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Running head: Conceptualizing perceptual information

**Towards a new ecological conception of perceptual information:  
Lessons from a developmental systems perspective**

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**Abstract**

Over the last two decades or so, empirical studies of perception, action, learning, and development have revealed that participants vary in what variable they detect and use and often rely on non-specifying variables. This casts doubt on the Gibsonian conception of information as specification. It is argued that a recent ecological conception of information has solved important problems, but falls short in explaining what determines the object of perception. Drawing on recent work on developmental systems, we sketch the outlines of an alternative conception of perceptual information. It is argued that perceptual information does not reside in the ambient arrays; rather, perceptual information is a relational property of patterns in the array and perceptual processes. What a pattern in the ambient flow informs about depends on the perceiver who uses it. Here, we explore the implications of this alternative conception of information for the ecological approach to perception and action.

Key words: developmental systems theory, ecological psychology, information, perception-action

**Towards a new ecological conception of perceptual information:****Lessons from a developmental systems perspective**

*Adding information to matter and energy is something like speaking of nations exchanging dollars, yen, and profits. The third term belongs on a different level. Not another form of currency, it describes a certain disposition and the use of currencies. Just as time or information can, under certain circumstances, “be” money, matter and energy can sometimes “be” information.*

(Oyama, 1985/2000, p. 40)

The concept of information is a strongly debated notion in the study of perception and action. Indeed, among the issues that separate contemporary approaches to perception and action is the idea of what information is and where it resides. Proponents of indirect theories of perception have asserted that the information involved in perception exists both in the environment and the perceiver. Roughly speaking, this theory holds that the stimulus information that impinges on the senses is impoverished and needs to be enriched (e.g., Fodor & Pylyshyn, 1981; Neisser, 1967; Ullman, 1980). Thus, information residing in the animal enriches the impoverished stimulus information that the senses receive from the environment. Advocates of the theory of direct perception, by contrast, have claimed that all the information that is needed for perception is “out there” in the environment. J. J. Gibson (1966, 1979/1986), the founder of the ecological theory, asserted that the ambient energy arrays contain information that is rich and sufficient for perception. Because information in the arrays is specific to environmental properties, enrichment processes can be dispensed with. Perception is simply the extraction of specifying information that resides in the ambient array.

Since its inception in the 1960s and 1970s, J. J. Gibson’s ecological theory of perception and action has inspired many researchers, giving rise to a fruitful experimental program, the results of which are steadily accumulating (e.g., Fajen & Warren, 2003; Riley & Turvey, 2001; Runeson, Juslin,

& Olsson, 2000; Turvey, Shockley, & Carello, 1999). The central question in this program has been: “What specifying variable in the ambient array is used to perform a particular task?” (see Fajen, 2005, for a nice overview). Although the theory of direct perception has gained credibility over the past couple of decades or so, several empirical studies have revealed inadequacies in the concept of information as specification. Participants were found to vary in the informational basis of their perception or action (e.g., Jacobs, Michaels, & Runeson, 2000; Jacobs, Runeson, & Michaels, 2001; Menger & Withagen, in press; Michaels & de Vries, 1998; Michaels, Arzamarski, Isenhowe, & Jacobs, 2008; Runeson et al., 2000; Runeson & Andersson, 2007; Withagen & Michaels, 2005b; Withagen & van Wermeskerken, 2009). Furthermore, several studies have revealed that participants often rely on variables that correlate with, but are not specific to, the to-be-perceived property (e.g., Caljouw, van der Kamp, & Savelsbergh, 2004; Jacobs et al., 2001; Michaels, Zeinstra, & Oudejans, 2001; Tresilian, 1999; van de Langenberg, Kingma, & Beek, 2006; van der Kamp, Savelsbergh, & Smeets, 1997). This means that in the ecological approach to perception and action a new conception of information is called for. In this paper, we sketch the outlines of such a conception.

First, we provide a portrayal of the Gibsonian theory of direct perception and its conception of information. Then, we summarize some empirical studies that have casted doubt on the Gibsonian notion of information. We argue that Chemero’s (2003b, 2009) alternative ecological conception of information solves important problems, but insufficiently explains what determines the object of perception. Drawing on recent work on information in developmental systems (Oyama, 1985/2000 2000), we then sketch a new conception of perceptual information. It is argued that perceptual information resides neither in the environment nor in the perceiver. Instead, perceptual information is a relation between patterns in the ambient array and perceptual processes. We end with exploring the implications of this conception of information for the ecological approach to perception and action.

### **J. J. Gibson’s theory of perception and its conception of information**

Although the central tenets of the theory of direct perception can be traced back to Aristotle (Lombardo, 1987; see also Heft, 2001), this theory is often conceived of as a relatively modern approach to perception. This is perhaps due to the fact that this theory is often attributed to James Gibson, who developed arguably the most influential version of the theory of direct perception in the 1960s and 1970s. At the time J. J. Gibson developed his ecological view, cognitive psychology was in its ascendancy. This more traditional psychology comprises a theory of perception that is almost diametrically opposed to the perspective that J. J. Gibson laid out. The cognitive theory treats perception primarily as a mental affair (see e.g., Fodor & Pylyshyn, 1981; Neisser, 1967). It is argued that the senses receive impoverished information from the environment. The energy patterns that impinge on the sense organs do not contain a specification of the environmental state of affairs; rather, they relate ambiguously to environmental properties. Thus, the same stimulus information can be the result of different environmental states of affairs, and the same environmental state of affairs can lead to different stimuli. The perceiver, then, has to construct a meaningful percept of the environment out of this ambiguous stimulus information. As Neisser (1967) put it:

Whatever we know about reality has been *mediated*, not only by the organs of sense but by complex systems which interpret and reinterpret sensory information. [...] [The] patterns of light at the retina are the so-called “proximal stimuli”. [...] One sided in their perspective, shifting radically several times each second, unique and novel at every moment, the proximal stimuli bear little resemblance to either the real object that give rise to them or to the object of experience that the perceiver will construct as a result.

