ABC 2017, 4(1):52-71
Animal Behavior and Cognition https://doi.org/10.12966/abc.05.02.2017

Cognitive Enrichment and Welfare: Current Approaches and Future Directions

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Citation – Clark, F. E. (2017). Cognitive enrichment and welfare: Current approaches and future directions. *Animal Behavior and Cognition, 4*(1), 52–71. https://doi.org/10.12966/abc.05.02.2017

Abstract – "Cognitive enrichment" is a subset of enrichment that has gained interest from researchers over the past decade, particularly those working in zoos. This review explores the forms of cognitive enrichment that have been attempted for laboratory, farmed and zoo animals with a focus on the latter, including various definitions, aims, and approaches. This review reveals the fundamental theoretical and practical problems associated with cognitive enrichment, leading to recommendations for further research in this field. Critically, more research is needed to elucidate what makes challenges appropriate for certain taxa, acknowledging that individual differences exist. Going forward, we should be prepared to incorporate more computer technology into cognitive tasks, and examine novel welfare indicators such as flow, competence, and agency.

Keywords – Agency, Animal welfare, Cognitive challenge, Competence, Flow, Zoo

The term "environmental enrichment" (shortened to enrichment) is now a routine part of modern captive animal management. As stated by Kim-McCormack, Smith, and Behie (2016), its definition is context-dependent but broadly consists of alterations or additions to the physical and/or social environment of captive animals. One of the most widely cited definitions of enrichment comes from the zoo setting: "an animal husbandry principle that seeks to enhance the quality of captive animal care by identifying and providing the environmental stimuli necessary for optimal psychological and physiological well-being" (Shepherdson, 1998, p. 1). Crucially, this definition recognizes that enrichment should enhance welfare, a concept that is still surprisingly overlooked by many enrichment studies (Young, 2013).

"Cognitive enrichment" is a subset of enrichment that has gained interest from researchers over the past decade (Clark, 2011, 2013; Clark, Davies, Madigan, Warner, & Kuczaj, 2013; Meyer, Puppe, & Langbein, 2011; Yamanashi, Matsunaga, Shimada, Kado, & Tanaka, 2016). Unlike other forms of enrichment that fall into intuitive (yet often overlapping) categories such as "food-based," "structural," and "sensory" cognitive enrichment is difficult to categorize. Consequently, there is currently no widely accepted definition of, or approach to, cognitive enrichment. The definition from Clark (2011) is perhaps the most comprehensive to date: cognitive enrichment "(1) engages evolved cognitive skills by providing opportunities to solve problems and control some aspect of the environment, and (2) is correlated to one or more validated measures of wellbeing" (p. 6). Critically, this definition includes a welfare component. However, it does not acknowledge any form of reward for the animal, which could either be intrinsic (internal, such as a sense of satisfaction on solving an enrichment task), or extrinsic (external, such as food or water). With reference to zoo animals, Carlstead and Shepherdson (2000) suggest that cognitive *challenge* (rather than enrichment) should "…put captive animals in a position where they can learn to actively control and explore some aspects of their environment" (p. 344). Similarly, with reference to farmed animals, Zebunke, Puppe, and Langbein (2013) stated that "Through cognitive interaction with the environment, the animals regain a certain control over their environment" (p. 70). They went on to state that resources such as food and water act as rewards for successful coping; there should be a tangible reward for behavioral responses.

Cognitive enrichment appears to be the least-used form of enrichment across captive settings. A meta-analysis of captive animal enrichment by de Azevedo, Cipreste, and Young a decade ago (2007) found that 4% of reviewed laboratory enrichment studies were "cognitive" (defined as the use of puzzles), 3% of zoo enrichment studies were cognitive, and no examples of cognitive enrichment were found from the farm literature. Since this publication, the number of studies on cognitive challenge and cognitive enrichment has grown considerably, particularly in the farm setting (Clark, 2011, 2013; Meehan & Mench, 2007; Meyer et al., 2011) but an up-to-date meta-analysis is lacking.

Captive Animals Want and Need Cognitive Challenges

Animals in the wild, and to a lesser extent in captivity, face challenges related to finding food, mates, and shelter, and evading predators (Shettleworth, 2010). These challenges require a toolkit of cognitive skills such as exploration, problem-solving, various forms of learning and spatial awareness (Shettleworth, 2010). The skills animals possess will depend on the type of challenges they currently face, have previously experienced, and their evolutionary history (Meehan & Mench, 2007).

