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Central coherence and the shaping of expertise in design: evidence from designers with autism spectrum conditions

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Abstract

This paper proposes to contribute to our understanding of the fundamental cognitive processes essential to designing by exploring the experiences of people who have different information processing behaviors to those found in most people. In particular, we focus on people with autism spectrum conditions (ASC) because they are known to have information processing behaviors that are both maladaptive and exceptional. Central to our study is the question: what can we learn from people with ASC about cognitive processes essential to designing? The scholarship on cognitive behaviors associated with the autism spectrum and narratives on the experiences with design practice by individuals with ASC are discussed in relation to cognitive processes associated with designing. In turn, the individuals commented upon the analysis of cognitive processes associated with designing in light of their personal experiences with design practice. We conclude that the weak central coherence theory of autism provides a useful prediction of the cognitive processes necessary for expertise in design, and that both the framework for expertise in design and the way it is studied may require updating.

Introduction

At least since Herbert Simon first postulated particular forms of reasoning associated with design practice (Simon, 1969, 1995), design cognition has been a central theme of design studies (Chai & Xiao, 2012). Scholars have been searching for the possibly unique and essential cognitive processes at the foundation of design practice, regardless of design discipline (Goel & Pirolli, 1992). Part of the challenge in this search is the very definition of designing. For the purposes of this paper, designing is defined as the act of conceiving an object, environment, or situation for an intended purpose. Methodologically, disproving a null hypothesis about a cognitive process essential to design is nearly impossible: a hypothesis such as "Analogical reasoning is essential to design cognition" is hard to confirm, as rejecting the null hypothesis that it is inessential would require a population of people who are impaired in this cognitive process and yet are able to design. Finding a population that lacks or is deficient in analogical reasoning is extraordinarily difficult, if not impossible.

To circumvent this methodological challenge, scholars have taken a comparative psychology approach by examining evidence of cognitive processes in nonhuman animals that may be relevant in the evolution of design cognition in humans. A review of cognitive processes found in the great apes identified representation, recursion, and curiosity as likely to be essential cognitive processes associated with the conceptual part of design cognition (Dong et al., 2017).

This paper proposes another approach: to examine evidence on the cognitive behaviors associated with people with autism spectrum conditions (ASC). People with ASC are known to exhibit both cognitive impairments and exceptional abilities for imagination. As imagination is considered the cognitive ability *sine qua non* for design practice, cognitive behaviors within the autism spectrum may shed light on the cognitive processes essential to design. As cognitive scientists clarify the specific cognitive impairments, exceptional abilities, and information processing biases in ASC (e.g., Frith, 2003; van der Lugt, 2005), it may become possible to compare them with our understanding of design cognition to identify a set of essential cognitive processes.

The remainder of this paper continues as follows. First, we briefly review the literature on design cognition to establish a provisional set of cognitive processes associated with designing. We then proceed to review the literature on cognitive behaviors associated with ASC in light of the scholarship on design cognition. Narratives of two individuals with ASC and their experiences with design practice are described and analyzed based upon the provisional set of cognitive processes associated with designing. The results of the analyses were communicated for commentary to the individuals, who generously provided feedback. The contextualization of their feedback is included within the discussion section on cognitive processes associated with designing. We conclude by discussing how this exploratory study helps us understand the nature of design cognition.

Cognitive processes associated with designing

One challenge in identifying a cognitive process associated with designing is that there is no agreed upon exhaustive list of cognitive processes. Cognitive scientists propose a high-level list of cognitive processes: Attention, Perception, Learning, Remembering, Speaking, Problem-solving, Reasoning, and Thinking (Eysenck, 1993). This list is *not* exhaustive though. In addition, the terms cognitive process, cognitive function, cognitive skill, and cognitive ability are polysemous and often used interchangeably. In this paper, a cognitive process refers to an (intrinsic) ability of the brain. A cognitive behavior is the outward, observable manifestation of a cognitive process. A cognitive skill refers to a task-oriented ability that must be learned through observation and practice, for example, solving a differential equation or designing a four-bar linkage. Designing is likely to involve a number of cognitive processes. Designing is an adaptive function of the brain's broad capability for imagination, that is, generating novel mental representations of content that is not available to the senses (Suddendorf & Dong, 2013). Like language, designing is a cognitive skill that must be learned even though the cognitive processes associated with it are intrinsically available to us. Just as it takes time to learn a particular language, such as English, Japanese, or Hindi, so too it takes time to learn to design a four-bar linkage. The interest in this paper is to identify those cognitive processes essential to designing, independent of the object of design. Cognitive skills associated with designing specific objects and environments transcend the scope of the review.

To identify a candidate set of cognitive processes, articles published in *Artificial Intelligence for Engineering Design, Analysis and Manufacturing (AI EDAM), Design Studies, Research in Engineering Design, and Journal of Engineering Design*, all four considered influential journals of design research (Gemser et al., 2012), were searched using Web of Science. Articles having the topic of cognition were identified (TS = cognition). In total, 84 articles were identified, as shown in Table 1. Articles about end-user cognition, history, theory, and criticism, literature reviews, and computational simulations were excluded. This resulted in a set of 67 articles.