Visual cognition, then, deals with the processes by which a perceived, remembered, and thought-about world is brought into being from as unpromising a beginning as the retinal patterns. (pp. 3-4)

To explain perception, then, is to reveal how the perceptual processes transform the impoverished stimulus into a meaningful percept.

J. J. Gibson (1966, 1979/1986) criticized the indirect perception theory on several grounds and developed an ecological view. He criticized the idea that the stimulus information available to the senses is ambiguous and needs to be enriched. Instead, J. J. Gibson proposed that perceptual information is specific to environmental properties. That is, information relates one-to-one to properties of the environment. He argued that such specifying information resides in the ambient arrays, the energy arrays that surround us. At several points, J. J. Gibson (1961, 1970) aimed at objectifying this specifying information—he tried to define it without reference to the perceiver. Indeed, the structured array is defined with respect to a (moving) point of observation in the environment that may or may not be occupied. As Costall (2003) put it,

In order to make ‘space’ in his theory for an *active* perceiver, Gibson no longer came to define information in terms of stimulation actually impinging upon the receptors. He attempted, instead, to define information *without reference to the perceiver* [...]. In his ‘ecological optics’, Gibson set the perceiver on one side, as it were, and defined information in terms of the ‘optic array’-the light structured by reflection against the surrounding surfaces and converging upon a static or moving ‘point’ in the environment. For Gibson, the purpose of this separation of information and the perceiver was to capture the idea that information is actively *obtained*, not imposed (pp. 75-76; emphases in original).

This distinction between obtained and imposed stimulation is central in his ecological view. J. J. Gibson fervently asserted that perception is an active process in which many bodily parts are involved. “I shall suggest that natural vision depends on the eyes in the head on a body supported by the ground, the brain being only the central organ of a complete visual system” (J. J. Gibson, 1979/1986, p. 1). Perceptual activity is not only involved in the detection of specifying information, it can also



create it. As just mentioned, J. J. Gibson defined information with respect to a point of observation. Any movement of this point of observation creates stimulus patterns that are specific to the environment and the animal-environment relation. Consider, for instance, optic flow that comes into existence when a point of observation “moves” through the environment. This flow field contains abundant information about the environment and the animal’s relation to it (see e.g., Warren, 1998). A classic example is the optical variable tau, which specifies the time to contact between an object and a moving animal. More precisely, the inverse of the relative rate of change of optical angle subtended at the point of observation relates one-to-one to the time remaining before contact (Lee, 1976; Knowles & Carel, 1958). Researchers have argued that tau is exploited by plummeting gannets to dive into water (Lee & Redish, 1981), by somersaulters to land on their feet (Lee, Young, & Rewt, 1992), and that tau can also be exploited to guide interceptive actions like catching balls (e.g., Savelsbergh, Whiting, & Bootsma, 1991). Elegantly, the change of optical angle not only depends on the motion of the point of observation but also on the object’s motion. In short, tau is thought to provide information about time to contact for a large variety of animals (i.e., from flies to birds to humans) to guide self-motion and actions targeted at moving objects.

J. J. Gibson’s idea that there are patterns in the ambient array that relate one-to-one to the environment (or the animal-environment relation) allows for a new, direct theory of perception. Because the information specifies the environmental property, inferential processes that transform impoverished stimulus information into a percept can be dispensed with. Perception is simply the extraction of specifying variables in the array, full stop. Indeed, proponents of the theory of direct perception assert that the perception of an environmental property is the result of the detection of a variable that is specific to it. That is, animals perceive the environmental property that the detected variable specifies (e.g., Turvey, 1990). Ever since its inception (in the 1960s and 1970s), this theory of direct perception led to an interesting experimental program that focused on the discovery of the specifying patterns that animals are hypothesized to use to perceive and act (e.g., Burton & Turvey, 1990; Carello & Turvey, 2004; Turvey & Carello, 1995; Turvey & Shaw, 1999).

J. J. Gibson's ecological psychology not only comprises a theory of how perception comes about, it also contains a hypothesis on the objects of perception. According to J. J. Gibson (1979/1986), the primary objects of perception are the action possibilities in the animal's environment. He coined these possibilities *affordances*. For example, a cup is graspable, the floor is walk-on-able, and a chair affords sitting. J. J. Gibson asserted that animals perceive their environment primarily in terms of such action possibilities. There are two issues worth mentioning about affordances at this stage. First, they have a peculiar ontological status. Affordances exist by virtue of the physical properties of the world relative to the action capabilities of the animal. It is the size of the cup relative to the size of the hand that makes it graspable. So the existence of an affordance implies a fit between animal and environment. This means that the same object can afford different behaviors for different animals. A cup of water affords drinking for a human being, but affords walking for a water strider. Second, an environment consisting of affordances is a meaningful environment. The affordances in the animal's environment determine what the animal can do in it, that is, what the environment means to it. As J. J. Gibson (1982) put it, "the meaning or value of a thing consists of what it affords" (p. 407). Hence, according to the ecological theory, meaning does not emerge in the perceptual process. Rather, the environment in and of itself is meaningful and this meaning can be directly perceived by detecting the information that specifies the affordances.