Animals are highly motivated to explore and acquire resources under a variety of conditions, even when resources are concurrently available with little or no cognitive or physical effort (Wemelsfelder & Birke, 1997; Wood-Gush & Vestergaard, 1991). In other words, evidence suggests that animals *want* to be challenged; as Spinka and Wemelsfelder (2011) state, "Challenges are there to be overcome" (p. 27). Captive rhesus macaques (*Macaca mulatta*) explored mechanical "puzzles" (boxes with latched doors) for up to ten hours and eventually learned to solve (open) them without any food reward (Harlow, 1950). More recently, Watson, Shively, and Voytko (1999) reported that female long-tailed macaques (*Macaca fascicularis*) sometimes declined the food they extracted from a transparent plastic finger maze in favor of accessing a more complex maze. Furthermore, laboratory primates and rodents will perform repetitive tasks such as bar-pressing, for the opportunity to explore novel stimuli or environments (e.g., Moon & Lodahl, 1956). Researchers have disputed whether the "drive" to explore novel or challenging situations is attractive or aversive (or indeed both). On the one hand, boredom may cause aversion to familiar environmental stimuli (Fowler, 1965; Myers & Miller, 1954), but, on the other hand, curiosity may cause attraction to novel stimuli (Berlyne, 1960).

The phenomenon of contrafreeloading, when animals invest effort to explore and acquire a resource such as food when it can be acquired with little or no effort, is well-documented (reviewed by Inglis, Forkman, & Lazarus, 1997). In a classic example, Neuringer (1969) demonstrated that pigeons repeatedly pecked at a disc to receive food when identical food was freely available. Despite many reports of contrafreeloading in animals, its functional significance remains ambiguous. The process of exploring and acquiring a resource seems to be more important than the resource *per se*. A plausible explanation is that contrafreeloading is adaptive in unpredictable environments; an animal might be motivated to monitor unpredictable resources that could become optimal in future (Inglis et al., 1997). In support of this theory, Watters (2009) noted that many zoo animals have a higher motivation to explore when the reward for doing so is uncertain rather than guaranteed.

There is also evidence to suggest that animals *need* to explore in order to have good welfare (Jensen & Toates, 1993; Morgan & Tromborg, 2007). "Behavioral needs" can be broadly defined as "behaviors that appear to be largely internally motivated, since they may occur even in the absence of appropriate trigger stimuli" (Morgan & Tromborg, 2007, p. 264). These include rooting in pigs (Horrell & Ness, 1995; Studnitz, Jensen, & Pedersen, 2007) and nest-building in hens (Duncan & Kite, 1989; Hughes, Duncan, & Brown, 1989). Jensen and Toates (1993) proposed that animals need not only perform the behavior, but also obtain a goal from performing that behavior. Furthermore, if an animal is prevented from performing a behavioral need in captivity, its welfare can be compromised (Poole, 1992). Hughes (1997) suggested that "sensory change" is a behavioral need in animals, that can be satisfied by intrinsic exploration (gathering general information about the surroundings) and, to a lesser extent, extrinsic exploration (directed towards a distinct goal such as finding food when hungry).

Cognitive Enrichment Attempts in Captive Settings

In contrast to their wild counterparts, captive animals tend to live in highly predictable and structured environments where they are challenged infrequently or inappropriately (Morgan & Tromborg, 2007; Wemelsfelder & Birke, 1997). The past decade has witnessed important research on the link between cognitive challenge and well-being (Meehan & Mench, 2007; Meyer et al., 2011). The type of cognitive challenge provided to laboratory, farm and zoo animals has varied greatly from broad environmental to narrow task-based challenge.

Laboratory animals. There have been two main approaches to cognitive enrichment in laboratory animals. First, cognitive enrichment refers to additions to the environment (such as larger cages, cage mates, toys, tunnels and running wheels) that enhance cognitive performance; in other words, their presence has been linked to improved performance on tasks aimed to test cognitive skills (Milgram, Siwak-Tapp, Araujo, & Head, 2006). The overarching aim of this form of cognitive enrichment is to understand the causes of age-related cognitive decline (i.e., dementia), and to try and slow this rate of decline. Exposure to this type of cognitive enrichment has been associated with enhanced or maintained performance on cognitive tasks and changes to brain activity (reviewed by Kramer, Bherer, Colcombe, Dong, & Greenough, 2004; Milgram et al., 2006). For example, mice exposed to increased environmental complexity perform better on maze navigation tasks and have increased cellular activity in the brain (Codita et al., 2012). Access to toys and cage-mates maintains the level of cognitive task performance in dogs (beagles) as they age (Milgram et al., 2005), and more formally-educated humans (i.e., those spending more years at school and university) show increased performance in cognitive tasks, and reduced incidence of degenerative brain disease (Dufouil, Alperovitch, & Tzourio, 2003). Despite the benefits of this "broad" form of cognitive enrichment, Milgram et al. (2006) lobby the criticism that it is practically impossible to determine which characteristic(s) of the environment affect cognition.