One author read each article and noted the cognitive processes studied therein. The list of cognitive processes was then analyzed to identify the set of most frequently studied cognitive processes. To create this set (see Table 2), a key phrase count of one to three-word phrases (with appropriate stemming) was performed over this list of cognitive processes identified. Single words counted were not allowed to be part of a phrase.

Table 1. Design cognition articles found in Web of Science

Journal	Articles
AI EDAM	15
Design Studies	58
Journal of Engineering Design	4
Research in Engineering Design	7

Cognitive behaviors in the autism spectrum

Autism–from the Greek word "autos" meaning self–is clinically classified as a "pervasive developmental disorder", manifesting itself in a set of behavioral characteristics, mainly with regard to social interaction and communication, and the presence of restricted, repetitive and stereotyped patterns of behavior (Wing, 1997; Happé, 1999; American Psychiatric Association, 2013). The term was first used by Kanner (1943) and Asperger (1944) to describe a group of children, seemingly living in their own private worlds and combining a great ingenuousness with a fundamental lack of knowledge about social interaction (Delfos, 2005). In the mid-1960s, well-founded theories started to explain what autism is about: a difference in information processing with a neurobiological cause (Rajendran & Mitchell, 2007), involving a more consistent, more detailed, and rather literal interpretation of perceived information (Noens & van Beckelaer-Onnes, 2004; Frith, 2008). Today researchers talk about a much wider autism spectrum (American Psychiatric Association, 2013), as autism-related conditions have been found to occur in a continuum of different forms and gradations. At one end of the spectrum, the so-called "Kanner/Asperger types" have rigid, concrete thinking patterns and definite problems with certain kinds of cognitive processes; at the other end, the so-called "low-functioning" or regressive/epileptic types, have sensory processing problems (Grandin, 1995*a*, p. 138). Below we discuss cognitive behaviors associated with ASC from both diagnostic and theoretical angles.

From a diagnostic angle

In order to understand the characteristics associated with ASC, we start from those that are determinative in the diagnosis of autism. Note that these are not necessarily all present and do not always hold for all subgroups to the extent described here. Starting from these diagnostic determinants may sketch an extreme picture, yet it is important not to reduce people to their diagnosis and continue considering them as people in the first place.

Although Kanner's original interpretation of the term "autism" underwent major changes, difficulties in social interaction are still acknowledged as one of the most important, if not *the* most important aspect of autism (Davis & Carter, 2014), which can express itself in a lack of *social* or *emotional reciprocity*. The diagnosis lists multiple aspects such as a lack of spontaneous urge to share with others certain experiences, good or bad, or difficulties in putting oneself in someone else's shoes, and related difficulties in being aware of someone else's emotions.

A second important characteristic associated with ASC relates to *communication* (Kim et al., 2014), both *verbal and non-verbal*. Some autistic individuals never learn to speak; others develop language only later in a sometimes-unusual way, both form- and content-wise (e.g., repeating collocutors' words or complete sentences). Other characteristics relate to difficulties in understanding directions or interpreting language non-literally. As far as non-verbal communication is concerned, visual thinking is often evident at an early age in high-functioning Kanner-type people (Park, 1992). Yet, even those who consider themselves as "visual thinkers" have difficulties in understanding body language, facial expressions, or eye-contact (Grandin, 1995*a*).

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Table 2. Cognitive processes identified in design cognition articles

Cognitive process	*n*	Representative article	Definition
Analogical reasoning	12	Ball et al. (2004)	A reasoning process entailing the transfer of properties from a source domain to a target domain
Problem-solving	11	Cross and Cross (1998)	The mental act of finding a process to create a desired goal from the present situation
Creativity	6	Kim et al. (2007)	The generation of novel ideas, objects, environments or situations
Decision making	4	Christiaans and Almendra (2010)	The cognitive selection of an object or course of action from a range of choices
Framing	5	Kleinsmann et al. (2012)	The inclusion and exclusion of facts about an object, environment or situation to produce a schema for its interpretation
Ideation	4	Hernandez et al. (2010)	The creation of an idea for an object, environment or situation
Team mental model	4	Dong (2005)	A mental representation of an object, environment or situation that is shared by a group
Mental imagery	3	Bilda and Gero (2007)	A mental representation of the perceptual experience of an object, environment or situation
Mental simulation	3	Wiltschnig et al. (2013)	The mental modification of a mental model of an object, situation or environment
Reflecting	3	Petre (2004)	A consideration of the theories and beliefs that underlie actions
Conceptual blending	2	Nagai et al. (2009)	The integration of properties from multiple objects or situations into a single object or situation
Fixation	2	Youmans (2011)	The repeated transfer of inappropriate or irrelevant properties from an object or situation to another object or situation
Naming	2	Khaidzir and Lawson (2013)	A description for a set of important elements in a design problem that require explicit attention
Visual reasoning	2	van der Lugt (2005)	The manipulation of a mental image in order to attain desired knowledge about an object, environment or situation

The *limited ability to imagine* things expresses itself probably most strongly in holding on to specific – not necessarily functional – rituals or routines and resistance to change (Ahrentzen & Steele, 2009; Sánchez et al., 2011; American Psychiatric Association, 2013). Trivial changes, such as a small modification in a furniture arrangement or use of a new tea set, might suffice to make autistic people lose their hold and cause major stress. This category of characteristics also focuses on their intense and sometimes limited interests. Both the intensity and focus are remarkable. Interests may range from questions of origin over dissecting the concrete structure of appliances to certain movements of processes, like a toy car's turning wheel or a sliding door that opens and closes continuously.

