MOVING INTO VIEW: ENACTING VIRTUAL REALITY

LASSE SCHERFFIG

Introduction: De-emphasizing Visuality

In the 1960s, the Brazilian artist Lygia Clark built a series of goggles and gloves exploring the human sensorium. These devices “hold small movable mirrors in front of the eyes, juxtaposing and fracturing reflections of the self and the surrounding world.” As art objects designed to be worn and used they form part of a practice that was grounded in the visual arts and constructivist movements of post-war Brazil, yet became increasingly concerned with “de-emphasizing visuality.”

Having already produced reductive and geometric paintings, Clark experimented with folding the plane of the canvas into the third dimension, creating “hinged sculptures that combined geometric shapes and organic movements.” This work resulted in Bichos (animals, or beasts): a series of three-dimensional objects made from geometric surfaces that “needed to be manipulated by the viewer to reveal their organic nature and unfold their multiple configurations.” The Bichos, with a focus on interactive exploration of formal configurations, were then followed by Clark’s work on goggles and gloves focusing on the interaction of perception and self-motion. In other words, “Clark began with the eye, but the entire body began to make itself felt early on.” Her “devices” thus aimed to “dissolve the visual sense into an awareness of the body.”

These works visually paralleled the first head-mounted display (HMD) built by Ivan Sutherland around the same time, including subsequent

---

4 Here and in what follows, Osthoff, “Lygia Clark and Hélio Oiticica,” 282.
5 Brett, “Lygia Clark,” 61.
developments in virtual reality (VR). The visual resemblance of Clark’s HMDs and sensorial artwork to these developments has already been noted (fig. 1) as an important conceptual legacy for questions of interactivity. The same is true for her trajectory from visual art towards art practices that focus on “relational objects,” participation, and experience. However, in this discussion “[t]he visual and cultural parallels between these and other investigations in art and science are as significant as they are unexplored.”

When Sutherland reported on his work in 1968, he noted that “users naturally moved to positions appropriate for the particular views they desired.” Sutherland suggests that user action may play a constitutive role in perceiving a virtual environment. In what follows, this combination of “moving” and “viewing” is used as a starting point for exploring the parallels to Clark’s investigations, opening the discussion of HMDs to a possible dissolution of the visual sense. This essay takes the non-visual foundations of HMD functioning to re-think virtual worlds as “relational objects” that presuppose active observers. In doing so, it proposes a new form of awareness of the body in VR research that includes an often-neglected theme: the relationship between action and perception as a cybernetic relationship of mutual dependence.

This argument is constructed by relying on sources that formulate a model of (spatial) perception centred on observer action. Starting with theoretical considerations by Henri Poincaré and empirical observations by Hermann von Helmholtz and Ernst Mach, this (re)construction culminates in

---

7 Osthoff, “Lygia Clark and Hélio Oiticica.”
10 Ibid.
11 Sutherland, “A Head-mounted Three-dimensional Display,” 301.
the physiological principle of “reafference” and the concept of “enaction” used in the cognitive sciences. I develop this line of thought with research into “presence” in VR and HMDs. The result is a notion of an embodied—or, rather, enactive—spatiality of VR whose perceived “realism” of virtual worlds is not only the result of visual similarity but, even more so, perceptuomotor couplings.

**Perceiving Space: Geometry and the Body**

How and why do we perceive a virtual three-dimensional environment in an HMD? How do we recognize the geometry of a three-dimensional scene once it is rendered as two two-dimensional images, each subsequently presented to each one of our eyes? The trivial answer is that perception manages to achieve this. But the relation between perception and space is surprisingly complicated because sensory stimulation (for instance, by images inside an HMD) is a necessary, but not a sufficient, condition for generating our notions of space and object. As early as 1902 Poincaré had formulated the counterintuitive assertion that it is not through our senses alone that we perceive the outside world.

Poincaré juxtaposes *geometrical space* with the *representative space* of our perception. The former, he argues, is defined as an infinite three-dimensional continuum both homogenous and isotropic; the latter shares none of these features. A first observation supporting this assertion is that the “visual space” of perception defined by the image on the retina is finite, two-dimensional, non-homogenous, and non-isotropic. It is only through the muscular accommodation of the pupil and the convergence of both eyes towards a common vanishing point that “complete visual space” acquires its

---

13 Henri Poincaré, _Science and Hypothesis_ , trans. William J. Greenstreet (London/Newcastle: The Walter Scott Publishing Company, 1905). Poincaré has contributed to a variety of scientific fields and is seen as one of the founders of topology. His work, however, is read here with a focus on his “forgotten” conclusions (as von Foerster points out) regarding the role that active motion plays in space perception, an idea I shall explore in what follows. See von Foerster, “Epistemologie der Kommunikation,” 275–276.
14 Poincaré, _Science and Hypothesis_ , 61.
15 Homogeneity in this context denotes the fact that spatiality is identical for each point in space, whereas isotropy asserts the same for each direction. Geometric space, according to this conception, does not assume positions or directions different from or privileged over any other. Poincaré, _Science and Hypothesis_ , 61.
16 Ibid., 61–62.
third dimension. This space is further supplemented (and complicated) by “tactile and motor space” created by tactile sensory input and those sensations accompanying muscular movements.¹⁷

Only together do these spaces construct what Poincaré calls representative space, which, “in its triple form—visual, tactile, and motor—differs essentially from geometrical space. It is neither homogeneous nor isotropic; we cannot even say that it is of three dimensions.”¹⁸ In order to transform representative space into geometric space, all sensations (and the spaces they entail) must be integrated because “[n]one of our sensations, if isolated, could have brought us to the concept of space; we are brought to it solely by studying the laws by which those sensations succeed one another.”¹⁹

But here senses alone are insufficient because any change to a sequence of sensations may be induced by two independent factors: either a change in the environment or a change in our relation to the environment caused by motion. To be able to distinguish between the two factors our notion of space must integrate our actions: “[S]tudying the laws by which those sensations succeed one another” entails studying the law-like relations between action and the changes in perception that it yields. Our “idea of space,” including its homogeneity and isotropy, must be based on a “muscular sense” and could not have developed if we were unable to move voluntarily. It can only be derived from the correlation and reversibility of external movement and self-motion.²⁰