The second approach to cognitive enrichment in laboratory animals is to provide animals with specific, cognitively challenging tasks and measure their performance on the same or different cognitive tasks at a later date. In humans, regular participation in "brain-training" computer-game-tasks (CGTs) increases cognitive performance (Schmiedek, Lövdén, & Lindenberger, 2010). However, in the largest human brain-training study of its kind on over 11,400 participants, Owen et al. (2010) showed that, whereas a subject's performance on a trained CGT improved over a six-week period, their performance did not transfer to similar untrained CGTs. In animals, Matzel et al. (2011) found that general cognitive decline in aging mice was reduced by life-long working memory exercises (navigation of 3D mazes). Most cognitive tasks provided to rats and dogs have been spatial (i.e., mazes and obstacle courses); therefore, it is difficult to determine whether cognitive performance in these cases is enhanced by "using the body" or "using the brain", or indeed both. Physical exercise is linked to improved cognitive function in humans and laboratory animals (Colcombe & Kramer, 2003; Radák et al., 2001; Radak, Kumagai, Nakamoto, & Goto, 2007). However, Klintsova, Dickson, Yoshida, and Greenough (2004) suggested that learning about a spatio-physical task (rather than physically undertaking it) promotes the formation of new brain synapses.

Farm animals. In farms, cognitive enrichment has been used to describe the provision of specific, short-term problem-solving tasks under moderately controlled experimental conditions (reviewed by Meyer et al., 2011). Ernst and colleagues (Ernst, Puppe, Schön, & Manteuffel, 2005; Puppe, Ernst, Schön, & Manteuffel, 2007) designed a task for young domesticated pigs (*Sus*, 7 to 20 weeks old) in the form of a mechanized feeding device. Subjects were required to correctly discriminate acoustic cues, then to perform an operant task to receive a food reward. Ernst et al. (2005) found that the pigs were willing to participate in cognitive challenge, spread at random times across the day, in order to obtain small food rewards. As stated by Puppe et al. (2007) "the presented cognitive enrichment may induce repeated positive appraisals in pigs by the association of successful coping with a demanding behavioural task rewarded by several small portions of food during the day" (p. 5). Similarly, Langbein, Siebert, and Nürnberg (2009) investigated the effects of an automated feeding device task on socially-housed dwarf goats (*Capra hircus*). In order to be rewarded with a drink of water, goats had to successfully discriminate between shape cues on a computer screen.

Cognitive enrichment studies on farmed animals have mainly investigated whether pigs and goats will invest cognitive effort to receive an extrinsic reward such as food or water (Ernst et al., 2005; Langbein et al., 2009; Puppe et al., 2007). For example, when water was concurrently available at a normal watering pipe and the device (i.e., as an extrinsic reward for the cognitive task), goats directed one third of their responses to the task (Langbein et al., 2009), providing some evidence that goats will "work" for a reward even when a "free" reward is concurrently available.

Participating in cognitive tasks has also been found to have wider effects on behavioral and emotional expression. Pigs that received sustained exposure (10 weeks) to cognitive tasks displayed a reduction in abnormal behavior, and increased exploration of a novel, open space (i.e., an "open-field test"; Puppe et al., 2007). A recent study by Oesterwind, Nürnberg, Puppe, and Langbein (2016) found that a combination of "structural enrichment" (the authors did not define or describe this condition) and cognitive enrichment (a computerized discrimination task with drinking water as a reward) improved how dwarf goats dealt with challenges in their wider environment; in an open field test the enriched goats were more curious and explorative of a novel object. In pigs, participation in cognitive tasks, similar to those described above, were associated with more relaxed feeding and positive emotions, as well as more exploratory behavior in an open-field test (Zebunke et al., 2013).

