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Digital Matters: Processes of Normalization in Medical Imaging

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Abstract

With the introduction of advanced computing technologies, medical imaging increasingly entails normalization through procedures that create, shape, and adjust comparable variables deduced from processes in the living body. The computational rationalities of imaging technologies such as functional magnetic resonance imaging (fMRI) and computed tomography (CT) not only determine how human bodies are envisioned and visualized, but also how they need to be aligned with apparatuses to answer experimental and diagnostic questions. By drawing on the theoretical concepts of computational rationality and intra-action as well as on ethnographic observations, we aim to disentangle the processes of normalization and the intra-actions of bodies and technologies in medical imaging on three levels. First, we show how, in the history of theoretical mathematics, dynamic processes were conceptualized as discrete and hence calculable, in particular how the ideas of Joseph Fourier informed the development of the fMRI algorithms currently applied in experimental contexts. Second, we analyze how the application of these algorithms enables and

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determines practices in fMRI-based research. Third, we explore how bodies and technologies are aligned with tomography scanners and thereby demonstrate the conceptual and physical convergence of digitalization and materialization, which opens up possibilities for visualizing and understanding human bodies. In a theoretical and analytical perspective, we argue that a critical analysis of digital imaging processes calls for scrutiny of the epistemic and operational preconditions that are actualized but concealed in the application of imaging technologies.

Introduction

Contemporary digital medical imaging processes, for example in magnetic resonance imaging (MRI) or computed tomography (CT), are based on mathematical models of the human body. Because these models relate to characteristics such as tissue density or average morphologies of organs, they determine the subsequent measurement, computation, and imaging of anatomical and functional characteristics. Mathematical paradigms for calculating physical properties and image reconstruction algorithms inform different stages of the imaging process and thereby not only dictate the epistemological conditions for the representation of bodies via images and the perception of aspects of bodies, but also impose very material constraints such as straps for immobilization and the use of contrast agents on patients during data acquisition.

The algorithmization of bodily processes in digital imaging serves to prepare and generate specific concepts of “normal materiality” in such a way that the individual body is standardized through algorithms that provide specific body standards and average values. In this respect, mathematical models of the human body are normalizing in two ways. First, models can describe only a certain range of a paradigm that represents the object under investigation. The parameter set to designate an object is always already the average of a large group. Second, this average, which initially framed a phenomenon technically in the laboratory, is epistemologically and materially translated back onto the body (Daston & Galison, 2010, pp. 183-190). Both these aspects of normalization are subject to “co-evolutionary” technologies (Slavin, 2011), resulting in a statistical body. Here normality must be understood as conceptually distinct from normativity (Link, 2013, p. 202; Link, 2014). Normativity describes all ethical, legal, and political principles of desirable human actions in a specific society. Normality by contrast is a historical phenomenon that arose with the ubiquitous datacizing of society and its individuals. The terms “datacized” or “datacizing” describe the mathematical translation processes from wetware (the human body) to hardware through apparatuses and back again. These processes oscillate in the high-tension alternating field of the organic and veer between standardization and individualization, normalization and appropriation. The “normal” in this case is the average of a mass; everything over or under its mean value is not part of normality (Link, 2013, p. 202). Normalization therefore describes the processual steps required to constitute normality.

Transforming the physical world into discrete and hence computable frequencies and functions means deciding and operationalizing what constitutes a part of, for example, the human body, and what does not. This begs the fundamental question of how the mathematical and computational foundations of technology enable and simultaneously provide knowledge of the body that is part of imaging processes as processes of normalization. Software studies scholar David Berry coined the term “computational rationality” to describe “a special sort of knowledge, [which] is essentially vicarious, taking place within other actors or combinations and networks of actors (which may be human or non-human) and formally algorithmic” (Berry, 2011, p. 13). In contrast to instrumental rationality, computational rationality denotes a “special sort of knowledge” that, through processes of algorithmization such as in digital medical imaging, codifies how bodies become visible and comprehensible, but also how they must be configured to produce contextually significant knowledge.

To disentangle the algorithmic and material processes at work in digital medical imaging, we focus on the intra-actions of imaging technology and the human body in order to analyze how normalization is encoded and operationalized. The theoretical concept of intra-action was introduced by the physicist Karen Barad who employed the notion as an example of quantum physics. Barad analyzed the interplay between a technological procedure and an object of investigation and used the term "intra-action" to describe "the inseparability of 'observed object' and 'agencies of observation'" (Barad, 2003, p. 814). She further explains the concept of intra-action:

> A specific intra-action (involving a specific material configuration of the 'apparatus of observation') enacts an agential cut (in contrast to the Cartesian cut – an inherent distinction – between subject and object) effecting a separation between 'subject' and 'object'.... In other words, relata do not preexist relations; rather, relata within phenomena emerge through specific intra-actions. (Barad, 2003, p. 815)

With Barad's notion of specific intra-actions, we can retrace and understand how agential cuts enact and constitute both relata and their relations in a material fashion, not only in terms of the material configuration of the "apparatus of observation" as Barad writes, but also with regard to the "living materiality" of human bodies, which is subjected to normalizing programs through computational rationalities.