### **Empirical studies of perception, action, learning, and development**

The search for specifying variables in the ambient array that animals are claimed to use to perceive and act has led to intriguing discoveries (e.g., Amazeen & Turvey, 1996; Savelsbergh et al., 1991). Over the last decade, however, several studies of perception and action have seriously questioned the viability of the ecological conception of information as specification. Inclined to an ecological perspective, these studies have searched for specifying patterns in the ambient arrays that uniquely constrain the perception or action. Yet they have revealed that humans often rely on variables that correlate with, but are not specific to, the to-be-perceived property (e.g., Caljouw et al., 2004; Mi-

chaels et al., 2001; Tresilian, 1999; van de Langenberg et al., 2006; van der Kamp et al., 1997). Furthermore, studies of learning and development have demonstrated that participants initially vary in what variable they exploit and often rely on variables that relate ambiguously to the environment. However, after feedback they can converge on more useful patterns in the ambient array, but often end up detecting variables that do not specify the to-be-perceived property (e.g., Fajen & Devaney, 2006; Jacobs et al., 2000, 2001; Kaye & van der Meer, 2000, 2009; Michaels & de Vries, 1998; Michaels et al., 2008; Runeson et al., 2000; Runeson & Andersson, 2007; van Hof, van der Kamp, & Savelsbergh, 2006, 2008; Wagman, Shockley, Riley, & Turvey, 2001; Withagen & Michaels, 2005b; Withagen & van Wermeskerken, 2009). It is beyond the scope of this paper to provide a detailed description of all these studies. Hence, we limit ourselves here to a couple of studies that make a case in point.

One illustrative series of experiments was conducted by van de Langenberg, Kingma, and Beek (2006; Kingma, van de Langenberg, & Beek, 2004) who examined the use of mechanical invariants in dynamic touch. Dynamic touch refers to the capacity to haptically perceive object properties (e.g., weight, length, form) by simply holding the object in the hand or wielding it (see e.g., Turvey & Carello, 1995). Kingma et al. studied the perception of rod length and weight. They tried to determine what mechanical invariant is used to perceive these properties in different mechanical conditions. One important result is that the same mechanical invariant is used to perceive different properties of the rod. Both the perception of weight and the perception of length are constrained by static moment ( $M$ ), at least in certain mechanical conditions. Thus, the detection of the same mechanical invariant can result in the perception of different rod properties. Another pertinent finding is that which mechanical invariants underlie the perceptual judgments depends on the mechanical context in which the task has to be performed.<sup>1</sup> For example, van de Langenberg et al. found that while holding a rod horizontally, the length judgment was a function of  $M$ . When holding the rod vertically, on the other hand, the length judgments are constrained by the rod's mass ( $m$ ). And when wielding the rod horizontally, both the first principal moment of inertia ( $I_1$ ) and  $M$  are

used to estimate the length. Apparently, the perception of length can be constrained by different mechanical invariants. Furthermore, these invariants correlate with rod length but are not specific to it. After all, the mechanical variables  $M$ ,  $m$ , and  $I_r$  are all functions of the length, material density, and radius of the rods. This means that equal-length rods can vary in these invariants. That is, these variables do not specify length, but relate ambiguously to it.

The insight that patterns in the ambient array can constrain the perception of a certain environmental property or guide a certain action is also demonstrated in studies of learning and development. The Gibsons (E. J. Gibson, 1963/1991; J. J. Gibson & E. J. Gibson, 1955; J. J. Gibson, 1966) argued that perceptual learning is a process of differentiation. The underlying idea of this theory is that patterns in the ambient array differ in degree of usefulness. Some of these patterns have a weak correlation with the to-be-perceived property, others have a moderate correlation, and some might be specific to that property. Hence, a perceiver can improve in the perception of some environmental property by learning to exploit the more useful, or even specifying informational variable. The Gibsons termed this process *the education of attention*, a process which has now been demonstrated in many studies of learning and development. Van Hof et al. (2006), for instance, studied the development of visually guided catching in early infancy. They found that the age-related improvements in catching skills are (partly) attributable to changes in the use of optical variables. More precisely, the babies changed from the exploitation of moderately useful monocular variables to more useful binocular optical variables (see also van Hof et al., 2008). Kaye and van der Meer (2000, 2007) showed similar developmental changes in variable use in the control of eye blinking movements during the first 6 months after birth. This process of the education of attention has also been demonstrated in several perceptual tasks: the visual perception of the pulling-force of a stick figure (e.g., Michaels & de Vries, 1998), the visual perception of the relative mass of colliding balls (e.g., Jacobs et al., 2000, 2001; Runeson et al., 2000; Runeson & Andersson, 2007), and height and length perception by dynamic touch (Menger & Withagen, in press; Michaels et al., 2008; Wagman et al., 2001; Withagen & Michaels, 2005b; Withagen & van Wermeskerken, 2009).<sup>2</sup> These studies

all show that the detected variables often correlate with the to-be-perceived property, but are not specific to it. Furthermore, they indicate that changing from one variable to another over time does not entail a change in the object of perception; rather, the same environmental property is perceived but the accuracy of the judgments changes. Thus, different variables can be used to perceive the same environmental property.