From a theoretical angle

The explanatory theories of autism that have been developed offer another angle to consider the characteristics associated with ASC by going into the underlying mechanisms.

The first theories about autism situate its cause in perception (Rajendran & Mitchell, 2007). An example is the *sensory theory* (Delacato, 1974). As suggested in the earliest reports by Kanner (1943), autistic people process sensory information in a special way, which can manifest itself in sometimes unusual reactions to stimuli–hyposensitivity, hypersensitivity, or inability to distinguish certain stimuli. According to the sensory theory, these difficulties in processing stimuli from the surrounding physical environment underlie the atypical behavior in autism (Iarocci & McDonald, 2006). Rocking to and fro or biting one's fingers are explained as attempts to compensate for these differences in sensory perception (Mostafa, 2007). Sometimes an autistic person has to make so much effort to process sensory information that other elements enter all the more strongly, which in turn may trigger strange behavior and frustrations. What may come across as maladjusted behavior results from an imbalance between the environment and a person's abilities to adjust to it (Sánchez et al., 2011). These problems are not unique to autism (Rajendran & Mitchell, 2007), however, suggesting that they might result from a deeper problem.

In the mid-1980s, the characteristics of autism were starting to be understood as the consequence of a primary cognitive condition. As a result, several cognitive theories were developed. Most discussed is the *Theory of Mind* (ToM) hypothesis (Baron-Cohen et al., 1985), also referred to as the "mind-blindness" theory (Baron-Cohen, 1990; Lombardo & Baron-Cohen, 2011). ToM is the ability to attribute to and recognize in oneself and others the entire spectrum of mental states like convictions, desires, intentions, imaginations, and emotions. This ability allows individuals to think about what is going on in their own and others' minds (Baron-Cohen, 2001). According to the ToM hypothesis, autistic people develop only to a limited extent an inner theory of how people think and feel (Delfos, 2005). They show impairments in representing or attributing mental states to both *self* and *other* (Baron-Cohen, 1990; Lombardo & Baron-Cohen, 2011). This hypothesis considerably furthered the understanding of the core social-communication impairments in ASC (Baron-Cohen, 1990; Lombardo & Baron-Cohen, 2011): to an autistic person, social interaction is a difficult process as it requires understanding what is going on in the other (Sánchez et al., 2011).

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Another theory is that of the *planning and executive functions* (Ozonoff et al., 1991; Rajendran & Mitchell, 2007). These functions are defined as the capacity to hold on to a fit set of problem-solving activities and reuse it in the future to obtain the desired goal state (Welsh & Pennington, 1988). This includes the intention to curb a reaction and delay it to the right moment, a strategic plan of successive actions or a mental representation of a task, including storing in memory the relevant information and desired state. These functions resemble domains such as attention, reasoning and problem-solving thinking, and differ from cognitive domains such as sensation, perception, language, and memory. Together they allow for flexibility in thought and action. Within the autism spectrum, it is precisely these central regulatory processes that are said to be sometimes disturbed. The behaviors are not correctly maintained by an "executive supervisory system". This might explain the often observed stereotypical and repetitive behavior in autistic people and their sometimes major resistance to change (Ozonoff et al., 1991; Delfos, 2005).

The final theory of autism that has been thoroughly investigated is that of the *weak central coherence*. Frith (2003) explains autism by a specific imbalance in integrating information from different levels. "Normal" information processing is characterized by an urge for "central coherence", that is, assembling diverse information in order to create meaning at a higher level that subsumes as many contexts as possible (Frith, 2003). Autism is characterized by a weak or absent urge for this central coherence (Frith & Happé, 1994). This tends to be translated as follows: "people with autism often do not see the wood for the trees. Sometimes they even do not see the trees, but they do see the grooves in the bark, the leaves and even the veins in the leaves" (Vermeulen, 2010). Therefore the theory is sometimes wrongfully reduced to the idea that autistic people are detailed thinkers and cannot oversee the whole (Vermeulen, 2010). In advancing this theory, however, Frith (2003) clearly distinguishes between local coherence at a low level and central coherence at a high level. Local coherence refers to seeing wholes. This occurs in an early stadium of information processing and can be done by autistic people equally well. Central coherence at a higher level addresses the need to fit information into a broader context and in this way assign meaning to the whole (Frith, 2003). This is precisely where the difficulty for autistic people lies: in distinguishing details that are important and deserve attention from other details. Most people do not consider a situation detail by detail. They first try to gain a general impression of the whole, the essence, and, based thereon, decide subsequently what details are worth their attention. Autistic people, by contrast, may perceive and store all details as a kind of compensation strategy (Frith & Happé, 1994) because they do not see the essence (cf. Grandin, 1995*a*). The theory thus points at the sharp eye for some details and the difficulty in distinguishing essentials from side-issues (Vermeulen, 2010). As a result, difficulties arise in recognizing faces and emotions, which require uniting aspects of intonation, body language, and expression, and in interpreting out of context (Sánchez et al., 2011).