To investigate the processes of normalization at work in digital imaging, we draw on Barad's notion of intra-action because it enables us to focus analytically on the applied technical apparatuses and their operational relations to bodies in order to explore the conditions of computational rationality and its agency in the two examples of fMRI and CT. These imaging technologies represent the currently most widely applied forms of digital imaging in medicine and illustrate important agential cuts. With the concept of agential cut, Barad describes the framework of a technical apparatuses that establishes a scientific phenomenon as well as who is observer and what is observed, who is subject and what is object.

In this article, we explore the epistemological and material preconditions of fMRI and CT. We do not intend to compare the two technologies, but rather to emphasize their very similar "apparatus of observation" of preconditioning digital data generation, especially since both fMRI and CT technologies are based on the Cartesian co-ordinate system. Physically aligning human bodies (even if only aspects are visualized) to the affordances of scanners illustrates how conceptual and material preconditions must converge in order to initiate the digital imaging process. Against the background of our critical expertise in these two imaging technologies, we here analytically and methodologically draw an “agential cut” in, as we hope to show, the conceptual and operational overlaps and similarities between these imaging processes.[1] We refer both to historical sources produced by developers and contemporary literature on medical imaging as well as to participant observations and interviews.[2] We start by scrutinizing the conceptual codifications of physical bodies in the history of mathematics and imaging algorithms that inform the field of fMRI. To show how these kinds of conception of a computational rationality are applied in CT, we then shift our focus to the rather material codification of bodies that enables the data generation process.

I. Conceptual Codification: Calculable Models of the Body

Digital imaging technologies transform the material human body into a visual medium through numbers (Balsamo, 1999, p. 223) so that the body becomes data (Balsamo, 2011; Halpern, 2014; Schinzel, 2009). By datacizing the organic, the body is turned into a consistent, endlessly reproducible and transportable “immutable mobile,” as Bruno Latour describes it (Latour, 1990, p. 27). Immutable mobile refers to the translation process from x-dimensional physical phenomena to two-dimensional laboratory objects:

> [T]he two-dimensional character of inscriptions allows them to merge with geometry.... The result is that we can work on paper with rulers and numbers, but still manipulate three-dimensional

> objects ‘out there’.... You cannot measure the sun, but you can measure the photograph of the sun with the ruler (Latour, 1990, p. 46).

Historically, different analogies and models have been employed to imagine human bodily processes. In the eighteenth century, at the very beginning of the industrial revolution the human body was first imagined as a machine by the French physician Julien Offray de La Mettrie in his essay *L’homme Machine* [1748] (Borck, 2010, p. 6). The human brain and its reasoning abilities were later compared to the computer and computer processes (Engel & Gold, 1998) while contemporary discourses often use the metaphor of dynamic networks (Halpern, 2014). In this article we use the term “model” not as a metaphor of how the human life sciences visualize their concepts of bodies and their functions; we limit our investigation to mathematical models as they provide the basis for the digitalization of the human body (Mehrtens, 2004). Models in this sense aim to describe dynamic processes by reducing a phenomenon to finite paradigms that can be measured and expressed in equations and algorithms.

The process of imaging living matter in the lab requires various preliminary decisions to manage the translation process from wetware (the human body) to hardware (the technical apparatus) by means of mathematical modeling. This is where models and average values of the wetware come into play. These models represent clinical and laboratory concepts and ideas relating to biological matter. With the introduction of advanced computing technologies, medical imaging increasingly entails normalization through procedures that create, shape, and adjust comparable variables “extracted” from living processes and processes of living.

The idea of codifying living processes (in particular, cranial processes) as discrete, subdivided but self-contained entities (and hence computable forms that can be rendered into images) can be traced back to early experiments in physiology. Codifying applies especially to the discipline currently known as neuroscience. In the nineteenth century, anatomists worked alongside physiologists who wanted to identify the essence of the human being/humanity in a laboratory setting but needed new ways of measuring what was deemed to be "living" on dead bodies (Hagner, 1997, p. 95). Physiologists began to measure (invisible) body processes such as blood flow, metabolism, reproduction processes, etc., at the molecular level (Raichle, 2008; Hagner, 1997).