### **Chemero's conception of information**

The above-mentioned studies raise serious questions on the viability of the conception of information as specification. Indeed, perceivers have been found to rely on patterns in the ambient array that correlate with the to-be-perceived property, but do not relate one-to-one to it. This questions not only the conception of information as specification, it also suggests that perception is sometimes indirect. Over the last decade, several ecological psychologists have addressed these issues (e.g., Michaels & de Vries, 1998; Runeson et al., 2000; Withagen, 2004; Withagen & Chemero, 2009). An important contribution in this respect is Chemero's (2003b, 2009) new ecological conception of information.

Drawing on the work of Barwise and Perry (1981, 1983) and Millikan (2000), Chemero (2003b, 2009) recently developed a sophisticated ecological theory of information that aims to overcome several difficulties.<sup>3</sup> What Chemero aims at is a conception of information that explains how nonspecifying variables can carry information about an environmental property. A nonspecifying variable correlates with an environmental property but does not relate to it one-to-one. Chemero's conception is therefore a significant break with the traditional ecological theory that defines information in terms of specificity. Following Barwise and Perry, Chemero argued that information is contingent on constraints. Situation X carries information about situation Y if there are constraints that connect X and Y. As an example, the previously mentioned optical pattern tau contains information about time-to-contact because the laws of ecological optics (constraint) connects this pattern to the time-to-contact. However, although laws are constraints, constraints are not al-

ways laws. In fact, local conventions and other regularities can also function as constraints. That is, they can also connect situations implying that one carries information about the other. Chemero provides the example of a beer can and its contents. Because the bottling factory reliably fills these cans with beer (constraint), the can carries information about beer presence. However, this constraint is not a law. Indeed, this convention is easily violated. In case of a practical joke or a malfunctioning bottling factory, the can may not be filled with beer. Yet in Chemero's view the can still carries information about beer. Arguing that information is contingent on constraints, and constraints can be laws, local conventions and other regularities, Chemero's conception of information allows nonspecifying variables to carry information about an environmental property. Variables that correlate with environmental properties (because of constraints) can still carry information about them. Following Millikan's teleosemantic view, Chemero places his theory of information in the context of evolutionary theory. A variable can serve as information if its correlation with the environmental property is "reliably enough that some animal can use it to guide its behavior" (Chemero, 2009, p. 119).

Although Chemero (2009) breaks with the traditional ecological conception of information as specification, it is important to note that he went at great pains to argue that his conception of information is consistent with the theory of direct perception (see also Withagen & Chemero, 2009). He asserted that the detection of nonspecifying variables does not entail that perception is mediated and based on computational processes and internal representations. Instead, Chemero defines direct perception as tracking (see Smith, 1996). That is, perception is direct if there is a "continuous column of disturbance" (Chemero, 2009, p. 115), beginning at the environment and ending at the animal. He provides the example of an outfielder visually tracking a ball. The column of disturbance means that the outfielder continuously tracks the ball—there is a strong (causal) connection between the outfielder and the ball. And such direct epistemic couplings can be established by the detection of both specifying information and nonspecifying information. As Chemero put it,

[t]he same optical patterns can be caused by the full moon and a light bulb on a cloudy night. And there will be some sort of continuous column of disturbance connecting a moth to each. So the moth will be effectively tracking whichever of the two it happens to be connected with. When the moth is effectively tracking the light bulb, it is making a mistake. But this does not mean that it is tracking the bulb via a mental representation of the moon. For if it did, then it would also be tracking the moon via a mental representation of the moon when it was doing things correctly and perception would never be direct. (pp. 115-116)

So in Chemero's (2003b, 2009) view, perception is always direct and the result of the exploitation of information, that is, patterns in the ambient array that specify or correlate with environmental properties.

*What problems does Chemero's conception of information solve?*

Chemero's (2003b, 2009) ecological conception of information is valuable in many respects. It elucidates that animals can directly perceive an environmental property even when relying on non-specifying variables. This has several advantages. First, it explains how animals can directly perceive environmental properties that are not specified in the ambient energy flows. Over the years, ecological psychologists have recognized that probably not all environmental properties are specified by ambient patterns (e.g., Chemero; Jacobs, 2001; Turvey & Carello, 1995; Vicente, 2003). Yet according to Chemero's theory of information, animals can still directly perceive such environmental properties by virtue of the exploitation of nonspecifying variables. Second, Chemero's conception is consistent with the recent demonstrations that humans often perceive an environmental property on the basis of a nonspecifying variable that correlates with it (e.g., Caljouw et al., 2004; Jacobs et al., 2001; Michaels & de Vries, 1998; Runeson et al., 2000; Runeson & Andersson, 2007; Tresilian,

1999; van de Langenberg et al., 2006; Withagen & Michaels, 2005b; Withagen & van Wermeskerken, 2009). Third, Chemero's conception of information is of special interest for studies of learning and development. Indeed, arguing that information is contingent on constraints, Chemero's conception of information allows different variables in the array to carry information about the same environmental property. Thereby it is consistent with the empirical finding that in the process of learning and development, the object of perception can remain the same while participants change in the variables they detect (e.g., Fajen & Devaney, 2006; Jacobs et al., 2001; Kaye & van der Meer, 2009; Menger & Withagen, in press; Michaels & de Vries, 1998; Runeson et al., 2000; Runeson & Andersson, 2007; van Hof et al., 2006; Wagman et al., 2001; Withagen & Michaels, 2005b; Withagen & van Wermeskerken, 2009).