More than one hundred years after its publication, this line of argumentation seems to accurately predict experimental results in perception psychology, where it has only “recently become clear that motor action and depth vision are internally linked as well: executing or preparing a motor action—indeed, of its sensory consequences—is often enough to modify the observer’s perception and representation of 3D space and shape.”²¹ Indeed, three-dimensional form can be reconstructed from two-dimensional optic flow on the retina on the condition that it changes with motion—a subject that has long been discussed as “structure from motion” or “kinetic depth.”²² This effect is always ambiguous with respect to the question: which is moving, the subject

¹⁷ Ibid., 62–64.
¹⁸ Ibid., 66.
¹⁹ Ibid., 67.
²⁰ Ibid., 64–66.
or the environment? Experiments show that motor action is a central factor in disambiguating both concurrent interpretations of visual stimulation.\textsuperscript{23}

In accordance with Poincaré’s prediction that the muscular sense must be part of any subjective construction of geometrical space, this effect becomes weaker if, for instance, an external force moves the head of the observer. Therefore, spatial perception not only integrates proprioception (which changes as a result of motion) but the neural “signals” that accompany (and cause) muscular activity itself, as “both motor and proprioceptive extraretinal signals can modify the perception of 3D shape.”\textsuperscript{24}

Poincaré’s claim that a motionless being would not develop an idea of spatiality received early empirical support in a famous experiment by Richard Held and Alan Hein.\textsuperscript{25} In this experiment, twenty newborn cats were raised in complete darkness except for three hours a day when they were exposed to light. The experiment was performed in a highly controlled environment comprised of a cylinder with striped walls wherein the cats were fixed to a mechanical arm limiting their movement to a circular stroll in a single direction. The cats were placed inside the cylinder two at a time, with only one of them capable of moving freely and the other dragged along while subject to the same visual stimulation (fig. 2). After eight weeks, all cats were exposed to light in a normal environment and their ability to exhibit visually guided behaviour was

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure2.png}
\caption{Held and Hein’s experimental system investigating the relation of spatial perception and active locomotion.\textsuperscript{26}}
\end{figure}

\textsuperscript{23} Wexler and van Boxtel, “Depth Perception,” 433.
\textsuperscript{24} Ibid., 435.
\textsuperscript{26} Ibid., 873.
tested. While the ten active cats behaved normally, the other ten behaved “as if they were blind.”

Perception of space does not rely on vision or the integration of vision with other perceptual modalities alone, not even when integration includes those changes in perception induced by action. Instead, it is only by correlating these changes with the neuromuscular activity responsible for motor action that our experience of space can emerge as the result of an internal linking of action and perception (which is ultimately constituted physiologically).

The Physiology of Spatial Perception

Although acknowledging an internal connection between action and perception may seem like a recent development, early discussions of the physiology of active perception date back much further. A prominent example from nineteenth-century physiology is von Helmholtz’s seminal handbook, *Treatise on Physiological Optics*, originally published in three volumes between 1856 and 1867. The third volume contains empirical evidence for treating vision as a process encompassing proprioception and muscular activity, and not solely based on the image the outside world leaves on the retina.

In Paragraph 29 of the third volume von Helmholtz examines “the direction of vision,” asking why we actually know where we direct our gaze, finding that the direction of vision is not identical to the position of the eye or the ocular muscles. This may seem surprising. Its empirical foundation, however, is familiar to everyone: if we manoeuvre the eyeball by pushing it with a hand or pulling the skin surrounding it, the world seems to move with that motion. However, if after-images are created on the retina, for instance, by looking directly at a bright light source, then these “appear to stay where they are while the eye is being pulled, although, as a matter of fact, they do move with the eye.”

---

With active eye movement the situation reverses: after-images move when we actively move our eyes while we take it for granted that the external world stays still whenever we do so—although in this case the world’s image on the retina is changed in a way indistinguishable from change affected by extraocular muscle pull. In order to prevent the visual world from jumping around with each gaze fixation, eye movement must exert active influence on visual perception. Further evidence for this has been observed by Albrecht von Graefe in 1854, whom von Helmholtz credits for observing that the perception of our surroundings may be set in motion by sheer willpower. If the muscles that pull the eyeball right or left are paralyzed, the intention to direct our gaze is not followed by eye movement. Yet, “the objects appear to move to the right, although the adjustment of the eye and the positions of the retinal images in it have not varied.”

It is, therefore, the “effort of will” alone that causes the apparent motion of our environment. Visual perception seems to “know” how our eyes would be moving if no muscle was paralyzed. The “intensity of the effort of will,” or, to put in more physiological terms, the “degree of innervation” of the muscles seems to determine both the perceived motion of the world in relation to the body and its visual consistency.

Poincaré’s deduction that spatial perception is based on the interplay between visual perception, body movement, and an internal consideration of muscular activity (neural causes in the form of a muscular sense) is implied in von Graefe’s findings. In 1886, Mach takes these observations to a radical conclusion.

In *The Analysis of Sensations and the Relation of the Physical to the Psychical*, Mach argued, like Poincaré later would, that geometrical and physiological space “are to be sharply distinguished.” Referring to “homogeneity” and “isotropy” as key reasons for sharp differentiation, Mach acknowledges that our concept of geometry must be grounded in perception. But in contrast to Poincaré, Mach underpins these theoretical considerations with concrete physiological observations that argue for the integration and

---

30 Grüsser, “Efference Copy and Reafference,” 44.
31 von Helmholtz, *Treatise on Physiological Optics*, 245
32 Here and in what follows, ibid., 250.
34 Ibid., 201.
35 Ibid., 120.
correlation of distinct spaces of perception, movement, and the processes causing motor action to synergistically enable spatial perception. After describing observations similar to von Helmholtz’s, Mach outlines an experiment that reproduced von Graefe’s findings without recourse to extraocular muscle paralysis by blocking the free movement of the eyeball using putty. Thus, he arrived at similar conclusions regarding the effort of will, stating that “the mere will to look to the right imparts to the images at certain points of the retina a larger ‘rightward value,’ as we may term it for brevity.”

It is the combination of the two phenomena, (a) a voluntary eye movement, if hindered by putty, causes an apparent jump of the outside world, whereas, (b) an unhindered motion of the eyeball does not entail any apparent motion, which leads Mach to conclude: “the will to perform movements of the eyes, or the innervation to the act, is itself the space-sensation.” Spatial perception, according to this view, is not a matter of vision, touch, or even proprioception. Rather, it must include the “will,” or the “innervation to the act,” that causes motor activity, as conveyed later on by Poincaré.