Wavelengths

With this objective in mind, the work of physicist and mathematician Jean-Baptiste Joseph Fourier proved very helpful in the description and comparison of physical processes in the form of mathematical equations. Through the study of heat flows in his *Théorie analytique de la chaleur* (1822/1878), Fourier developed the method of dimensional analysis which enabled him to codify objects or natural phenomena by conceptually fragmenting them into different properties characterized by their wavelengths. His analytical theory had an enormous impact on physics, mathematics, and, ultimately, on digitalization today. Fourier's initial and innovative thesis was "that we may develop in convergent series, or express by definite integrals, functions which are not subject to a constant law, and which represent the ordinates of irregular or discontinuous lines" (Fourier, 1878, p. 22). The epistemological impact of Fourier's theory was groundbreaking in that it not only overturned previous ideas on the calculation of material properties, but also called for a more application-oriented mathematics. Fourier included in this mathematics the description and differentiation of the physical characteristics of objects such as waveforms of heat in his attempt to find a baseline for calculating and comparing corresponding properties in different objects. This allowed him to conceptually transform the physical world into discrete (and hence calculable) frequencies and functions. For him, such mathematical descriptions were equivalent to the laws of nature.

> Mathematical analysis has therefore necessary relations with

> sensible phenomena; its object is not created by human intelligence; it is a pre-existent element of the universal order, and is not in any way contingent or fortuitous; it is imprinted throughout all nature. (Fourier, 1878, p. 25)

The basic assumption underlying Fourier's method is that a small number of invariable and simple natural laws exist and that, by considering objects as an assemblage of different properties, the object as a whole can be rendered amenable to measurement and computation. Fourier proclaimed nothing less than the absolute countability of objects and physical reality. The shift from an atomistic concept of materiality to an oscillatory and process-driven idea of physical phenomena was the actual epistemic turn and the reason why Fourier is seen as the pioneer of digitalization (Siegert, 2003, pp. 17-18; Donner, 2006). This led to a completely different understanding of the analytical frameworks in physics. It was Fourier's analytical toolkit and his idea of fragmenting and transforming material objects into wavelengths and frequencies that enabled the interweaving of analysis with calculability and predictability. The entanglement of calculability and predictability ultimately resulted in an era of risk assessment typical of digital processes. Risk assessment here refers to the scientific collection of data to generate epistemic value from not just describing, but also prognostically evaluating, its future meaning.

Fourier understood that he had established a way to mathematize the human body because, for him, "mathematical analysis has outrun observation, it has supplemented our senses, and has made us in a manner witnesses of regular and harmonic vibrations in the interior of bodies" (Fourier, 1878, p. 24). For Fourier, the application of his mathematical theorem to physical objects not only led to the conclusion that natural laws could be calculated, but also that their mathematical description could be used to forecast possible behaviors.

Axioms

At the end of nineteenth century, theoretical mathematicians started another revolutionary (in mathematical terms) discussion about the meaning and the intentions of axioms in mathematical theory: What does it take for an axiomatic rule to be deemed to be true? An axiom is a mathematical principle presented as evident and taken to be true. Axioms serve as starting points for further reasoning and as arguments for mathematical problems. At the beginning of the twentieth century, however, the meaning of axioms in mathematics changed fundamentally owing to the work of mathematician David Hilbert (1862-1943), who invented a new axiomatic system for Euclidean geometry (Hilbert, 1899; Heintz, 1993). As the mathematician and philosopher Eva Müller-Hill writes, this new notion came up in response to the questions of

> what are the features that make the availability of mathematical proof a necessary or sufficient condition for mathematical knowledge? What is the role of formalizability in this context? In what sense of 'formalizable' is formalizability essential for the epistemic significance of mathematical proof? (Müller-Hill, 2011).

The debate triggered by Hilbert's work not only provided the foundations of theoretical mathematics, but also gave rise to its paradoxes. And as axioms no longer needed to have any relevance to, or justification in, practical experience, therefore the question of what makes an axiom true had a new answer: It is self-evident and true as long as no other axiom holds that its meaning is false. Through this formal understanding of axioms, mathematics developed its own language, not simply on the basis of numbers or classifications of mathematical parameters, but through the interrelation of mathematical objects as points, lines, planes, and surfaces. With Hilbert's principle, the objects defined by the axioms can also become true if no contradictions to them can be stated. For Hilbert, this was the new criterion for defining truth and existence in mathematics (Heintz, 1993, p. 28).

This new mathematical freedom from materialization and empirical experience allowed mathematical equations to become very productive in the creation of new worlds (Heintz, 1993, p. 27). With this second shift, we witness the loss of reference to practical and empirical experience.