*What problems emerge?*

Although Chemero's (2003b, 2009) conception of information overcomes several difficulties, we think that it insufficiently explains what determines the environmental property that is perceived. Recall that according to the traditional ecological perspective, animals perceive the environmental property that the detected variable specifies. So if a certain pattern in the ambient array specifies environmental property  $X$ , detecting that pattern results in the perception of  $X$ . That is, it is the variable that is detected that determines what environmental property is perceived. Arguing that variables that correlate with an environmental property can also carry information about it, Chemero cannot explain the object of perception solely in terms of the variable that is detected. Although his advocacy of Millikan's (2000) teleosemantic perspective puts some constraints on what determines the object of perception, Chemero's theory insufficiently explains what environmental property an animal perceives when it detects a variable. After all, a pattern in the array can correlate with and thus carries information about many environmental properties. For example, because of constraints (i.e., the laws of mechanics) the abovementioned variable  $M$  correlates with the length, the weight, and perhaps even with the color of rods. So what determines that a participant



perceives the length of the rod and not its color when detecting this variable? Especially in the light of recent experimental findings, this question is all the more relevant. Indeed, we have seen that recent studies found that the detection of the same variable can contribute to the perception of different environmental properties (e.g., Kingma et al., 2004). Furthermore, animals can perceive the same environmental property on the basis of different variables (e.g., Cutting, 1991; Jacobs et al., 2001; Michaels & de Vries, 1998; van de Langenberg et al., 2006; van der Kamp et al., 1997; Withagen & van Wermeskerken, 2009). Although extremely valuable, a conception of information in terms of correlation does not help to explain what environmental property is perceived when detecting a variable.

However, one might wonder whether the information concept should be capable of explaining the object of perception. After all, one can always introduce internal processes to explain what is perceived. For example, based on Kingma et al.'s (2004) finding that *M* is used to perceive both rod length and weight, one might argue that the perceiver's intention determines which of these properties is perceived at a particular moment in time. However, we believe that this is not the track ecological psychologists should follow. After all, it implies that perception includes more than the detection of information. In fact, it runs the risk of introducing processes that transform a pattern in the stimulus array into a percept, an idea that is not consonant with the fundamental principles of the ecological approach. Ideally, the theory of direct perception contains a concept of information that also explains the object of perception, that is, what environmental property is perceived. A possible solution is to define information relationally. Not in terms of the relation between a pattern in the array and the environment (as Gibson and Chemero did), but as a relation between this pattern and the perceiver. In the remainder of the paper, we sketch the outlines of such a conception.

### **A developmental systems approach to perceptual information**

It is our contention that recent work on information in developmental systems theory (DST) can

help in developing a concept of perceptual information that fits with the fundamental assumptions of the ecological approach. In biology, the idea of developmental systems is rather old (e.g., Gottlieb, 1970; Lehrman, 1953; Lewontin, 1983). However, this approach gained currency over the last decades partly because of the works of several eminent authors (for an overview see Oyama, Griffiths, & Gray, 2001). Among these authors is Oyama (1985/2000, 2000) who forcefully asserted that animal form is the result of multiple factors (or “interactans”) that mutually constrain and even define each other.

Before we lay out the developmental systems perspective, it is important to note that we are not the first ecological scientists who draw attention to DST. Over the years, DST had inspired several ecologically inspired researchers. In fact, DST has become rather popular in the ecological approach lately. For example, the developmental psychologists Thelen and Smith (1994) used the insights of both J. J. Gibson (1966, 1979/1986) and Oyama (1985/2000) in their dynamical systems approach to the development of cognition and action (see also Dent-Read & Zukow-Goldring, 1997). The anthropologist Ingold (2000) combined ecological psychology with phenomenology and DST, arguing that these different perspectives share a common ground (e.g., p. 173). Recently, Wagman and Miller (2003) and Turvey (2009) also explored the links between ecological psychology and DST. And Withagen and Chemero (2009) proposed a developmental systems approach to understand variation in the use of variables (see also Menger & Withagen, in press; Withagen & van Wermeskerken, 2009). However, up to this point, ecological psychologists have barely referred to the work of developmental systems theorists with respect to the conceptualization of information in perception-action. As far as we know, the only exceptions are Michaels (2000) who made a quick reference to the work of Oyama, arguing that we need more theory to understand how optical variables become information; and Costall who, contrary to many ecological psychologists, aimed at a mutualist conception of information. The fact that DST is not central in the ecological study of information is, in our opinion, unfortunate. Indeed, we believe that the concept of ontogenetic information that emerges in the work of Oyama can help in reconceptualizing perceptual informa-

tion. The main argument for this contention is perhaps the striking parallel between recent findings in the ecological study of perception-action, and considerations on the role of genes in ontogenetic processes that proponents of DST put forward. As previously mentioned, recent studies of perception have found that the same variable in the ambient array can constrain the perception of different environmental properties. Analogously, proponents of DST claimed that the same piece of DNA can result in different animal forms (e.g., Lewontin, 2001; Oyama et al., 2001). Conceptually this is identical. So for researchers of perception and action, there might be some lessons to learn from DST when it comes to the nature of information. Below we first sketch the developmental systems perspective of Oyama (1985/2000, 2000). Then we explore how her concept of information can be applied to the ecological study of perception and action.