However, in an unexpected radicalization of these ideas, the perception of our direction of vision for Mach seems to incorporate will, or innervation, into a computation. If looking upwards fails to yield an apparent downward movement of the environment, although it causes such a displacement of the environment’s image on the retina (fig. 3), it follows that “the physiological process which conditions the voluntary raising of the eye can entirely or partly take the place of the height-sensation, is homogeneous with it, or, in brief, algebraically summable with it.”

![Figure 3: Direction of vision: looking up/downwards yields an opposing displacement of the environment’s image on the retina.](image)

The notion of physiological processes being “summable” is surprising, since it refers to something that is as simple as it is radical. Like numbers, sensations and the will to perform motor actions can be added or subtracted.

---

36 Ibid., 128–129.
37 Ibid., 129.
38 Ibid., 128.
39 Ibid., 127.
The perception of a stable outside world is not only based on sensory stimulation and self-motion, but their relation to each other is based on manipulating abstract “values” associated with action and perception.

Mach drives his point to a surprising conclusion, suggesting a formal model for the relation of motion perception to muscular activity in the form of a block diagram (fig. 4). The diagram depicts the abstract relation of a hypothetical “terminal organ (TO)” (EO in fig. 4, original German acronym) detecting acceleration of the body, to the centres controlling voluntary and involuntary innervation (WI and UI) of the loco-motor (LM) and oculo-motor (OM) apparatuses. Mach indicates the relation through the use of feathered and non-feathered arrows representing excitation and compensation of motion perception.

Since, for Mach, space-sensation is identical to the act of will (innervation) that initiates movement, TO is not the source but rather a broker of sensation. If excited when sensing movement, it reacts by directing UI to cause involuntary “compensatory movements” that reverse external motion. In the case of voluntary motion, it inhibits UI, preventing any compensation and, thereby, causing the perception of self-motion. If, in turn, an external motion is perceived, it is because TO has inhibited its compensation. According to this model any sensation of motion is based on an act of will that either causes motion or inhibits its compensation.

![Figure 4: Mach’s block diagram of motion perception.](https://www.mediatropes.com)

Mach’s model of “antagonistic innervations” agrees with Poincaré’s conclusion that changes in position can only be distinguished from changes of

---

40 See also Grüsser, “Efference Copy and Reafference,” 51.
41 The functioning of the vestibular system was still being disputed during Mach’s time. Mach, *Analysis of Sensations*, 117.
42 Ibid., 165–166.
43 Ibid., 166.
44 Ibid.
45 Ibid., 179.
state because changes in position can be reversed by active movements. In
addition, Mach argues that the innervations that cause muscular movement are
to be found in the perception of the end results of said movements, for instance,
in visual perception, where it holds that “when the eye is moved voluntarily, the
displacement of images on the retina corresponding to this movement should be
compensated by the voluntary movement in respect of space-value.”46

This model, together with its block diagram, may be regarded as an
early formulation of the type of internal linkage required to enable the
combination of action and perception to create a subjective experience of
space.47 In what follows, I demonstrate how this model is a proto-cybernetic
model of spatiality anticipating the idea that HMDs enable immersion in a
literal cyberspace.

Cybernetics of Perception: The Principle of Reafference

I want to insist: the term “cyberspace,” coined by William
Gibson in his novel Neuromancer in 1984, is less about “space”
(which is a metaphorical term here) than about cybernetics (the
fact that the prefix “cyber-” is derived from Norbert Wiener’s
“cybernetics” is a kind of forgotten media-cultural fact today).48

In fact, the situation is even more complicated. The term “cyberspace” has
been used most widely to denote the virtual worlds created by HMDs and other
VR systems. Although conceptually cyberspace was inspired by examining the
“closed loop” between video games and their players,49 today it almost
exclusively refers to the three-dimensional spaces that these systems entail.

Insisting instead on its forgotten media-cultural roots, I turn now to an
examination of the role that the closed loops of action, machine response, and
perception play in the creation of these spaces.

46 Ibid., 186.
47 In fact, Mach’s diagram has been described as the “the first block diagram” of this internal
48 Wolfgang Ernst, “Beyond the Archive: Bit Mapping,” Media Art Net (2004), accessed
49 Larry McCaffery, “An Interview with William Gibson,” in Storming the Reality Studio: A
Casebook of Cyberpunk and Postmodern Science Fiction, ed. Larry McCaffery (Durham: Duke
Defined by Norbert Wiener as the study of “control and communication in the animal and the machine,” cybernetics can be understood as the product of a paradigm shift in control theory and communication engineering. With this shift the application of negative feedback became a central method in both fields, uniting them into a single classical control theory.

Negative feedback makes use of the margin of error a control system exhibits. This margin, understood as the difference between the system’s actual output and the desired goal, can be turned into a signal that is fed back into the system as a negative input that reduces the system’s deviation from the goal, yielding stable convergence to it. Classical control systems exert control depending on error, resulting in technological self-correction. The application of negative feedback turns open systems of linear causality (where only the input affects the output) into closed systems wherein causality is circular (where the output affects itself). Often these systems are described in block diagrams focusing on input-output relations alone.

With this paradigm shift engineers started using the feedback-based methods of classical control theory not only for the machines they were building but also to describe the behaviour of the operators of these machines, creating the possibility of perceiving control theory as a theory of animals and machines alike. This “totalization” of feedback control lies at the heart of Wiener’s definition of cybernetics.

56 Of course, cybernetics was itself part of a broader trend of inclusion of feedback principles into a variety of scientific disciplines. For an early overview see Volker Henn, “Materialien zur Vorgeschichte der Kybernetik,” Studium Generale: Zeitschrift für interdisziplinäre Studien 22 (1969): 164–190.
Conceptualized as a meta-science of anything that exhibits behaviour, cybernetics and the techniques of classical control theory have naturally influenced research in physiology that followed the work of von Helmholtz and Mach. By contrast, many in the field had long held that “[t]he connection between perception and action has classically been studied in one direction only: the effect of perception on subsequent action.” As physiology is characterized by experimental systems aimed at measuring electrical activity of sensory, muscle, and nerve cells, this practice raises the question, “what lawful relationships hold between impulses which are generated by external stimulation and travel inward into the CNS and those which—either directly or indirectly—reemerge from it; that is, the question of the relations between afference and efference?”