The Decision Problem

The discussion of axioms in theoretical mathematics was accompanied by new forms of application-oriented endeavors in practical mathematics. Alan Turing (1912-1954) found an answer that applies this new conception of axioms to algorithms and computing, by solving the *Entscheidungsproblem* (decision problem). The decision problem refers to the difficulty of identifying the generality of expressions mechanically. A general procedure had to be established to decide whether or not a theoretical sentence could be proved. In formal mathematics, there are two main types of algorithm: questions requiring a “yes/no” answer (decision algorithms) and “what” questions (calculation algorithms) (Heintz, 1993, p. 74). Alan Turing shaped the concept of algorithms by suggesting a solution to the decision problem, which was the subject of much discussion in the mathematical research community, in particular within the circle at Göttingen University that gathered around Hilbert. In his paper *On computable numbers* (1936), Turing provided a new interpretation of the *Entscheidungsproblem*, which, instead of suggesting a new axiom, proposed a concrete construction: an apparatus. Turing gave expression to the new mathematical language through the invention of a formal machine that could process a couple of “yes/no” questions. Implementing formal logic in a machine allowed Turing to limit the decision process to “yes/no” questions and thereby reduce the number of human decisions at the outset. Turing was aware that computing is based on mathematical regulations and that the very human decision problem had to be solved for algorithmic processing, so in *argumentum e contrario* it was clear that human beings who follow a regulatory requirement are performing in a mechanical way. An algorithm is not necessarily mathematical; it can be a pattern of specific steps to be performed mechanically, without thought. And vice versa: something that can be performed mechanically can also be performed by a machine. Through this new understanding of the algorithm, Turing turned the idea of mathematical calculation upside down and accorded a major role to the technical apparatus (Turing, 1936). Turing did not choose an abstract physical quantity as the starting point for computable functions; rather, he took the concept of the calculation process itself as the basis for an algorithmic procedure. But it was the detection of Fourier series and continuous Fourier transforms that marked the mathematical shift from analysis to synthesis, which remains to this day the source for every digital media-based system. This is also true for fMRI where several Fourier transforms produce the picture of a "thinking" (i.e., blinking) brain map.

It is not possible in this article to outline the whole history of brain imaging, nor the epistemic shifts that occurred in neuroscience and cognition theory from the mind-brain dualism to contemporary computational neuroscientific methods. What we want to show with our brief review of the changes in theoretical mathematics and application-oriented physics is the intertwining of the logics of methodological approaches and the knowledge of physical properties produced through them. With the birth of computational logic, the human brain and its thought processes have always been related to the computer metaphor, and this has accompanied all the changes the concept of the computer has undergone over the last hundred years. Orit Halpern describes the current neuroscientific understanding of the computer metaphor for cognition in the human brain: "Reframing memory and decision making in terms of information, recoding, and data compression, the psychologist George Miller created a new account of psychology, arguing cognition was an algorithmic process that could be manipulated" (Halpern, 2014, p. 201).

To summarize: Fourier reduced physical values and qualities to wavelengths so that physical characteristics could be represented in mathematical equations. A turn in theoretical mathematics at the beginning of twentieth century transformed the idea of algebraic truth and the concept of an axiom. From now on, the concept of an axiom held to be true no longer need rely on experiential or physical reality; an axiom was now effective when no other axioms contradicted it. With this shift, theoretical mathematics became self-referential and the essence of empirical proof as preconditions for the calculation process. Turing enabled the sequential calculation of a chain of algorithms without human intervention by building a machine that proposed subsequent options after one algorithm had been answered. Every answer to a "yes/no" question led to a new "yes/no" question. Turing used human courses of action as templates for computed actions. To do so, he reduced mechanical courses of action to simple steps in order to minimize their complexity and store them in a schematic order. This epistemic change served as the foundation for the development of digital imaging processes and thus formed the basis for images of processes.

Fragmenting the Body

To understand the logic of medical digital images of the inner human body in particular parts such as the brain as an object of investigation, this logic must be related to the mathematical approaches of these datacizing processes. In the generation of medical visualization technology that followed, the human body and brain was modeled and virtually fragmented into small entities that could be measured and made amenable to further computerization and normalization. Today, brain processes in modern computed neuroscience are framed as dynamic neural networks. The idea of the neuronal network is based on mathematical equations of synaptic growth (i.e. deep learning) and an operationalized definition of characteristic processes. That means the concept of a computer is still a metaphor for the brain. However, with the development of high performance processors and complex networks, the idea of the brain also changed. Algorithm-based methodological ideas for analyzing the brain became the overall representation of the brain as such: “Most broadly, looking through the lens of computer science can teach us about the nature of the human mind” (Christian & Griffiths, 2016, p. 4). Through this epistemic change in the neurosciences, the brain is seen as a network handling a bunch of calculable processes.

II. Algorithmic Codification to Measure the Brain

Fourier’s investigations paved the way for the digital codification and production of images of the human brain in fMRI. The computational rationality paradigm that Fourier provided is part of a new epistemic framework of materiality produced in natural scientific laboratories. In the last thirty years, digitalization procedures have been implemented more broadly in technical equipment and laboratory apparatuses which are not only used for measuring or examining existing entities, but also announce a new logic of scientific enquiry. Following on from the long scientific tradition involving observation and description of natural phenomena, technical laboratory practice has turned toward the creation of referential and ideal reality (Cetina, 1997).