In his hypothesis about *context blindness*, Vermeulen (2010) builds on the theory of weak central coherence, in particular on the aspect of context. Context does not refer to the whole as such but to the whole of contextually relevant elements, in both environment and memory, which may also include details. "Context blindness is a deficit in the ability to use this context spontaneously and unconsciously in assigning meaning." It concerns "not using" the context rather than "not seeing" it. Moreover, autistic people are able to consciously use the context when someone points out to them that multiple possibilities exist: "Context blindness is a deficit in the ability to use context spontaneously and unconsciously in assigning meaning, when information is vague, unclear or ambiguous" (Vermeulen (2010). When the meaning is not directly clear, when information is unclear, vague or incomplete, context thus plays a role.

Experiences with designing by individuals with ASC

So far, we identified a set of cognitive processes associated with designing and discussed cognitive behaviors observed in the autism spectrum. To further our understanding of which cognitive processes are essential to design, we now describe the experiences with designing by two individuals with ASC. Both were selected because of (a) their diagnosis on the autism spectrum, (b) their experiences with design, and (c) the available documentation of these experiences.

The first is Temple Grandin, a professor of animal science and successful "humane" livestock facility designer. Grandin wrote extensively about her life with autism, including her way of designing (Grandin, 1995*a*, 1995*b*, 2009). The second is Roland, who is schooled in chemical engineering, works as a self-employed consulting engineer, and is a certified inventor. Roland redesigned the interior of his house (Baumers & Heylighen, 2015). Grandin was diagnosed as a child and describes herself as a Kanner/Asperger type; Roland was diagnosed with Asperger's at age 50.

In what follows, we analyze their experiences with designing based on their own accounts. In the case of Grandin, our analysis relies on her written accounts of her way of designing, which we found in several publications she authored (Grandin, 1995*a*, 1995*b*, 2009). In the case of Roland, our analysis relies on an account of his way of designing by Baumers and Heylighen (2015), which is based on two weblogs in which Roland documented his design process, a guided tour through the house under renovation, and an in-depth interview with Roland in that house. These accounts are analyzed in light of the above-mentioned (a) cognitive behaviors within the autism spectrum and (b) cognitive processes associated with designing to draw a connection between both.

We then sent Grandin and Roland a draft of this paper, which included our analysis of their first-person accounts of their experiences with designing and as individuals with ASC. For both Grandin and Roland, we invited them to answer the following question: Would you agree with our analysis that the difficulty with central coherence associated with autism influences the flexibility of your design process? The second question asked them to comment on specific alternative strategies they took if they agreed with our analysis. For Grandin, we asked whether she mentally simulated different parts of livestock equipment in detail and, to Roland, we asked whether design patterns helped him to compensate for the lack of flexibility. Their responses to our analysis and questions are included in the Discussion section of this paper.

Analogical reasoning

When designing, Temple Grandin seems to rely heavily on analogical reasoning. To understand interactions with people when designing, she compares them with something she has read or experienced: "For instance, in my equipment-design business, an argument between myself and one of my clients is similar to

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something I have read about the United States and Europe fighting over trading right." (Grandin, 1995*b*) She describes the acquisition of case examples as adding to a "video" library over which she searches to find solutions to analogous problems. "Since my mind works similar to an Internet search engine, my ability to solve problems got better and better as I had more and more experiences and read more and more books and journal papers. This provided lots of images in my memory for the search engine in my mind to search." (Grandin, 2009, p. 1438)

To some extent, analogical reasoning can be found also in Roland's design approach. The source he relies on is Alexander et al.'s book "*A Pattern Language*" (Alexander et al., 1977), containing 253 "patterns" each of which describes a problem related to towns, buildings or construction and offers a "solution" (Baumers & Heylighen, 2015, p. 335). Among these patterns, he identifies appropriate experiences that could be related to the interior's redesign, such as "Sitting Circle", "Built-in-Seats" or "Intimacy Gradient". "And the clever thing is", according to Roland, "that Christopher Alexander managed to establish exactly these experiences and linked them to concrete solutions." Roland drew upon these solutions to redesign the interior of his house.

From their recollections it is impossible to determine whether Grandin and Roland engage in mostly case-driven analogizing, invoking concrete elements of prior design solutions as the basis for the present solution, or schema-driven analogizing, drawing on the principles of prior solutions (Ball et al., 2004). Yet, their direct references to specific cases (Grandin) and concrete prior solutions (Roland) would suggest a stronger reliance on case-driven analogizing, a pattern presently attributed to novice designers (Ball et al., 2004).