In 1950, physiologists Erich von Holst and Horst Mittelstaedt took on the task of turning the above question on its head. As afference and efference in physiology denote the in- and output of the central nervous system (CNS), both terms, at the time, were part of a classical reflex theory that understood the CNS as “a sort of automat, which reflexively delivers a given ticket when a particular coin is inserted in it.” According to this view, the nervous system reacts to external stimuli and inhibits these reactions based on volition or adaptation (in a conditioned reflex).

Counter to this reflex theory, von Holst and Mittelstaedt propose “a complete reversal of the usual way of looking at the system,” so that instead of asking for the influence of (afferent) sensation on (efferent) action, they “start with the efference and ask: what happens after the efference has caused changes in the organism via the effectors, and then is reverberated back into the CNS by way of the receptors, as afference?” The re-entry of efference into the nervous system is termed reafference, and it is this reversed way of looking at the perceptuomotor system that follows Mach’s idea of viewing the will to perform movements as the source of spatial perception.

The argument for von Holst and Mittelstaedt’s reversal starts with a finding that reads as if elaborating on Mach’s considerations. When an insect

---

60 Ibid.
61 Here and in what follows, ibid., 42.
(in this case a fly of the species *Eristalis*) is placed in a rotating cylinder whose walls are vertically striped black and white—just as the walls of the apparatus in which Held and Hein would later torture cats—"the insect starts to turn in the same direction. It attempts to maintain, or stabilize, its visual field." Classical reflex theory calls this corrective or compensatory motion *optomotor* or the *optokinetic reflex* which will not emerge so long as the animal is actively moving inside the resting cylinder—although, in this case, the visual stimulation caused by the stripes moving across the insect’s eyes may be identical. This raises the question of "why the optokinetic reflex does not force the fly back into its starting position, as soon as it begins to turn."

Reflex theory answers this question: "during spontaneous locomotion the optokinetic reflex is inhibited." Here, however, is where von Holst and Mittelstaedt branch off by exclaiming, "but that answer is wrong!" An indicator for this exclamation is obtained by the complete reversal of looking, which should be taken quite literally, as they force it on the insects:

*Eristalis* has a slender and flexible neck which can be rotated through 180° about its longitudinal axis. If this is done, and the head [is] glued to the thorax, the positions of the two eyes are reversed […]. In this way a clockwise rotation of the cylinder produces image movement across the retina, which, under normal circumstances, would be produced by counter-clockwise rotation. The stationary fly responds to rightward movement of the cylinder by turning itself promptly to the left.

While this observation is still compatible with conditioned reflexes, the situation changes as soon as the insect starts to move. Classical reflex theory would predict that the (now reversed) optokinetic reflex should be inhibited during active locomotion, and thus the animal should exhibit normal movement. However, in this case "*Eristalis* turns continuously to the left or right in tight circles, or else short sharp turns to the left and right follow one another in rapid succession, until the insect eventually stops, ‘freezing’ in an atypical posture."

It appears that the active movements of the fly with imposed-reversed vision do not simply inhibit the optokinetic reflex. Instead, the movement of its legs seems to interact with the changes in stimulation on the retina. From this the researchers deduce: "[t]he moving insect ‘expects’ a very specific change..."

---

62 Here and in what follows, ibid., 42–43.
63 Ibid., 43.
64 Ibid.
in retinal stimulation which, insofar as it occurs, is ‘neutralized’ in some way. But, following interchange of the two eyes, there is retinal motion opposite to that which is expected, and the optomotor response is immediately evoked. This movement, however, magnifies the unexpected retinal motion, and thus the process is self-reinforcing.”65

Not surprisingly, this self-reinforcing process reflects the central problem of the feedback systems of classical control theory: feeding a system’s error back into itself, under certain circumstances, may cause the system to become unstable and reach catastrophic collapse. This happens whenever all error corrections overshoot the goal and make further corrections necessary—a self-reinforcing process referred to as hunting in control engineering and singing in communication engineering.66 It appears that the self-moving Eristalis seems to “calculate” with its own motion. There must be a way by which “the CNS ‘knows’ which type of retinal image motion to expect,”67 and, using that knowledge, the CNS must be “calculating the direction and speed of body motion in order to compare them with the retinal reafference.” To them the internal interaction of physical motion and retinal stimulation seems to be a calculation, as suggested by Mach.68

This idea is developed by focusing on the utricus otolith,69 an organ in the inner ear of vertebrates responsible for sensing gravitational acceleration and, as such, is the modern equivalent of Mach’s terminal organ. The utricus otolith reacts to any shearing force that tilts a vertebrate (a fish, in this case) away from its regular posture and causes a motion proportional to that shearing force which compensates for it. This postural reflex is not merely a reflex but also takes into account the animal’s motion. When, for instance, the fish voluntarily assumes a certain position, postural reflexes are not merely inhibited. Instead, “[t]he ‘intended’ or ‘goal’ postures” are now, by themselves, “maintained against external perturbations by exactly the same kind of corrective movements which serve to maintain normal posture!”70 The influence of voluntary motion on the corrective motion initiated by the postural reflex thus really seems to be a “quantitative influence.” Following the cybernetic terminology of “‘goal’ postures,” von Holst and Mittelstaedt re-

65 Ibid., 44.
66 Mindell, Between Human and Machine, 125.
67 Here and in what follows, von Holst and Mittelstaedt, “Principle of Reafferece,” 44.
68 Mach’s findings are also based to a large extent on observation of animals in rotating cylinders. See Mach, Analysis of Sensations, 147–154.
69 von Holst and Mittelstaedt, “Principle of Reafferece,” 44.
70 Ibid., 45.
formulate the postural reflex as an abstract classical control system based on Mach’s conception that innervations can be antagonistic and are summable.

In what follows, this abstract control system is further generalized (and radicalized) as the *principle of reafference* (fig. 5). Formulated as a block diagram, the principle is the epitome of what began with Mach almost 50 years prior. It assumes a general centre, \( Z_1 \), that controls some effector, \( EFF \), and, in turn, is innervated by higher centres, \( Z_{2...n} \). A command, \( K \), from these centres (i.e., a change in the stream of impulses entering \( Z_1 \)) creates an efference, \( E \), which causes a movement of the effector, \( EFF \), that causes a related change in perception—the (re-)afferece, \( A \). However, in addition, the efference is accompanied by “a strictly correlated neuronal response,” which the authors term *efference copy* (\( EK \)).