#### *Oyama's relational conception of information*

Oyama's (1985/2000; 2000) work is primarily concerned with the process of ontogeny. Typically, ontogeny has been conceived of as a genetically determined process. That is, developmental information, residing in the genes, specifies the ontogenetic process that gives rise to the animal form. As argued by several authors (e.g., Ingold, 2000, 2006, 2008; Oyama, 1985/2000, 2000; Thelen & Smith, 1994), this idea rests on an assumption that is almost central in Western thought—form is the result of a design or program that imposes structure to a material substrate. So the program already contains the form, albeit in a rather abstract code. In the case of ontogeny this means that the animal form already exists in the genetic program and manifests itself in the developmental process. Although there are many theories of ontogeny, Oyama demonstrated that the vast majority is based on the assumption that developmental information pre-exists the animal and gives rise to it.

Oyama strongly argued against this view. Indeed, her seminal book titled *The ontogeny of information* (1985/2000) is laced with arguments against the idea that ontogenetic processes are the result of genetic programs. There is no central controller in the ontogenetic processes. To her

mind, animal form is not the expression of a form that already exists in the genes. Rather, animal form is continuously generated. There is a myriad of factors (see Oyama, 2000, p. 73-74), the interaction of which gives rise to the development of the organism. Oyama coined her view *constructivist interactionism* but was quick to point that her perspective is not an instance of conventional interactionism—the almost void statement that animals are the result of the interaction between genes and environment. According to Oyama, such a view is mistaken in several respects.

First, Oyama (1985/2000, 2000; Oyama et al., 2001) claimed that the distinction between genes and environment is artificial and arbitrary. In the ontogenetic process many factors are involved and none of them is in control or has logical priority. Thus, grouping all the non-genetic factors together, calling it the gene's environment and conceiving it as one of the two interactants in the process is oversimplified. It does not capture the complex interaction between the many factors and levels that are involved. Indeed, according to Oyama regulation is distributed among these factors. The non-genetic factors are not just supportive in that they provide the building blocks for the ontogenetic process. Rather, they are formative; that is, they have a constitutive role in the ontogenetic process and thereby co-determine the animal form (see also Gottlieb, 1998, 2007; Lewontin, 2001).

Second, conventional interactionism generally treats genes and environments as separate entities that can interact. However, Oyama argued that genes and environments are not self-contained entities. Instead, genes and environment define each other. That is, the environment determines what constitutes a gene, and vice versa. Oyama thereby followed a mutualist line of thinking that earlier authors like Lewontin (1983) and J. J. Gibson (1979/1986) had developed. As we have seen, J. J. Gibson argued that the environment consist of affordances and is, thus, animal relative. Indeed, the action capabilities of the animal determine what constitutes the affordances and thus the environment. In like fashion, Oyama claimed that gene and environment are mutually dependent. As Lewontin summarized her position, “[o]rganisms are the nexus of external circumstances and DNA molecules that make these physical circumstances into causes of developmental

in the first place. They become *causes* only at their nexus, and they cannot exist as *causes* except in their simultaneous action” (in Oyama, 1985/2000, p. xiv; emphases in original). Thus, the factors involved in the ontogenetic process not only interact, they also determine and define each other. They have no meaning in themselves. This is what Oyama (1985/2000) called *reciprocal selectivity*, which forms the hallmark of her view.

Oyama (1985/2000, 2000) explored the wide implications of her developmental systems perspective for evolutionary theory, morality, the nature-nurture divide, epistemology, experimental research, and many other themes. However, for the purposes of our paper, we limit ourselves here to her ideas about genes and developmental information. Although Oyama rejected the idea of a genetic program, she defended a conception of developmental information. She followed Bateson (1972, p. 315) in defining information as “a difference that makes a difference” (Oyama, 1985/2000, p. 3). However, and this is central to our argument, Oyama strongly pursued the notion that developmental information can only be understood relationally. That is, information does not pre-exist the animal, it does not reside in the genes or the environment. To the contrary, information emerges in the developmental process. As Oyama (1985/2000) put it, “Yet information ‘in the genes’ or ‘in the environment’ is not biologically relevant until it participates in phenotypic processes. It becomes meaningful in the organism only if it is constituted as ‘information’ by its developmental system” (p. 16). Therefore, a certain interactant becomes information only in the ontogenetic process. Furthermore, what it does and, thus, what information it conveys depends on this process. “Chromosomal form is an interactant in the choreography of ontogeny; the ‘information’ it imparts or the form it influences in the emerging organism depends on what dance is being performed when, where, and with whom” (Oyama, 1985/2000, p. 26). Again, we see here the reciprocal selectivity that we mentioned above. What a factor is and what difference it does make depends on the context in which it participates. Hence, in Oyama’s view information is not reified, it does not reside in material substrates, it does not pre-exist the ontogenetic process. Rather, it emerges in this process. As Klopfer (1973) asserted, “[a cell is] an information *generating* device,

not an information *containing* device” (quoted in Oyama, 2000, p. 42; emphases in original).

