you see the cystic artery yet?" A simple matter of trust. *Journal of Pragmatics*, *43*(2), 521–541. doi:10.1016/j.pragma.2009.09.009

Litchfield, D., & Ball, L. J. (2011). Using another's gaze as an explicit aid to insight problem solving. *The Quarterly Journal of Experimental Psychology*, *64*(4), 649–656. doi:10.1080/17470218.2011.558628

Luchins, A. S. (1942). Mechanization in problem solving: The effect of Einstellung. *Psychological Monograph*, 54, (whole No. 248).

Martindale, C. (1999). Biological bases of creativity. In R. Sternberg (Ed.), *Handbook of creativity* (pp. 137–152). Cambridge: Cambridge University Press.

Merleau-Ponty, M. (2002). *Phenomenology of perception*. London: Routledge.

Murray, M. A., & Byrne, R. M. (2013). Cognitive change in insight problem solving: Initial model errors and counterexamples. *Journal of Cognitive Psychology*, *25*(2), 210–219. doi:10.1080/20445911.2012.743986

Neisser, U. (1967). *Cognitive psychology*. New York, NY: Appleton-Century-Crofts.

Newell, A., Shaw, J. C., & Simon, H. A. (1958). Elements of a theory of human problem solving. *Psychological Review*, *65*(3), 151–166.

Ohlsson, S. (1992). Information-processing explanations of insight and related phenomena. In M. T. Keane & K. J. Gilhooly (Eds.), *Advances in the psychology of thinking* (Vol. 1, pp. 1–44). New York, NY: Harvester Wheatsheaf.

Ohlsson, S. (2011). *Deep learning*. Cambridge: Cambridge University Press.

Ormerod, T., & Ball, L. (2010). Cognitive psychology. In C. Willig & W. Stainton-Rogers (Eds.), *The Sage handbook of qualitative research in psychology* (pp. 554–576). London: Sage.

Pedersen, S. B. (2015). *The cognitive ecology of human errors in emergency medicine: An interactivity-based approach* (Ph.D.), Odense: University of Southern Denmark.

Pedersen, S. B., & Steffensen, S. V. (2014). Temporal dynamics in medical visual systems. *Cybernetics & Human Knowing*, *21*(1–2), 143–157.

Reed, E. S. (1996). *Encountering the world: Toward an ecological psychology*. Oxford: Oxford University Press.

Robbins, P., & Aydede, M. (2009). *The Cambridge companion to situated cognition*. New York, NY: Cambridge University Press.

Ryle, G. (1949). *Concept of mind*. London: Hutchinson's University Library.

Seifert, C. M., Meyer, D. E., Davidson, N., Patalano, A. L., & Yaniv, I. (1995). Demystification of cognitive insight: Opportunistic assimilation and the prepared-mind perspective. In R. J. S. J. E. Davidson (Ed.), *The nature of insight* (pp. 65–124). Cambridge: The MIT Press.

Simon, H. A., & Reed, S. K. (1976). Modeling strategy shifts in a problem-solving task. *Cognitive Psychology*, *8*(1), 86–97.

Stanford, K. (2013). Underdetermination of scientific theory. In E. N. Zalta (Ed.), *The Stanford Encyclopedia of philosophy* (Winter 2013 Edition). Stanford. Retrieved from http://plato.stanford.edu/archives/win2013/entries/scientific-underdetermination/.

Steffensen, S. V. (2011). Beyond mind: An extended ecology of languaging. In S. J. Cowley (Ed.), *Distributed language* (pp. 185–210). Amsterdam: John Benjamins.

Steffensen, S. V. (2013). Human interactivity: Problem-solving, solution-probing and verbal patterns in the wild. In S. J. Cowley & F. Vallée-Tourangeau (Eds.), *Cognition beyond the brain: Computation, interactivity and human artifice* (pp. 195–221). Dordrecht: Springer.

Steffensen, S. V. (2015). Distributed Language and Dialogism: notes on non-locality, sense-making and interactivity. *Language Sciences*, *50*, 105–119. doi:10.1016/j.langsci.2015.01.004

Steffensen, S. V. (in press). Cognitive Probatonics: Towards an ecological psychology of cognitive particulars.