![Figure 5: Block diagram of the principle of reafference.](image)

Efference copy and reafference interact in a way the authors understand as literal summation, even replacing Mach’s arrows representing excitation and compensation by the corresponding arithmetic operators: “we shall arbitrarily label the efference and its copy positive (+), the reafference negative (−).” By doing so the efference copy takes on the role of a goal state that is compared to the actual outcome of a movement, represented by the reafference. When an organism performs a voluntary movement, the efference copy (+) is strongly related to the reafference (−) and both “compensate for each other exactly in \( Z_I \)” When, instead, motion is caused externally, there is no efference copy and the afferent signal (−, now termed *exafference*) leaves a negative *residual bias* functioning as a sensory report, \( M \). Feeding this report back to higher centres

---

71 Here and in what follows, ibid., 50–51.
72 Ibid., 51.
and having it interact with a descending command changes commands in exactly the way that postural reflexes in fish are adjusted according to goal postures. “In this case,” the authors make clear, “the system consisting of $Z_2$ and the lower units becomes a feedback control system in the technical sense.”

The principle of reafference explains the central findings of both von Helmholtz and Mach. Reafference predicts that when the command, $K$, is sent to a paralyzed (through the use of putty, nerve damage, or drugs) effector, $EFF$, the world will seem to jump accordingly simply because, here, the efference copy, $EK$, will not be compensated by the reafference, $A$, and, thus, will itself become the report, $M$, of apparent motion. “In this experiment,” the authors state, “the efference copy itself is, so to speak, made visible.”\textsuperscript{73} The complementary finding is also predicted: if the eye is moved by an external force, this will likewise yield a shift of the visual field since the passive movement causes the retinal exafference, $A$, that is not compensated by the corresponding efference copy, $EK$. Thus, looking with moving eyes at an apparently constant world functions as a combination of both:

Let us now combine the first condition with the second, namely, move a paralyzed eye passively at the very moment when the movement command is given (and in the same direction). Or—obviously, so much easier—let us make a normal eye movement with the intact eye: in either case, there are indeed two complementary trains of impulses [...] an efference copy which, on its own, makes the visual scene move to the right, and an afference which, on its own, makes it move to the left. Since, however, these two cancel each other out at the low level of $Z_1$, no report ascends higher, and we see neither movement; as witnessed by our everyday experience, the environment remains stable. And that, in the present instance, is objectively correct. The “right” perception turns out to be the sum of two opposite “false” perceptions.\textsuperscript{74}

Using the principle of reafference to analyze a number of perceptuomotor circles found in animals and humans, von Holst and Mittelstaed explain not only the perceived stability of the environment but also the ability to discern movement of the environment from bodily movements.\textsuperscript{75}

\textsuperscript{73} Ibid., 53.
\textsuperscript{74} Ibid.
\textsuperscript{75} At about the same time, the physiologist Nobel laureate Roger Wolcott Sperry published a study on the optomotor response (based on fish whose eyes had been surgically turned upside down) that uses a similar complete reversal of vision and arrives at similar conclusions (barring
Mach’s incomplete model of antagonistic compensatory innervations therefore denotes an early template for a cybernetic model of perception whose conceptual focus is completely reversed: instead of focusing on external stimulation as generating perception, it focuses on action that causes changes in sensory stimulation.76

Viewed in this light, spaces created by HMDs read as literal cyberspaces because we can understand them as the result of a computational comparison between the predicted (or desired) outcomes of motor actions (based on the efference copy) and the actual outcomes of changed stimulation (reafference). As Poincaré concluded, our experience of these spaces relies on “studying the laws” that connect action to perception. And so when von Helmholtz answers the question of the direction of vision with the “effort of will,”77 he also gives us the tools to understand cyberspace as cybernetic spatiality.

Cyborg Bodies: From Sensory Substitution to Enaction

Assuming that the perception of an external environment is based on reafference, Poincaré’s prediction, coupled with Held and Hein’s findings concerning the dependence of spatial perception on self-motion, are necessary deductions. If we are unwilling to accept the implicit premise of neuroscience and physiology—namely, that the neural circuits of perceptual processing, and the generation of action, generalize from species to species (from insects, fish, and cats to humans)—and instead seek evidence closer to human experience,78 we may look at how perceptual technologies create entirely “new” sensations.

A famous example is the work of the psychologist Paul Bach-y-Rita, who, beginning in the late 1960s, developed systems for sensory substitution—the replacement of one sensory modality by another. Bach-y-Rita famously

---

76 An even more radical focus on perception and action as circular loops of prediction and error has recently been discussed in cognitive science. Karl J. Friston, Christopher Thornton, and Andy Clark, “Free-energy Minimization and the Dark-room Problem,” Frontiers in Psychology 3 (2012): 1–7.

77 The “effort of will” can be understood as the efference copy. Grüsser, “Efference Copy and Reafference,” 47.

78 Similarly argued in Varela, Thompson, and Rosch, The Embodied Mind, 175.
used vision to replace touch by mapping camera images to the vibrations of an array of mechanical elements placed on the back of a chair. Blindfolded persons sitting on the chair initially perceived changing patterns of tactile stimulation on their back. This changed, however, when subjects were permitted to move the camera: “extensive practice led some of them to experience stationary objects in front of the camera.”

These results only raise the question of how objects are recognized, but also how sensation on the surface of the body can be attributed to something outside the body. This is obviously a problem when the sensation in question is touch, but from a physiological viewpoint this is not much different from vision since the light-sensitive cells of the retina are no different from skin cells in their relation to the environment. In general, attributing something on the body’s surface (something proximal) to a source distant from it (something distal) is discussed as the question of distal attribution. To this day, the answer neuroscience offers to this question is exactly that of Poincaré: the laws connecting action to perception create the distal environment. Only when we explore the relation of our own actions to the changes in perception they entail (like the cats in active locomotion) can we externalize proximal stimulation to a distal environment. Moreover, only the law-like relation of the motion of the camera to the change of the vibrotactile pattern on the back can give rise to perception of a distal environment: “a translation of the input that is precisely correlated with self-generated movement of the sensor is the necessary and sufficient condition for the experienced phenomena to be attributed to a stable outside world.” It is “the extraction of a correlation between self-movements and resulting stimulation” which “is a necessary condition for the acquisition of the concepts of space and object.”