The Human Brain as a Computational Network

In this section, we examine how the computational rationality of fMRI is conceptualized by understanding the human brain as a computational network that can be measured using digital imaging technologies. In particular, the algorithms involved in the multiple transformation processes required to visualize the brain in the field of fMRI are interesting in terms of how the brain is algorithmically codified and which agential cuts are enacted through and in laboratory practices. Keeping in mind that a number of non-visible computational steps must be taken to articulate the human brain as a physical object in the form of visual data, we explore the underlying mathematical steps necessary to render the brain in this form, including (but not limited to) those steps that involve categorizing different aspects of the physical brain. By exploring the epistemic dimension of algorithms in brain imaging, we seek to understand its resulting effects on conceptions of the brain as such. To accommodate the human body in fMRI measurement procedures, various steps are required. Empirical science is mostly hypothesis-driven and demands that the complexity of the object of investigation be reduced to paradigms that can be examined by apparatuses (Dumit, 2004; Fitsch, 2012). Even if they are not explicitly articulated, certain assumptions guide the research, expectations, and interpretation of its outcome. The trained psychologist Tyler Lorig, who teaches in an interdisciplinary neuroscience program, maintains that the fundamental theoretical and, in particular, epistemological question of functional brain research is the *where* question because any localization of physiological activity must apply an anatomical map of the brain (Lorig, 2009, p. 18).

To measure the functional activity of a human brain with a magnetic resonance tomograph (basically a huge magnetic field), the brain is treated conceptually as if it consisted of small entities of information, so-called *voxels*. The magnetic resonance scanner applies a Cartesian co-ordinate system to divide the brain virtually: first into slices and then to subdivide each slice into a grid along the x and y axes. Single slices are scanned one after the other and aligned on a z axis in order to represent a third dimension. The next step in producing data and creating an image is to manipulate the magnetic field strength using changing gradient fields.

> The MR signal is actually produced by the clever use of electromagnetic coils that generate and receive electromagnetic fields at the resonant frequencies of the atomic nuclei within the static magnetic field. This process gives the name “resonance” to magnetic resonance imaging. Because most atomic nuclei of interest for MRI studies have resonant frequencies in the radiofrequency portion of the electromagnetic spectrum (at typical field strengths for MRI), these coils are also called radiofrequency coils. Unlike the static magnetic field, the radiofrequency fields are turned on during small portions of the image acquisition process

> and remain off the rest of the time. (Huettel, 2009, p. 35)

Through several algorithmic steps, such as Fourier transforms, the datacized frequencies are translated into numbers, and every located *voxel* in the Cartesian coordinate system is arranged as a grey tone that indicates its activity value.

After the measurement of, and translation into, grey values, several preprocessing steps follow. The data has to be cleansed to remove artifacts, for instance motion corrections or slice scan time corrections to name just two kinds of preprocessing corrections among others.[3] To compare individual brain data, the researcher must standardize the scanned brains in terms of size and shape, average activity, etc.

This standardization step is called "normalization" and describes the process of adjusting the anatomical brain data to a unified brain; each individual brain is thus adapted to the size of standardized brain co-ordinates. The "normalization" of the anatomical brain data is necessary to superimpose and reconnect the functional brain data on and to the anatomical data in order to provide evidence for the functional data by locating it in the anatomical cartography of the brain. An interesting ambivalence arises here in the data analysis process. There are algorithms in brain imaging analysis software that co-register functional data on the anatomical, but most neuroscientists prefer to do this manually because they do not trust software-based templates:

> So there is also an algorithm for computational co-registration, but when I see how badly this co-registration of functional and anatomical data works, I have no confidence in using algorithms; instead I want to SEE the data and do the co-registration myself. (Interview 2009: 19 min., translation HF)[4]

Once the data has been prepared by following the relevant statistical preprocessing steps (cleansing the data of noise and setting average qualities for the greyscale shading), the process of analyzing the functional data can start (Fitsch, 2014, p. 93).

Intuitive Intention

To return to the ambivalent behavior highlighted in the above interview extract: What is at stake when researchers analyze computed imaging data but simultaneously question the quality of algorithmic processing? What is the impact of algorithmic codification on the analytical process, especially if the researchers do not have confidence in the algorithms? How does the use of imaging processes change our understanding of living matter if imaging technologies seemingly allow us to open up the human body to analysis in real time? The interview extract indicates that the process of analyzing algorithmic data relies on human interpretation. The evaluation and interpretation process is based on implicit, tacit knowledge (Polanyi, 1966) influenced by the research question and personal everyday circumstances, and how the images of the scanned brain are used to adapt the research results or reject them as inappropriate. This also includes how scientists remember the probands (i.e., particular subjects being studied). For example, lower activity levels are accepted without problematization as the data can be explained by the fact that the subject was a woman, and thus lower activity is expected.

This process-driven characteristic can be described with the term *intuitive intention* (Fitsch, 2014, p. 217), a concept that enables the articulation of the entanglement of the scientific community's presumptions and daily-life knowledge on the one hand, and the digitalized and visualized data produced through apparatuses in measuring and calculating processes in fMRI on the other. The terms "intuitive" and "intention" are not intended as fixed concepts of opposing positions; on the contrary, bringing these two concepts together demonstrates how intertwined the two notions are. When speaking of *intuitive intention*, the computer-driven analytical process is understood as an interplay of apparently "objective computational data" (generated by standardized technologies and algorithms in the measuring processes) with subjective, everyday knowledge and aesthetic decisions.