Problem-solving

Both Grandin and Roland take linear and apparently fixed approaches to design problem-solving. In drawing on her "video" library, Grandin describes her design approach as almost algorithmic. She is able to combine fixed, structural elements from previous design solutions to generate a new solution. When designing livestock equipment, she takes bits and pieces of other equipment she has seen in the past and combines them to create a new system: "My mind works like the computer programs that are used to make high-tech special effects in movies; I can take many different bits and pieces and combine them into new images. I use this method when I design equipment in my livestock equipment-design business. The more bits and pieces I have in my 'video library', the better I can design equipment. I have videos of many things, such as metal posts, sheet metal, bearings, cattle, motors, gates and so on. To create a new design I pull the bits out of memory and combine them into a new piece of equipment." (Grandin, 1995*a*, p. 142)

Similarly, Roland redesigned his house's interior by drawing from multiple design patterns (Baumers & Heylighen, 2015, p. 335). Yet, rather than integrating properties from different patterns into a new solution, he seems to rely on one pattern at a time, redesigning and completing the interior in a gradual way: he designs something, builds it (or commissions to build it), and then proceeds with the next part of the design; there is only a rough master plan. Their descriptions of rather rigid "bottom-up" design approaches contrast sharply with the recollections of expert designers, who have been reported to take a "systems approach" starting from "first principles" (Cross, 2003, 2004).

Mental imagery

Grandin's writings suggest that she can imagine herself being an animal: "I am successful in designing livestock systems because I can imagine myself as an animal, with an animal's body shape and senses. I am able to visualize myself as an animal going through one of my systems. This 'video' is complete with touch, sound, visual and olfactory sensations. I can play this 'video' from two perspectives. The perspective is either I am watching the animal, or I am inside the animal's head looking out through its eyes" (Grandin, 1995*a*, pp. 149–150). According to Grandin, many systems used in meat plants are designed poorly because the engineers never thought about what the equipment would feel like when it contacted the animal's body. She attributes the fact that she does to her ability to set her own emotions aside: "I can imagine realistically what the animal would feel because I do not allow my own emotions to cloud the picture" (Grandin, 1995*a*, pp. 149–150). Other factors that might help explain Grandin's complete "videos" of being an animal are her outspoken interest in the way subjects of her work see their world, evidenced by the fact that she gets in a chute herself, and her hypersensitivity to noise and other sensory stimuli, illustrated by her description of her roommate's hair dryer as "a jet plane taking off" (Grandin, 1995*b*). Her recollection suggests that she can create a mental image of herself inside a livestock system. Through this image, she develops empathy for the animals. Her ability to create this type of mental imagery is similar to humans' general ability to imagine themselves in a previous time and place. We can imagine and play a video of ourselves walking through our childhood home as an adult today. Grandin's recollections suggest a limited ability to imagine how something might work when she has not yet previously experienced this object. This limitation is compensated by a heightened ability to store and retrieve details of objects from prior experience and then to imagine her using or being in the object she is designing. The level of detail in Grandin's mental images may be higher than in most people's.

Mental simulation

In redesigning the interior of his house, a major challenge for Roland was to anticipate how the design would be experienced (Baumers & Heylighen, 2015, p. 335). Therefore, for each partial design, he made a mock-up (a simulation to the actual size) on site using material at his disposal. Once this mock-up was made, he considered it important "to take the time to sit down, and to feel whether the design induces the right emotion." If this turned out to be the case, Roland drew that part or piece of furniture, and built it (or commissioned to build it). The advantage of this method, which Roland learned from Alexander, is "that you can all the time optimally experience how the design feels" (Baumers & Heylighen, 2015, p. 335). Yet, despite building a mock-up and taking the time to experience it, Roland seemed to have difficulty imagining how it would be, as the quotes on his blog suggest: "I wonder whether it will work as I thought"; "I'm really curious what this will actually look like"; "I can't wait to see whether it will all end as I imagine it now"; "I don't think it's beautiful, but you only really know when it's finished". Striking is also that, each time a pattern had been applied, he attached a label with its number to the piece of furniture. By explicitly referring to Alexander's patterns, these labels sought to name the intended experiences associated with all people interacting with the interior so that he could recall their experience.

In exploring and evaluating her own design cognition, Grandin will "run simulations under many different conditions and rotate the machine in my head. I don't need computers with fancy graphics programs, because I have a sophisticated drawing and graphics computer in my head. In my imagination I can duplicate the most sophisticated, computerized virtual-reality systems" (Grandin, 1995*a*, pp. 149–150). Grandin's mind works slowly, however: drawing a detailed three-dimensional drawing takes several hours. Moreover, while her account would imply a complete ability for mental simulation, her mental simulation is limited to objects similar to those she has previously experienced. Grandin seems to have difficulties simulating the operation of an object she has not yet experienced. She says she needs to experience things to store them literally in her "video" library: "To obtain a good concept of cats or churches, *I need to experience many different ones to fill up my 'video' library*. There is no generalized cat concept. I can manipulate the car or church 'videos'. I can put snow on the roof and imagine what it would be like during different seasons" (Grandin, 1995*a*, p. 142) (emphasis added). Once Grandin has a "video" of how something works, she can then replay it in her mind. Yet, when she has not personally observed the object she is designing, she struggles to understand its possible operation.