The correlation referred to above is defined as linkage. Perception of a distal environment is therefore based on comparison between predicted and actual sensory change introduced by the principle of reafference (fig. 6). By comparing von Helmholtz’s effort of the will with its perceptual results, space (the distal environment) is reformulated once more as a cyberspace. As such, bodies engaged in that space may be understood as cyborg bodies constituting

80 Ibid., 116.
83 Ibid., 116.
new systemic wholes incorporating, instead of merely using, sensory technologies.\textsuperscript{84}

![Figure 6: Distal attribution as block diagram.\textsuperscript{85}](image)

The possibility for establishing new and different linkages that would create entirely new spaces and objects is both implied and relatively untouched by academic research. In a little known experiment from 1971, a team led by Heinz von Foerster worked with the perception of four-dimensional cubes through \textit{motor-sensory correlation}. The cubes were presented on a stereoscopic display as three-dimensional projections of four-dimensional objects that could be manipulated using both hands. The resulting experience bears an uncanny resemblance to sensory substitution: “the realization that these strangely changing entities are nothing but the projections of one and the same object (a ‘generating invariant’) is usually gained by most of the naive test-persons by a loud and enthusiastic, ‘Oh, I see,’ within 20–40 minutes, \textit{if they themselves are permitted to use the manipulators}.”\textsuperscript{86}

The cybernetics of perception does not differentiate sensory modalities according to what subjects sense. It does not, in other words, assume that visual perception is inherently spatial—or even visual. Instead, it assumes a (re)construction of the outside world based on bodily activity. Every aspect of a stimulus—its nature as visual, olfactory, or auditory—thus becomes a question of how its perception changes with our actions. For this reason, Kevin O’Regan and Alva Noë have suggested the term \textit{sensorimotor contingencies} for the linkage of motor action and perception, or “the structure of the rules governing the sensory changes produced by various motor actions.”\textsuperscript{87}

\textsuperscript{85} Loomis, “Distal Attribution and Presence,” 114.
\textsuperscript{86} von Foerster, “Cybernetics of Epistemology,” 240; my emphasis.
The structure implied above forms not only the basis of our capacity to discriminate between sensory modalities, but also the discernment of discrete entities within modalities, as the shape of an object is the sum of all possible “changes that surfaces undergo when they are shifted or tilted, or when we move with respect to them.”\(^8\) In this sense: “the visual quality of shape is precisely the set of all potential distortions that the shape undergoes when it is moved relative to us, or when we move relative to it.” As part of a genealogy of action-centric views on perception, questions of reafference and distal attribution lead to what in cognitive science has been proposed as *embodiment* and, more importantly, *enaction*. Both of these notions were originally introduced by Francisco Varela, who represents one of the few links (both personal and theoretical) between cognitive science and its cybernetic roots.\(^9\)

In 1991, when Varela, Evan Thompson, and Eleanor Rosch introduced enaction and embodiment in *The Embodied Mind*, they referred in detail to the work of Maurice Merleau-Ponty—in particular his study on the structure of behaviour. As if addressing the vibrotactile elements on the back of Bach-y-Rita’s subjects, Merleau-Ponty writes:

> The organism cannot properly be compared to a keyboard on which the external stimuli would play and in which their proper form would be delineated for the simple reason that the organism contributes to the constitution of that form.\(^9\)

In a statement elaborated on with apparent reference to the discussion on reflex theory versus its reversal in the principle of reafference, and the circular relation of action and perception, Merleau-Ponty goes on to write:

> Since all the movements of the organism are always conditioned by external influences, one can, if one wishes, readily treat behavior as an effect of the milieu. But in the same way, since all the stimulations which the organism receives have in turn been possible only by its preceding movements which have culminated in exposing the receptor organ to external

---

\(^8\) Here and in what follows, ibid., 942.


influences, one could also say that behavior is the first cause of all the stimulations.

Thus the form of the excitant is created by the organism itself, by its proper manner of offering itself to actions from the outside. […] This would be a keyboard which moves itself in such a way as to offer—and according to variable rhythms—such or such of its keys to the, in itself, monotonous action of an external hammer.

As the circularity of feedback systems suggests, the relation of body, world, and experience is understood to be reciprocal. Indeed, a reafferent relation to the world is one in which stimuli (co)determine actions but are nevertheless (co)determined by the actions they influence. The result is that the worlds we interact with become products of that inter-acting:

Cognitive systems [...] not only respond to external perturbations in the traditional sense of producing the appropriate action for a given situation, they do in fact actively and asymmetrically regulate the conditions of their exchange with the environment, and in doing so, enact a world or cognitive domain.91

In what follows, we will see how this “enacting” of worlds also takes place in the virtual worlds of HMDs.

**Presence**

Ever since the development of Sutherland’s work on the first HMD, embodied and enactive views on cognition and perception has been historically paralleled by VR research and development. Yet, how a virtual environment is subjectively perceived in the context of VR research is not posed as the central question concerning what makes perceiving these environments possible. Rather, discussion has centred on the question of presence, often defined as the subjective feeling of being physically present in a virtual environment.92

---


92 Maria V. Sanchez-Vives and Mel Slater, “From Presence to Consciousness through Virtual Reality,” *Nature Reviews Neuroscience* 6 (2005), 333. A related concept that has had various characterizations is immersion, currently understood as the overall technological fidelity of a
As HMD development largely occurred in computer science, “[p]resence research was initiated and has largely remained within the ambit of technologically oriented research departments,” focusing on factors that either enhance the subjective experience of virtual environments or the experimental correlates of being in a virtual world (heart rate, galvanic skin response, or postural reflexes). However, as presence research is ultimately concerned with how the feeling of being in a certain location is constructed, it is, nevertheless, a fruitful source of insight into the relation between moving and viewing in VR.

Sutherland’s HMD already relied on presenting stereoscopic images to both eyes, but the three-dimensionality it evoked was not solely derived from that. Sutherland himself noted that other factors might be of greater importance: “although stereo presentation is important to the three-dimensional illusion, it is less important than the change that takes place in the image when the observer moves his head.” Because of the dependence on kinetic depth, which implies that “moving perspective images appear strikingly three-dimensional even without stereo presentation,” the system’s most important feature responsible for its success was, most likely, its head-tracking capability. As Sutherland notes in a preliminary study using “a crude optical system which presented information to only one of the observer’s eyes,” in addition to an ultrasonic head position sensor, “the three-dimensional illusion was real.”