Neuroscientists working with brain data describe the production and mediation of knowledge through computed images as highly intuitive. The word "intuitive" is used an appreciative way, in the sense of the "most natural," the most intelligible form of knowledge representation for human perception. By "intuitive" it is meant, that the data can be understood straightforwardly. The word "intuitive" links the objective technique of imaging with an evaluation based on subjective decisions, which can, however, take on an objectified status through the appeal to the images – which is the most natural way of making nature speak. This brings together that which ultimately constitutes the status of the image in the laboratory: The image holds the promise of a scientific fact that only has to be interpreted correctly.

The term "intention" outlines the overall formalization and mathematization process we described earlier in this article (starting with Fourier and Turing), and incorporates the entire computed knowledge production, which Berry defines as "computational rationality" (Berry, 2011). Algorithmically and aesthetically guided intentions enter into the images through the highly preconditioned apparatuses and formalized processes, but they are read as expressions of the phenomenon itself and thus seemingly neutral. As a result, implicit knowledge structures find their way into the interpretation of the algorithmically produced images. They are read as "objective factuality" but power and power relations are inscribed. Interpreting brain maps leads scientists to rely on aesthetic and subjective assessments when reading and working with the visual logics of the brain image. This means normative comparisons relating to aesthetic ideas enter into the analysis process and are heavily influenced by common-sense notions of gender, sexuality, or ethnicity.

As we see in the next section, the body to be scanned, or the brain as a more specific part, needs to be normalized in line with the program of computational rationality that guides the scanner's operation, in this case a CT scanner.

III. Intra-actions in/of Diagnostic Imaging

In this section we shift our focus to the material and technological preconditions of a digital imaging process using CT as an example. In a scanner suite, the conceptual codifications of measurement and visualization need to be materially aligned with the patient's physical body. The operational and material basis for acquiring and visually comparing image data as described above are the actions undertaken in the scanner suite. They physically enact agential cuts to establish context-specific processual and, especially, spatial relations between body, technology, and image. In this respect, the differences between radiological scanning technologies remain largely insignificant, even though MRI and CT employ different physical properties and serve different epistemic functions. Yet the dispositives of MRI and CT scanning suites share similar features when embedding human bodies in scanners.

In the field of CT scanning, the computational rationality constituted conceptually and algorithmically entails very material prerequisites for the imaging process. Current practices for imaging living human bodies in CT are based on a fundamental precondition that the body's mobility must be framed and immobilized before any imaging process can start. In this section we show how, with today's radiological imaging technologies, this prerequisite becomes a force with highly practical consequences for the body.

In the initial data acquisition phase using an MRI or CT scanner, the body is aligned with the affordances of the scanner. By following the protocols of positioning the patient inside the scanner ring, technicians adjust the space of the body to the space of the Cartesian co-ordinate system, which determines the geometric references for tomographic scanning.

Some of the positioning procedures also entail rigid immobilization of the patient with the aid of straps in order to prevent motion artifacts in the subsequent images. In order to generate and process a contextually significant image, body and machine need to be materially and spatially intra-acting.[5] Only by adjusting and aligning the somatic and technological spaces can the transformation between digital and physical processes (and hence their normalization) be initiated so as to activate the computational rationality of radiological scanning.

As mentioned above, Karen Barad coined the terms "intra-action" and "agential cut" to shift the analytical focus toward the situated interplay between a technological procedure and an object of investigation that established both the *relata* and their relations for a specific epistemological and operational regime – in this case, a diagnostic insight. While Barad's analysis is directed toward intra-actions that enact agential cuts *during* an experiment, transferring the concept of intra-action to diagnostic contexts in medical imaging is productive as a means of examining the more routine measures that need to be taken *before* an imaging process can be initiated in a non-invasive and therefore seemingly immaterial procedure. Barad offers a method for critical thinking about technologically configured sets of apparatus and practices that generate knowledge about bodies and their dynamic materiality. The apparatuses' own logic mutually (re)generates and aligns paradigms derived from mathematical epistemology and hence operating according to a processual logic of normalization, in both the sense of conceptualization prior to technological applications and the reconfiguration of materiality in the course of applying digital technologies. Materiality in this sense must be understood not only as the physicality of a body or a technical apparatus, but also as a conceptual codification or epistemic program, which is inseparably linked to, or inscribed in, materiality.