Grandin relies on images of direct experiences and Roland relies on external prototypes as strategies for understanding how a product might work. They do not report mentally simulating the mechanical and functional properties of a product by altering their mental representations of it.

Discussion

The lived experiences with design practice recounted by individuals with autism have important implications for the interpretation of cognitive processes associated with designing. This paper started out with a putative definition of designing as conceiving an object, environment, or situation for an intended purpose. Based on this definition, high-functioning individuals with ASC clearly can design. By a conventional understanding of expertise, Grandin could even be described as an expert in the area of livestock systems; she has designed livestock equipment across the world, has received numerous industry awards, and is one of *Time* magazine's 100 most influential people. The profiles of expertise in design (Lawson & Dorst, 2009) would not neatly describe Grandin's and Roland's capabilities though. We, therefore, frame our discussion on what we can learn about the fundamental cognitive processes essential to designing through our understanding of individuals with ASC in relation to expertise in design rather than the duality of being able/unable to design. In using the term expertise from hereon in, we will mean expertise as described in the framework proposed by Lawson and Dorst (2009) and in a number of empirical studies of expert designers.

According to Lawson and Dorst (2009) competent designers should be able to select the elements of a design problem that are relevant and devise a plan to address them. Proficient designers perform this task almost immediately. With expert designers, this task may not even be evident since the reasoning is argued to be intuitive. Expert designers tend to mix top-down and bottom-up approaches (Ball & Ormerod, 1995; Ball et al., 1997). Grandin's design process would not appear to satisfy this criterion of design expertise. Her problem-solving strategy is purely bottom-up. "All my thinking is bottom-up instead of top-down. I find lots of little details and put them together to form concepts and theories. (…) When I solve the problem, it is not top-down and theory driven. Instead I look at how all the little pieces fit together to form a bigger picture" (Grandin, 2009, p. 1437). As Grandin stated in her response to our analysis, her design approach for her original designs included visiting "every feedlot in Arizona and many places in Texas. It was a bottom up approach. Some part of the facilities I visited worked well and others worked poorly, but they may have had one small part of the facility that was good. The next step was to combine all the good parts into new designs and not use the bad parts. … All my design thinking is in still pictures and videos. My thoughts are all photo realistic. Nothing is abstract." (Grandin, 2016)

Rather than presenting a design approach that is contingent upon the problem, Grandin describes an approach that appears relatively fixed. For Grandin, her frame is always the animal's natural behavior patterns (Grandin, 1995*b*) and not, for example, the ease of assembly or transport of the livestock equipment or the human operators. Being able to have engaged empathy (Henry, 2014) with the animal to be slaughtered was a novel frame relative to previous livestock equipment design, and her empathy may be considered more a point of view rather than a design frame. Her frame (or point of view) remains fixed throughout the design process, and there is no apparent evidence of reframing. The same can be said of Roland's adherence to Alexander's patterns and concrete solutions. In his response to us, Roland stated, "Personally, I think I use both the step-by-step pattern approach and the intuitive approach." By intuitive, he means that his "brain combines information that is already there during sleep to formulate the solution" such that he finds "a solution to a problem without any reasoning or step-by-step method", often in his sleep (Angenent, 2016).

The rigidity means neither Grandin nor Roland report any reframing of design problems, a key indicator of design expertise. Roland responded that reframing was not necessary for the furniture design he described because "there is usually a fixed part and a 'design space'. The fixed part being the house and other furniture you do not want to alter for fitting in the new furniture. I usually can find a solution within the design space. So, I do not need to 'work outside the box'. So, I have no need to reframe." He nonetheless thought that "Reframing is an interesting concept; I will try to use it in forthcoming design processes." (Angenent, 2016)

However, none of the differences in information processing behaviors associated with ASC necessarily limit their ability to design, as the narratives of Grandin and Roland portray. Instead, both Grandin and Roland have found compensatory strategies. In this regard, the weak central coherence theory of autism (Frith & Happé, 1994) provides a useful prediction about the sorts of cognitive processes essential to *expertise* in design rather than design *per se*. This theory describes individuals with ASC as having a processing bias: using fixed procedures as the basis for solving design problems, rather than abstracted principles, may hamper the development of design expertise, as defined by the abovementioned profiles. A well-accepted axiom of design practice is that designers construct meaning from representations by engaging in a reflective conversation with the design situation (Schön & Wiggins, 1992). The lack of a tendency to find higher order meaning in experiences sharply contrasts with Schön's description of designing as a reflective practice and the importance of framing therein: “In order to formulate a design problem to be solved, the designer must *frame* a problematic design situation: set its boundaries, select particular things and relations for attention, and impose on the situation a *coherence* that guides subsequent moves” (Schön, 1988, p. 182) (emphasis added). The ability to frame and reframe successfully is attributed though to productive design practices (Paton & Dorst, 2011) found in experts (Kleinsmann et al., 2012) and is not an essential element of design cognition if by designing we mean the definition stated at the start of this paper.