*Applying Oyama’s conception of information to perception-action*

To what extent can Oyama’s conception of information be applied to the study of perception and action? In her books, Oyama herself made some brief comments about this. “I suspect that many ideas of sensory information (and, while we are at it, of mental representations) are not only as problematic as their genetic counterpart in discussions of development; they are, finally, instances of the same usage” (Oyama, 2000, p.17). We agree. Perceptual information is too often reified, claimed to reside in patterns in the ambient array (e.g., J. J. Gibson, 1961; see Costall, 2003). Recall the traditional ecological view developed by J. J. Gibson and the prominent neo-Gibsonians. According to this view, the structured energy patterns are defined with respect to a point of observation. A pattern is claimed to contain information about an environmental property if it relates one-to-one to it. Thus information is intrinsic to the pattern. Of course, and as we have seen, by occupying (and changing) their point of observation, perceivers often create the patterns in the array (e.g., Warren, 1998). This means that these patterns can also specify properties of the animal and its (changing) relation to the environment. Yet, the perceiver is of no account in determining what information the pattern conveys. Indeed, it has been claimed that detecting a pattern results in the perception of the environmental property (or animal-environment relation) that is specified by that pattern. As previously mentioned, Chemero’s (2003b, 2009) alternative conception of information is different in that it does not define information in terms of specificity but in terms of correlations. Indeed, Chemero claimed that information is contingent on constraints that do not necessarily imply one-to-one relations between patterns in the array and environmental properties. Although he argued that the correlation needs to be reliably enough that an animal can use the variable to guide its actions, Chemero still defined information in terms of relations between the environment and patterns in the array. That is, information is still claimed to reside in the environment, existing independently of the perceiver. What does it mean to apply Oyama’s ideas

about information to the ecological study of perception-action? What conception of perceptual information does it result in? And, more importantly, what problems does it solve?

First, applying Oyama's conception of information to the study of perception-action means that perceptual information is not reified. It does not reside in patterns in the ambient array or a material substrate. Just as there is no developmental information in the DNA, there is no perceptual information in the ambient array. This is not to deny the highly structured energy patterns in the ambient arrays that animals can use (e.g., tau, optic flow). However, *perceptual information cannot be equated with such patterns.*

Second, and related to this, applying Oyama's conception to the study of perception-action means that perceptual information is defined relationally. A pattern in the ambient array can become perceptual information only in the process of perception, just as DNA can become developmental information only in the ontogenetic processes. As Johnston (1997) put it, "information defines a kind of relation, not a kind of substance. An informational relationship exists between two systems [...] if one of them can influence the other in some systematic way" (p. 89). Furthermore, just as the information that is conveyed by a chromosomal form depends on the ontogenetic process, what perceptual information a pattern in the array conveys depends on the perceptual processes. As Oyama (1985/2000) put it, "the impact of sensory stimuli is a joint function of the stimuli and the sensing organism; the 'effective stimulus' is defined by the organism that is affected by it" (p.38). Thus, the same pattern can convey different information for different animals, or even for the same animal at different moments in time. This is in keeping with recent experimental findings in the ecological study of perception and action. Indeed, as mentioned above, recent studies have found that the detection of the same pattern in the array can result in the perception of different environmental properties at different moments in time (e.g., Kingma et al., 2004). So what a pattern in the array informs about is co-determined by the perceptual process it is participating in. Defining perceptual information relationally also means that different patterns in the array can convey the same information. This conception of perceptual information is thus consistent with recent studies

of perceptual learning and development. As we have seen, these studies have revealed that in the process of learning and development, perceivers often change in the pattern they detect, but still perceive the same environmental property (although the accuracy of the perception changes) (e.g., Fajen & Devaney, 2006; Jacobs et al., 2001; Menger & Withagen, in press; Michaels & de Vries, 1998; Runeson et al., 2000; Runeson & Andersson, 2007; van Hof et al., 2006, 2008; Wagman et al., 2001; Withagen & Michaels, 2005b; Withagen & van Wermeskerken, 2009).

Third, applying Oyama's conception of information to the ecological study of perception-action implies a shift in focus on the animal-environment system. Traditionally, ecological psychologists have tried to understand perception or action by examining the variables in the ambient arrays. Defining information relationally, however, implies that this "distal focusing" does not suffice to understand perception and action. A pattern in the ambient array gets its meaning in relation to the perceptual process it is participating in. Hence, the study of this process is as important as the examination of the ambient array. An important question now is how to conceptualize this process. In the cognitive approach, the perceptual process is conceived of as a process of enrichment—the stimulus information is enriched by internal knowledge and thereby transformed into a percept. However, applying Oyama's conception of information to perception-action keeps us far from introducing such cognitive processes to account for perception. Just as a gene is not transformed into an animal in the ontogenetic processes, a pattern in the array is not transformed into a perception in the perceptual processes. An alternative conceptualization of the perceptual processes is in terms of exploration. This is more in line with the Gibsonian framework and, thus, with the perspective we aim at. After all, J. J. Gibson (1966; see also E. J. Gibson, 1988) claimed that exploratory behavior (which basically can involve everything from eye movements to whole body movements) is crucial in creating and detecting patterns in the array. However, to understand how perceptual information grows out of the relation between the variable and the exploratory process, a different perspective on the latter is required. In the study of exploratory activity, ecological psychologists have often assumed that this activity provides a window into the use of variables in the array



(e.g., Riley, Wagman, Santana, Carello, & Turvey, 2002; van de Langenberg et al., 2006; van Doorn, van der Kamp, de Wit, & Savelsbergh, 2009). That is, the detection of a certain variable is accompanied by particular exploratory behavior. We agree that the exploitation of patterns in the array requires movement. However, we believe that exploratory behavior not only serves in creating and detecting a variable, but that it also has a *formative* function in determining the perceptual information the variable conveys and, thus, the object of perception. The detection of the same pattern in the ambient array can be accompanied by different exploratory movements, which determine which environmental property is perceived. This sets a new line of empirical research in the ecological study of perception and action.