Thomas, L. E., & Lleras, A. (2007). Moving eyes and moving thought: On the spatial compatibility between eye movements and cognition. *Psychonomic Bulletin & Review*, *14*(4), 663–668. doi:10.3758/BF03196818

Unsworth, N., Heitz, R., Schrock, J., & Engle, R. (2005). An automated version of the operation span task. *Behavior Research Methods*, *37*(3), 498–505. doi:10.3758/BF03192720

Vallée-Tourangeau, F. (2012). Utilities in the 2–4–6 task. *Experimental Psychology*, *59*(5), 265–271. doi:10.1027/1618-3169/a000152

Vallée-Tourangeau, F. (2013). Interactivity, efficiency, and individual differences in mental arithmetic. *Experimental Psychology*, *60*, 302–311. doi:10.1027/1618-3169/a000200

Vallée-Tourangeau, F., Euden, G., & Hearn, V. (2011). Einstellung defused: Interactivity and mental set. *Quarterly Journal of Experimental Psychology*, *64*(10), 1889–1895. doi:10.1080/17470218.2011.605151

Vallée-Tourangeau, F., & Payton, T. (2008). Graphical representation fosters discovery in the 2–4–6 task. *Quarterly Journal of Experimental Psychology*, *61*(4), 625–640. doi:10.1080/17470210701268039

Vallée-Tourangeau, F., Steffensen, S. V., Vallée-Tourangeau, G., & Makri, A. (2015). Insight and cognitive ecosystems. In D. C. Noelle, R. Dale, A. S. Warlaumont, J. Yoshimi, T. Matlock, C. D. Jennings, P. P. Maglio (Eds.), *Proceedings of the thirty-seventh annual conference of the cognitive science society*, Austin, TX: Cognitive Science Society.

Vallée-Tourangeau, G., & Vallée-Tourangeau, F. (2014). The spatio-temporal dynamics of systemic thinking. *Cybernetics & Human Knowing*, *21*(1–2), 113–127.

Van Orden, G. C., Holden, J. G., & Turvey, M. T. (2003). Self-organization of cognitive performance. *Journal of Experimental Psychology: General*, *132*(3), 331–350. doi:10.1037/0096-3445.132.3.331

Vartanian, O. (2009). Variable attention facilitates creative problem solving. *Psychology of Aesthetics, Creativity, and the Arts*, *3*(1), 57–59. doi:10.1037/a0014781

Vartanian, O., Martindale, C., & Kwiatkowski, J. (2003). Creativity and inductive reasoning: The relationship between divergent thinking and performance on Wason's 2–4–6 task. *The Quarterly Journal of Experimental Psychology: Section A*, *56*(4), 641–655. doi:10.1080/02724980244000567

Vartanian, O., Martindale, C., & Kwiatkowski, J. (2007). Creative potential, attention, and speed of information processing. *Personality and Individual Differences*, *43*(6), 1470–1480. doi:10.1016/j.paid.2007.04.027

Vartanian, O., Martindale, C., & Matthews, J. (2009). Divergent thinking ability is related to faster relatedness judgments. *Psychology of Aesthetics, Creativity, and the Arts*, *3*(2), 99–103. doi:10.1037/a0013106

Villejoubert, G., & Vallée-Tourangeau, F. (2011). Constructing preferences in the physical world: A distributed-cognition perspective on preferences and risky choices. *Frontiers in Psychology*, *2*, Article ID: 302. doi:10.3389/fpsyg.2011.00302

Walton, D. (1999). Rethinking the fallacy of hasty generalization. *Argumentation*, *13*(2), 161–182. doi:10.1023/A:1026497207240

Weisberg, R. W. (2015). Toward an integrated theory of insight in problem solving. *Thinking & Reasoning*, *21*(1), 5–39. doi:10.1080/13546783.2014.886625

Wittenburg, P., Brugman, H., Russel, A., Klassmann, A., & Sloetjes, H. (2006). *ELAN: A professional framework for multimodality research*. Proceedings of LREC.