Second, analogical reasoning in expert designers is characterized by an ability to refer to principles underlying prior design solutions rather than their structural elements (Ball et al., 2004). Both Grandin and Roland describe that they do not generally attempt to find thematic relations in their experiences. For example, for Grandin, there is no general concept of a cat, only experiences of various kinds of cats. Therefore, it is unlikely that they would engage in schema-driven analogizing. Roland (Angenent, 2016) did not agree with our assertion that designing with patterns is a form of analogical reasoning, though. To him, the use of design patterns was more akin to the application of “prior knowledge to solve a problem, and I think this is what I do when using a pattern. Instead of seeing this as case-driven analogizing, I see it as a scientific method to create a design, what i.m.h.o. should be done by ‘expert designers’ instead of designing from ‘first principle’ (scratch).” While their technique of case-driven analogizing is likened to novice designers, their narratives suggest that an inability for schema-based analogizing does not diminish their potential to create award-winning designs. Providing designers with a large and detailed database of designs can compensate for this information processing bias.

Lastly, Grandin and Roland report an inability to imagine how a design that they have never experienced before would work. Neither of them reports any challenges in creating mental images of their designs though; Grandin reports having highly detailed mental images. Roland responded in agreement that he and Grandin have exceptional abilities with respect to storing visual memories of prior designs and then creating new designs by assembling various parts of previous designs that they had either directly observed visually or read about. Roland commented, “The idea of a database of construction parts as Temple describes is something I think I have too, just not in video-form” (Angenent, 2016).

Mental models that contain relationships between objects support mental simulation. Identifying the relevant relationships in a particular situation requires that individuals be able to reason about the principles underlying the objects; the weak central coherence theory predicts that this reasoning is impaired in individuals with ASC. Second, the actual mental simulation is intended to reduce uncertainty where gaps in information and knowledge exist. So far as we can tell from Grandin’s accounts, her memory is vivid, like a video. If scenes from the video are missing in her memory, it is not clear whether she could perform the mental simulation to fill the gaps. Rather, her approach combines existing images into a new one: “I’m always forming new visual images when I invent new equipment or think of something novel and amusing. I can take images that I have seen, rearrange them, and create new pictures” (Grandin, 1995*b*). Mental simulation in design is generally attributed to fillings gaps in knowledge about a design where exact realization through other means (e.g., sketching, prototypes, computational simulations) is impractical or impossible (Christensen & Schunn, 2009). However, the compensatory strategies adopted by Grandin (having more videos of existing designs) and Roland (making prototypes) suggest that mental simulation is not essential to design cognition. Indeed, Roland reports that in his furniture design, the mental simulation was not necessary because “furniture does not have many moving parts that do something difficult you would like to simulate” (Angenent, 2016). In his e-mail response to our paper, Roland claimed that he could perform mental simulations, but his descriptions of mental simulations were really of mental representations, such as of a hovercraft floating or various configurations of furniture (Angenent, 2016). It might only be essential in situations of breakthrough designs where prior case examples do not exist and the construction of any prototype is impractical during ideation.

In summary, in connecting the narratives of individuals with ASC to the set of cognitive processes associated with designing, we find that their information processing biases with regard to some of these cognitive processes can be explained by the weak central coherence theory of autism. Judging from the individual accounts, the structured design processes described by Grandin and Roland can lead to success, but their over-structured approaches are not likely to be successful under situations requiring them to start from first principles. The key to expertise in design seems to reside in the flexibility of approach (Cross, 2006). The design cognition scholarship has not to date attributed the inability to work from first principles to possible cognitive and neural differences.

The central coherence theory adds to our understanding of design cognition by pointing toward the mental capability to find higher-order underlying structure and principles as essential to expertise in design. Finding high-order underlying structure is likely to be a cognitive skill that some individuals will not develop through practice due to differences in neural processing. As Roland related to us, “If your conclusion is that design expertise needs the ability to mentally move back and forth between higher-order underlying structure and principles and concrete designed object, I think this is correct. … My (autistic?) way of getting to the higher order is that I use someone else’s principles and take them for granted. I do not invent my own principles. My higher order ‘principles’ are Alexanders Patterns” (Angenent, 2016). The mental capability to find higher-order underlying structure may have neural requirements, but the principles themselves could be taught. Roland believes they can be taught or at least communicated: “It would be interesting to research the higher order principles of Expert Designers and get a list of what these principles really are.” It may also be relevant in generating “new to the world” novelty by finding a novel coherence between the facts of the design situation as a new frame for the design problem. While Roland does not believe that he has any “difficulty in seeing higher order”, he agreed that “When there is no prior knowledge, the designer will have to construct the higher order himself. If there is prior knowledge, this knowledge should be structured in terms of higher order in a way the designer can use this in his design process.” Given the existence of Alexander’s patterns, Roland believes that their use is superior in terms of a design methodology than starting from first principles of furniture design. If we accept the premise that novel framing of problematic situations is foundational to design thinking (Paton & Dorst, 2011), then we could conclude that central coherence is an essential cognitive ability *for design expertise* and not just an information process bias as theorized by Frith (2003).