Media studies scholar Scott Curtis identified the tension between dynamic liveliness and diagnostic epistemology as a basic struggle of medical hermeneutics:

> The human body is … frustratingly resistant to contemplation, study, and interpretation …. In this sense, medicine's foundational hermeneutic dilemma rests on a dialectic of movement and

> stillness that is mimicked by the use of motion pictures in medicine and is re-enacted in digital medical imaging techniques. (Curtis, 2004, pp. 220-221)

But before the bodies' movements can be reconstructed using moving images or functional imaging, a paradox must be solved: How is an agential cut drawn that transforms the properties of a dynamic process into discrete and computable entities that can be fed into a mechanical process of abstraction?[6]

By focusing on two different material measures taken in the process of the data acquisition in diagnostic CT imaging, we demonstrate how agential cuts are physically enacted and targeted to produce codes of material substances (i.e., digital images of tissue densities). The examples of material measures we use to illustrate this intra-action are techniques for positioning the patient in the scanner and applying contrast media. These particular procedures are designed to bridge the operational gaps between living bodies and computational rationalities such as scanning algorithms by enacting agential cuts between them and mediating their intra-actions to generate a valid diagnostic image. By analyzing historical texts written by the developers of CT and drawing on our own and secondary participant observations in scanning suites, we attempt to disentangle the material operations aimed at establishing the intra-actions between bodies and scanner technology so as to enable the agential cuts for digital images. This analysis reveals the obstacles and resistances to aligning somatic and technological materialities.

Positioning the Patient

The techniques for positioning the patient in a scanner are designed to align the patient's body with the technology's Cartesian co-ordinate system and thereby establish common spatial reference points that enable the transformation and identification of spatial measurements through both algorithmic processes during computation and human actions in the course of producing images. Positioning techniques mainly concern the position the patient needs to adopt on the bench when inside the scanner ring (Saunders, 2008, pp. 111-113). In order to compare anatomical landmarks and the geometric reference system projected automatically by the scanner onto the body, technicians must align the reference systems by instructing or moving the patient. The basic geometric and mathematical reference of the Cartesian co-ordinate system, which is the basis for the scanner's operation (as in the MRI scanner) and guides the measurement and imaging processes, becomes manifest and quite instructive in this positioning phase. The human body becomes part of an operational geometry that affects its own physical configuration and imposes a process of normalization derived from the computational rationality of CT since each body must be measured according to the same reference system.

In the early experimental phase of CT scanning, neuroradiologist James Ambrose emphasized the need for stillness during the phase of data acquisition:

> A small amount of movement will introduce aberrations into the readings. This will reduce the quality of the pictures. A considerable amount of patient co-operation is therefore required and … four minutes is a long time for a patient to remain perfectly still, and some small movements nearly always occur. (Ambrose, 1973, pp. 1038-1039).

Scanning was a longer process in the technology's early days. However, remaining immobile and in some cases also holding one's breath during scanning are still prerequisites for the generation of clinically valid images.

Contrast Media

A further example of the codification of somatic materiality and, in particular, the vivacity of the patient in line with the rationalities of the imaging process, is the use of contrast media. Contrast media such as barium- or iodine-based substances are used to enhance the "extraction" of diagnostically significant signals from the large quantity of measurements taken by the scanner. The assumption that body and contrast media will intra-act in a standardized and hence reliable manner demonstrates the expectation that images generated in this way will have “enhanced visibility.” Contrast media will adhere to highly specific parts of tissue or aggregate in cavities and thereby indicate malfunctions or pathologies. In such locations, the X-ray beams of the CT scanner are attenuated in a different way and therefore highlight a certain condition in the body. The contrast medium as a material substance is intended to change the body’s own materiality in intra-action with the X-rays; measurements can then be digitally presented and diagnostically reviewed.

As with the use of positioning techniques, the use of contrast media is intended to prepare the patient’s body to reflect the computational rationality of medical imaging before any image is even generated. The mathematical system applied by establishing a spatial reference frame for both technology and body (i.e., the Cartesian co-ordinate system) also enables specific material properties such as tissue density to be addressed. Thus technology and body intra-act to enact an agential cut that stems from the computational rationality encoded by imaging algorithms that enable radiological diagnostics.

IV. Conclusion

Normalization processes and intra-actions of bodies and technologies in medical imaging can be traced on different levels. As we have argued throughout this article, a critical analysis of digital imaging processes calls for scrutiny of the epistemic and operational preconditions actualized but concealed in the application of imaging technologies. They are effective on multiple levels: conceptual, applied algorithmic, and material. As we have shown, the idea of digitizing dynamic processes has inscribed itself into the algorithms that operate inside tomography scanners. By shifting the analytical focus to the modes and conditions of the computational rationality of certain technologies and to the operational and epistemological gaps entailed in the transformation of living entities into algorithmic processes (e.g., the role of intuitive knowledge in image interpretation), we have shown that it is not only formal and deterministic processes that are operative. Thought processes "translated into a mechanical process of action" (Trogemann, 2010, p. 43) also guide the intra-action of these thought processes, their algorithmic codification, and the material forms they take as they retroact at another level on a material, cultural, and social world evidently affected by them (Trogemann, 2010, p. 44).