### **Implications for the ecological approach to perception and action**

The present conceptualization of information is a significant departure from both the traditional conception of information as specification and Chemero's alternative view. Although these conceptions are critically different in several respects, they both assume that information resides in the environment. The conception of perceptual information that we laid out in this paper differs from this idea in at least two respects. First, our conception does not define information in terms of relations between patterns in the array and the environment. Rather, the relation between the patterns and the perceiver is taken to be central. Indeed, following Oyama's conception of information, we have argued that what information a pattern in the array conveys co-dependes on the perceiver or actor for whom it makes a difference. This does not mean that the relation between the pattern and the environment is of no account. Indeed, the correlation between the patterns in the array and the to-be-perceived property determines the usefulness of a pattern in constraining the perception or action (see Jacobs & Michaels (2007) for a nice portrayal of the usefulness of variables). Variables that are specific to the property are more useful than variables that moderately correlate with the property. Hence, their exploitation is more likely to result in accurate perception and action. Yet in our conception of information, the relation between the pattern and the environment

does not solely determine what information the pattern conveys. This brings us to the second difference with the earlier ecological conceptions of information. Claiming that information resides in the ambient array, the earlier conceptions reified perception information. It is “out there” in the array, available to be picked up and used (e.g., J. J. Gibson, 1961, 1970; see Costall, 2003). Our conception does not reify perceptual information. Perceptual information does not reside in the ambient array; rather, perceptual information is a relation between the variables in the array and the perceiver. Hence, in the absence of perceivers, there is no information “out there” in the arrays.

Our claim that there is no information “out there” in the environment, might make one wonder whether our conception of perceptual information is consistent with the ecological theory of perception-action? More precisely, can perception still be defined as direct? As previously mentioned, our new conception of information implies that in the ecological approach, the study of perceptual processes should be on par with the study of the patterns in the array. It is the relation that determines what information a pattern conveys. Yet, this focus on perceptual processes implies by no means that we give up on the idea of direct, unmediated perception. In fact, we think that our conception of information does complete justice to this idea. The reason is that with our relational conception of information we can also explain the object of perception, a problem that was insufficiently solved by Chemero’s conception. After all, the information a pattern in the array conveys grows out the relation between this pattern and the perceptual/exploratory processes. This relational conception of information thus prevents the introduction of internal processes that determine what environmental property is perceived. It is the information concept itself that is doing all the work here. Thus with our conception, perception can be nothing more than the exploitation of structured patterns in the array.

Although we break with earlier ecological conceptions of information, it is important to note that we do so by following a relational line of thinking that arguably forms the ontological foundation of the ecological movement (Chemero, 2003a; Costall, 1995, 2003, 2004; Dent-Read & Zukow-Goldring, 1997; J. J. Gibson, 1979/1986; Heft, 2001, 2007; Ingold, 2000; Withagen & Michaels, 2005a;

Withagen & van Wermeskerken, in press). As mentioned above, both Oyama (1985/2000) and J. J. Gibson (1979/1986) adopted relational thinking in developing their perspectives (see Dent-Read & Zukow-Goldring, 1997; Ingold, 2000; Turvey, 2009; Wagman & Miller, 2003). Oyama took it central to her conception of information, and J. J. Gibson adopted it in describing the animal's environment. At a conceptual level, our conception of perceptual information that we derived from Oyama's work is indeed reminiscent of J. J. Gibson's concept of affordances. Recall that affordances refer to the action possibilities that the environment offers the animal and are thus animal relative. For example, a cup of water affords drinking for a human being, but affords walking for a water strider. Hence, an affordance is not an inherent property of the environment; rather, it is a relation between environmental properties and the action capabilities of the body.<sup>4</sup> The same physical property can afford different actions to different animals and to the same animal at different moments in time. The conception of information we laid out here is ontologically similar to affordances. Information does not reside in patterns in the array; rather, it is a relation between those patterns and perceptual processes. The same pattern in the ambient array can inform about different things for different animals, and even for the same animal at different moments in time. Thus our conception of information rests on a relational line of thinking that is similar to the one J. J. Gibson used in describing the environment. Hence, our conception of information is not only consonant with the idea of direct, unmediated perception and action but also with the ontological foundation of the ecological movement.

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## Footnotes

<sup>1</sup> Recently, Menger and Withagen (in press) demonstrated that what mechanical variable is exploited in dynamic touch does not depend only on the mechanical context, but is a joint function of context, feedback, and perceiver characteristics. This is in line with Withagen and Chemero's (2009) theory that multiple organismal and environmental factors jointly determine what variable is exploited to perform a task.

<sup>2</sup> Jacobs and Michaels (2007) developed a rather sophisticated theory of this learning process, arguing that there is a specificity relation between feedback and the changes in variable use. However, the reported individual differences in learning trajectories cast doubt upon this suggested specificity relation (Menger & Withagen, in press; Withagen & van Wermeskerken, 2009; see also Withagen & Chemero's (2009) evolutionary analysis of perception).

<sup>3</sup> It is interesting to note that Runeson (1988) was also inspired by the work of Barwise and Perry (1981, 1983). However, he used the concept of constraint to explain how patterns in the array can be specific to environmental properties. Chemero (2009), by contrast, used the concept of constraint to explain how nonspecifying variables can carry information.

<sup>4</sup> It is important to note that not all ecological psychologists conceive affordances as relations. Turvey (1992), for instance, argued that affordances are dispositional properties of the environment, and Reed (1996) conceived of them as resources. It is beyond the scope of this paper to discuss all the ecological conceptions of affordances. We refer the reader who is interested in these discussions to Chemero (2003a).