What central coherence is exactly in designing deserves further conceptualization. We conclude with some possible conjectures. First, we believe that central coherence goes beyond the concept of design concept or parti (Heylighen & Martin, 2005). Rather, we conjecture that central coherence entails the discovery or creation of a pattern that connects multiple levels of abstraction about the designed object. Individuals perceive visuo-spatial features of the designed work and classify them arbitrarily, possibly into generic categories such as function, structure, and behavior, but with arbitrary labels depending upon the design situation. In this way, central coherence is similar to deep learning models in artificial intelligence. In deep learning, the machine learning system automatically discovers representations in raw data and passes those representations into a higher level of abstraction, which, in turn, learns a new abstract representation, and so on (LeCun et al., 2015). If this learning is performed recursively, a complex function can be learned from the raw data. Similarly, to achieve central coherence, individuals build abstractions at multiple levels simultaneously and find a pattern or rule to characterize the set of abstractions in particular ways. This mental process is influenced by the designer's stylistic predilections (Tonkinwise, 2011).

A major weakness in the weak central coherence theory is the lack of understanding of the cognitive and neural mechanisms that underlie weak coherence (Happé & Frith, 2006). At present, it is not possible to state whether central coherence is a cognitive process, a property of a number of cognitive processes, or a consequence of neural architecture. Nonetheless, our analyses indicate that finding central coherence is likely to be a foundational cognitive ability associated with expertise in design.

Conclusion

In an attempt to contribute to our understanding of the fundamental cognitive processes essential to design, we explored in this paper the experiences of people who have different information processing behaviors than most people. Our study focused on people with ASC because their information processing behaviors are known to be both maladaptive and exceptional.

The profiles of expertise in design (Lawson & Dorst, 2009) and studies comparing the differences between expert and novice designers do not neatly categorize Grandin's and Roland's capabilities though. Grandin is clearly an expert (Lawson & Dorst, 2009) given her achievements, but her design process is not necessarily situation- or strategy-based, precursors to being an expert. Roland is competent, but his reliance on explicit cases as prior examples suggests a novice design approach. These profiles of individuals with ASC who demonstrate appreciable design capabilities suggest that the framework for expertise in design and the methodology of studying expertise may require updating. Specifically, the framework may need to consider the level of outcome in addition to ways of operating in design practice.

What can we learn from individuals with ASC about cognitive processes essential to designing? Analyzing narratives on their experiences with design practice in light of the scholarship on design cognition and cognitive behaviors associated with ASC suggests that the weak central coherence theory of autism provides a useful prediction of the cognitive processes necessary for *expertise* in design. While this implies that the jury is still out as to which cognitive processes are essential to designing, it does contribute to our understanding of design cognition. As such our study confirms the value of including in design research the experiences of designers who are different from the "typical" designer, as suggested by earlier studies (Heylighen & Nijs, 2014). In addition, studying individuals with ASC adds to the critical review and development of design theories, some of which assume neurotypical cognitive processes. For example, inferential design theory (Arciszewski & Michalski, 1994) theorizes a set of knowledge transmutations that convert an initial design specification into a desired design. At least three of the transmutations – abstraction, agglomeration, and reformulation – will be challenging for some individuals with ASC due to real limitations in finding central coherence as the basis for abstraction, agglomeration, and reformulation. According to our preliminary analysis, it is likely that these three knowledge transmutations are useful but not essential to design cognition. Other design theories such as C-K theory (Hatchuel & Weil, 2009) do not specify any cognitive processes. Observing the overlap in cognitive processes by individuals with and without ASC as they alternate their reasoning between the concept space and the knowledge space can narrow down the cognitive processes associated with the C-K theory of design.

Our study analyzed the experiences of two designers only. Further research should include the design experiences of more designers with ASC. Moreover, our study analyzed their experiences with a design based on the designers' accounts only. Relying on self-reporting risks a diverted presentation of design processes (Lawson, 1994), and provides little insight into how these processes are situated in and distributed across a sociomaterial environment. Further research should include a more diverse set of data collection methods that allow to include multiple sources of evidence, for example, design documents used and produced by autistic designers, and accounts of colleague designers or other actors who work(ed) with them. Finally, not all cognitive processes associated with designing have been researched by design journals. Some cognitive processes, such as decision-making, may have been researched as an activity instead. A broadening of the scope of the review could identify other candidate cognitive processes but should maintain focus on those processes relevant to the conceptual part of design cognition (Dong et al., 2017).

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