In this section, to connect the two case studies we analyzed in this article, we employ an example based on the practice of fMRI but utilize material constraints similar to those illustrated with the example of CT: the fMRI head coil. The fMRI head coil exemplifies the convergence of epistemic and operational preconditions of imaging in a single object. It also enables further discussion of our notion of agential cuts in the context of normalization within and through different levels of digital imaging processes. As we outlined above, the magnetic resonance tomograph is based on a huge static magnetic field that aligns the hydrogen protons in human tissue (MRI) or in blood (fMRI) in one direction. Under normal conditions, nuclear magnetic dipoles in the body are randomly arranged; but, if a strong external magnetic field is applied, the molecules inside the body become polarized. The head coil is responsible for activating the radiofrequency fields to distract the protons for a short period of time in order to measure how long they need to return to their previous (i.e., aligned) position (see also the description in Section II). In the coil placed over the head to measure the so-called functional activity of the brain, the operative-technical normalization is aligned with mathematical-epistemic knowledge. What is measured through the magnetic resonance and the nuclear spinning movement is essentially the assumption that the presence of fresh blood is an indicator of brain activity: "Neural activity is linked to susceptibility changes in the following way: it increases local metabolic demands, and these are compensated for by an increase in local blood flow and capillary volume" (Roskies, 2008, p. 23).

There are many presuppositions in the fMRI head coil technique. These start with general body regulations: People with a wider body volume do not fit into the scanner and under the head coil; people with claustrophobia are unable to take part in the experiment because the scanner and the head coil are very tight, and patients have to lie still for one to two hours during the experiment, due to the risk of producing motion artifacts. The frequency rate depends on various conditions. For example, to start the scanner, a technician has to enter the patient's gender, which is coded as a binary option of female/male. The frequency rates refer to different gender standards in the specific absorption rate of the brain material (Dimbylow, 2005).

By analytically tracing three agential cuts, we have sought to disentangle the intra-actions in digital processes on the above-mentioned three levels (i.e., conceptual, applied algorithmic, and material). Examining the history of theoretical mathematics and its effects on experimental imaging practices demonstrated that this computational rationality constitutes an ontological "space of possibilities." The shift initiated with Fourier's new understanding of "nature" (i.e., the change from an atomistic concept of materiality to an oscillatory and process-driven idea of physical phenomena) is merely a methodological shift in digital medical surveying technologies. The translation process from wetware to hardware has to convert complex physical matter into wavelengths in order to subdivide and describe their characteristics through sine and cosine functions. However, for visualization, diagnostic or analytical purposes, these wavelengths have to be resituated onto a digital map of the body or the brain. This digital and visual (re)localization of bodily characteristics constitutes a new digital matter: They create statistical maps that combine the virtual and visual object, yet are at once a representation of something (i.e., the "thinking" brain) and its quantification. Mapping defines a landscape and is always necessarily a project to install a norm. Through this "tendency to convert abstract concepts into entities" (Gould, 1996, p. 56) (i.e., by locating them in the human brain), digital medical images such as fMRI images become highly relevant to society's normalizing discourses, for instance, by constructing what a gendered brain looks like and the kinds of behavior it supposedly gives rise to. Their becoming actual and plausible takes place *in* the application of imaging technologies whose logics of quantification are enclosed and completed but nevertheless shape our perception and understanding of brains and bodies. Thus the experimental and diagnostic inquiries that can be addressed to these imaging technologies are inherently limited by their computational rationalities. Only the questions and decisions that were conceptually and algorithmically encoded in the scanner's software and hardware can be addressed and answered by employing imaging technologies. A critical analysis of digital imaging processes must therefore extend the scope of study to the epistemic preconditions that encode and actualize the agential cuts and intra-actions that generate experimental knowledge and lead to diagnostic decisions. Technologies themselves hide the agential cuts, they enact and obfuscate the difference and agency of subjects and objects; that means, to uncover inherent normalization processes, the analytical disentanglement of intra-actions that precede visualizations are a fundamental attempt.

Notes

[1] To focus on conceptual codifications, we take the brain as a more specific part of the body as it is also the focus of attention in the context of the experimental research we explored.

[2] We refer to a research corpus generated through field studies that included interviews and participant observation in 2008 and 2009 at the Max Planck Institute for Brain Science in Germany.

[3] For a broader introduction to the technique of fMRI see Toga & Mazziotta (2000), Gallagher (2008), and Fitsch (2014).

[4] Fitsch used *Technografie*, see Rammert & Schubert (2006) (i.e., an

ethnography with a focus on technology) as a methodology based on qualitative methods such as participant observation, interviews with experts, and document analysis, see Fitsch (2014).

[5] For the collective and perceptual dispositions activated when reading CT scans, see Friedrich (2010).

[6] For more on the visual culture and visual history of medicine, see Holtzmann Kevles (1997) and Cartwright (1995).

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