Sutherland’s observation suggests that a single (hence non-stereoscopic), finite, two-dimensional, non-homogenous, and non-isotropic image is sufficient to create the experience of three-dimensional space. When “[u]sers naturally moved to positions appropriate for the particular views they desired,” they were exploiting the sensorimotor contingencies or linkage established by the device, relying on the fact that “a translation of the input that is precisely correlated with self-generated movement of the sensor is the necessary and sufficient condition for the experienced phenomena to be attributed to a stable outside world.” The relation between moving and viewing, which his subjects established, should be understood similarly as...
proposed by Poincaré, von Helmholtz, and Mach, for whom spatial perception presuppuses an internal influence of self-motion on perception.

Similar observations have been made repeatedly, especially on the crucial role of lag-free tracking of head position and direction in a number of studies.\textsuperscript{99} Using heart rate as an objective measure of presence in a stress provoking HMD environment, Meehan et al. showed that latency between head-tracking and visual response seems to be a crucial factor for a virtual environment to generate the physiological correlates of stress.\textsuperscript{100} More recently, Regan et al. have shown that performance in small-scale spatial judgment tasks is positively influenced by “either stereo or head tracking, with the best performance achieved with the combination of both stereo and head tracking.”\textsuperscript{101} Likewise, subjectively reported levels of presence have been shown to be “significantly higher when head tracking and stereoscopic cues were provided.”\textsuperscript{102} Few studies have tried to dissociate the effects of stereoscopic presentation and head tracking, though the effect of image motion in virtual environments on presence can be “considerably larger than that of stereoscopic viewing.”\textsuperscript{103} While an understanding of three-dimensional spatial structures is enhanced by both head-tracking and stereo presentation, there are results indicating that the effect is smaller for stereo compared to head coupling.\textsuperscript{104} Likewise, the accuracy of tracing virtual lines in an HMD-based environment is positively impacted by head tracking more than through stereoscopic presentation.\textsuperscript{105} Others have found that “head tracking significantly improved the reported level of presence whereas the addition of stereopsis did not.”\textsuperscript{106}

\begin{thebibliography}{99}
\item Sanchez-Vives and Slater, “From Presence to Consciousness,” 333–335.
\item Ragan et al., “Studying the Effects,” 886.
\item Claudia Hendrix and Woodrow Barfield, “Presence within Virtual Environments as a Function of Visual Display Parameters,” \textit{Presence} 5, no. 3 (1996), 274.
\item Wijnand Ijsselsteijn et al., “Effects of Stereoscopic Presentation, Image Motion, and Screen Size on Subjective and Objective Corroborative Measures of Presence,” \textit{Presence} 10, no. 3 (2001), 298.
\item Woodrow Barfield, Claudia Hendrix, and Karl-Erik Bystrom, “Visualizing the Structure of Virtual Objects Using Head Tracked Stereoscopic Displays,” in \textit{Proceedings of the IEEE Conference on Visualization}.
\end{thebibliography}
Comparing stationary displays that create a three-dimensional image either through stereoscopic presentation or head tracking, Colin Ware et al. concluded that “head coupling is probably more important than stereo in 3D visualization.”107 The authors suggest developers of real-time three-dimensional displays should consider “coupling the displayed image directly to the viewpoint of the observer. Once this is done the subjective results suggest that stereopsis may add only marginally to the perception of three dimensionality of objects.” In addition to the evidence supporting that the three dimensionality of virtual environments is best facilitated when a VR system incorporates motor activity, other studies in presence research provide further insight into the role of the relation between moving and viewing for successful HMDs.

As if re-enacting the experiments by Held and Hein, but with human subjects, evidence suggests driving a car in VR creates a stronger feeling of presence when it is actively controlled as opposed to being passively experienced as a “passenger.”108 Moving through virtual environments generally yields a stronger sense of presence when accompanied by bodily activity that, under normal circumstances, yields the corresponding motion. For instance, when movement in an HMD virtual scene is triggered by pointing gestures or “walking in place,” the latter creates a stronger sense of presence than the former.109 Unsurprisingly, perhaps, “real walking” (using a wide area motion-tracking system) generates an even stronger result than walking in place. Generally speaking, presence seems to be “positively associated with the amount of whole body movement [...] and head movements [...] appropriate to the context offered by the VE.”110

While there is plenty of evidence to suggest VR-based cognitive behavioural therapy (CBT) for treating anxiety is as effective as “real-life” CBT,111 bodily integration proves to be of benefit: treating arachnophobia using an actual spider model (that can be touched) together with a virtual one.

---

107 Here and in what follows, Ware, Arthur, and Booth, “Fish Tank Virtual Reality,” 42.
does not only improve therapeutic results, but “[b]eing able to physically touch the virtual spider during therapy heightened the degree of realism, the sense of presence, and the amount of anxiety experienced by the participants during treatment.”

Taken together, these results suggest the sense of presence in virtual environments depends on the extent to which they react to our bodily actions. In this way, we can understand the sense of presence generated by HMDs as a function of distal attribution. Establishing presence in an HMD, then, is a process by which the linkage between action and perception is explored and subsequently incorporated, producing an externalization of the interactive virtual world as a distal environment. As tactile visual substitution relies on explicitly non-visual stimulation, but, at the same time, allows one to “experience stationary objects in front of the camera” through “extensive practice,” we may regard it as a radically non-visual model for how virtual worlds are created. Thus the spatiality of distal worlds in VR is not so much the result of HMDs presenting two two-dimensional renderings of virtual geometry to our eyes. Instead, it is based on our mastery of their sensorimotor contingencies both learned and continuously exercised.

**Realism and Current-Generation HMDs**

Another strong argument for a de-emphasis of the visual in discussions around HMDs is the inability of pictorial realism in virtual worlds (understood as level of detail or rendering quality) to affect presence. Even when comparing virtual reality to real environments the latter do not necessarily entail a greater sense of presence. A study by Martin Usoh et al. found almost no difference in presence questionnaires after a group of subjects completed a search task in both an office space and an HMD-based simulation of it. While this casts some doubt on the overall usefulness of presence questionnaires, the same questionnaires are able to detect differences between head-tracking and stereoscopic presentation of virtual environments, which supports the somewhat unexpected conclusion that “the evidence to date does not support

---

the contention that visual realism is an important contributory factor to presence.\textsuperscript{116}

The majority of VR research is based on the first wave of VR systems of the 1990s and early 2000s. Recent development in low-cost commercial HMDs has yet to take effect in experimental research. However, the findings discussed above are reflected in the technological setup of current-generation devices. Developers of contemporary HMDs seem well aware of the role reafference plays in the creation of the worlds their devices offer. Already in late 2012 Michael Abrash, the developer of \textit{Oculus Rift}, made it clear in a blog post that “latency is fundamental” for virtual and augmented reality,\textsuperscript{117} arguing for a quick re-entry of our afferent actions into the perceptual system. Abrash subsequently redefined realism as something based on action: “by ‘real,’ I don’t mean that you can’t tell they’re virtual by looking at them, but rather that your perception of them as part of the world as you move your eyes, head, and body is indistinguishable from your perception of real objects.”\textsuperscript{118}

As if trying to support the theory of sensorimotor contingencies and its implication that “the visual quality of shape is precisely the set of all potential distortions that the shape undergoes when it is moved relative to us, or when we move relative to it,”\textsuperscript{119} Abrash argues that it is not the visual similarity of virtual scenery to some reality that is crucial for its perceived realism, but rather its relation to what we do within that environment. If the structure of the rules (or Poincaré’s laws) governing how the perception of objects changes when we move our eyes, head, and body is familiar, a virtual world will feel real.

Arguments like Abrash’s led the \textit{Oculus Rift} developers to replace its initial motion sensor with an in-house development featuring a higher sampling rate and less latency.\textsuperscript{120} Moreover, this was also the basis for the decision to include predictive tracking in the sensor software so as to fully eliminate latency between tracking data acquisition and its effect on rendering by using a filter that can “reliably predict the future orientation at the time the user

\textsuperscript{116} Sanchez-Vives and Slater, “From Presence to Consciousness,” 333.
\textsuperscript{118} Ibid.
\textsuperscript{119} Here and in what follows, O’Regan and Noë, “A Sensorimotor Account,” 942.
observes the rendering output." As the new sensor (composed of a gyroscope, accelerometer, and magnetometer) could accurately measure only head rotation, the team experimented with integrating position information but found the method to be “only effective over a few seconds.” With this observation, the developers included a camera to track head position and lateral motion in their prototype. Camera tracking was also added to the second version of the system, further acknowledging that the tracking of head position and lateral motion is just as essential to an HMD as rotation tracking.

The *Oculus Rift* developer documentation also makes a point of stressing the role of low-latency tracking. Potential developers are therefore reminded that virtual reality is not based on stereoscopic images alone because “head movement [...] is extremely important for conveying depth and providing a comfortable experience to the user.” Even the cheap, and apparently simple, *Google Cardboard*, which turns regular mobile phones into HMDs, relies on the phone’s sensors for tracking head rotation.

Consequently, the HTC Vive HMD, an upcoming device, includes a laser-based position tracking system that measures head position and orientation within a physical room, allowing for “real” walking. For current technology journalists, the resulting system seems “incredible” because “what this headset nails—and I mean fucking nails—is a sense of presence.” “Nailing” presence is, to this day, not a question of image quality and pictorial realism—it is a question of accurately moving objects, and worlds, into view.

---

122 Ibid., 194.
124 Ibid.
Conclusion

The cultural parallels between Clark’s relational objects and HMDs can be answered in part by historical circumstance. The paradigm shift towards classical control theory and its radicalization towards cybernetics is part of a great de-stabilization of the perceived boundaries between human, animal, and machine, which was rooted in a re-thinking of both cognition and perception through notions of feedback and circular causality. Though founded in abstraction and formalism, this shift paradoxically implied a focus on the body and its activity simply because cybernetic feedback control produces systems that dynamically determine their own sensations through action. The construction of Sutherland’s HMD, the development of Bach-y-Rita’s sensory substitution systems, and Clark’s head-mounted and sensorial works—all at roughly the same time—may be understood against this techno-cultural background.

It is of no surprise that recent interest in Clark’s work was driven by technological developments toward our “telematic future.” Distal attribution and sensory substitution have also been discussed irrespective of their therapeutic implications, when, during the 1990s, “the newly developing technology of teleoperator and virtual displays” raised the questions of presence discussed above.

And while presence research has largely taken place within the field of human factors that focus on engineering and design, it has been noted that there are inherent “conceptual interactions between the apparently distant fields of presence and neuroscience research.” Body-centred definitions of presence which assume that “the sense of ‘being there’ is grounded on the ability to ‘do’ there” can be recognized as resulting from the experimental evaluation of HMDs and VR grounded in bodily activity.

Results regarding the relation of presence to bodily activity directly express the active nature of spatial perception. And if spatial perception results from establishing a linkage between action, perception, and environment, if it results from studying the “laws by which those sensations succeed one

130 Osthoff, “Lygia Clark and Hélio Oiticica.”
132 Here and in what follows, Sanchez-Vives and Slater, “From Presence to Consciousness,” 337.
another” in a cybernetic comparison of the efference copy and reafferent change in perception, then an awareness of the body and its motion is needed to understand virtual space.

Certainly, that pictorial realism may be of little relevance for perceiving virtual worlds as “real” further establishes HMDs as reafferent devices. Perception of VR, in this sense, does not function as an “automat, which reflexively delivers a given ticket [spatial impression] when a particular coin [image] is inserted in it.” Like von Holst and Mittelstaedt, we may rather have to perform a “complete reversal” of the idea that virtual worlds are rendered, perceived, and acted within and towards a view assuming that our action causes the spatiality of virtual worlds as an effect of the interaction of internal “will” or “innervation” and external stimulation. As such, HMDs are not only visual but relational devices, closer, perhaps, to the cyborg augmentations proposed by sensory substitution than to pictorial traditions.

Clearly, then, Clark’s body of work is not only the result of the same techno-historical climate that underlies the creation of perceptual technologies, and raises fundamental questions about the nature of cognition and perception. Her gradual dissolution of the sense of vision and her progression towards bodily awareness can be regarded as a model for how to understand the devices her goggles and gloves reference visually. Conceptually, these relational objects reference the cybernetic principle of goal and margin of error, action, and the predicted versus real changes in stimulation. They make apparent how in perceiving a virtual environment we are not the “keyboard on which the external stimuli would play,” but are permanently enacting virtual realities like “a keyboard which moves itself in such a way as to offer [...] such or such of its keys to the, in itself, monotonous action of an external hammer.”

Acknowledgements

The publication of this article for MediaTropes was made possible by the Image Knowledge Gestaltung. An Interdisciplinary Laboratory Cluster of Excellence at the Humboldt-Universität zu Berlin (EXC 1027/1) with the financial support from the German Research Foundation as a part of the Excellence Initiative.