In a yoked control experiment, cows (Holstein–Friesian heifers) that independently learned to open a gate leading to food showed greater behavioral indicators of excitement and had a higher heart rate (presumably in anticipation of the reward) than cows given access to the food without learning to open the gate themselves (Hagen & Broom, 2004). Five of the six experimental heifers learned to open the gate; therefore, it was not possible to compare the behavior of cows that were successful and unsuccessful at the task. The level of excitement experienced by the cows can be likened to the "Eureka effect" in humans, where discovering the answer to a problem is linked with positive feelings (Perkins, 2000). This effect has also recently been demonstrated in beagle dogs in a university laboratory setting (McGowan, Rehn, Norling, & Keeling, 2014). In this study, subjects had to perform operant tasks via various devices (for example pressing a key on a children's piano) in order to gain access to a reward (food, human contact, or dog contact). Dogs that learned to control their access to rewards showed behavioral signs of excitement (e.g., increased tail wagging and locomotor activity) when they were successful, whereas control group dogs showed signs of frustration (e.g., mouthing the operant device). The most positive responses were seen towards the food reward. Finally, similar to long-term laboratory studies on cognitive enrichment, pigs that interact with cognitive tasks have more changes to the opioid receptors in the amygdala region of the brain, which has a role in processing positive affects by stimulus-reward learning, compared to control subjects (Kalbe & Puppe, 2010).

Zoo animals. Until recently, little attention has been given to tasks that aim to enhance the well-being of zoo animals by specifically challenging cognitive skill. The term "puzzle-feeder" is commonplace in zoo enrichment literature, particularly for primates, but is used as a moniker for a certain style of food-concealing object rather than a scientifically validated cognitive task. Puzzle-feeders typically hide food within objects such as boxes, pipes, or balls; food can be accessed by poking, shaking or rotating these objects before falling out of openings under the force of gravity (e.g., Bloomstrand, Riddle, Alford, & Maple, 1986). Puzzle-feeders make food harder to access than it would be during routine feeding; therefore, puzzle feeders occupy time that might otherwise be spent eating food from a plate or bowl, performing aberrant or abnormal behaviors, or being inactive (Brent & Eichberg, 1991).

However, it is well-documented that primates can lose interest in puzzle-feeders within several hours of exposure (Bloomstrand et al., 1986; Csatádi, Leus, & Pereboom, 2008).

In zoos, the closest approximation to the types of cognitive enrichment described above in farm animals was a phase of animal management popular in zoos across North America and Europe in the 1970s and 1980s known as "behavioral engineering" (Markowitz, 1982). Markowitz and colleagues trained zoo animals to manipulate devices that released food as an extrinsic reward. A classic example, of which there are many variations, was a feeding device for monkeys including white-handed gibbons (*Hylobates lar*) and Diana monkeys (*Cercopithecus diana*, Markowitz, 1982). Monkeys were trained to pull a lever at one end of their exhibit, move rapidly to the other end several meters away, pull a second lever and receive a food reward if this action was performed within a certain period of time. Sometimes this type of task incorporated the exchange of tokens for food. Another classic example of behavioral engineering devices allowed zoo animals and visitors to "play" against each other; for example, a mandrill (*Mandrillus sphinx*) competed against visitors to press a lighted button (Markowitz, 1982). Whoever touched the light first would "win," and if the mandrill won it received a food reward.

Similar to farm animal challenge devices with incorporated food/water rewards, behavioral engineering allowed animals to "work" for food when it would otherwise be freely available at normal feeding times. The effects of mechanical device interactions on zoo animal welfare are mostly descriptive (Markowitz, 1978, 1982), suggesting that tasks are highly engaging but can also result in highly patterned learned behavior. For example, mechanical device-use by gibbons was associated with an increase in general activity levels and decrease in social aggression (Markowitz, 1978). However, a male Diana monkey showed a highly "stereotyped" response to an apparatus, moving toward the device using exactly the same locomotory pattern each time (which was unnecessary for solving the task). Furthermore, Markowitz and Line (1989) found that a rhesus macaque pressed a control switch around 130,000 times in one week to obtain a food reward, when it could have been expressing more naturalistic behaviors. The highly mechanized Markowitzian approach to enrichment was heavily criticized for being "artificial" (Forthman Quick, 1984), and was superseded by a more naturalistic approach to zoo "environmental enrichment" (Shepherdson, 1998).

Zoo-based enrichment commonly satisfies the behavioral need of animals to search for food; for example, by hiding food inside puzzle-feeders and using scent-trails (Young, 2013). However, it has been rare to stimulate sustained foraging problems requiring high levels of cognitive skill (reviewed by Clark 2011, 2013). Furthermore, problem-solving tasks without the incorporation of an extrinsic food reward are exceptional in a zoo setting. To address this, Clark and colleagues (Clark & Smith, 2013; Clark et al., 2013) designed cognitive challenges for socially-housed chimpanzees (*Pan troglodytes*) and bottlenose dolphins (*Tursiops truncatus*) that were intended to provide abstract problems (3D vertical mazes solved using the hands or rostrum respectively) and could be tested with and without extrinsic rewards. They were inspired by laboratory cognitive tests (e.g., great ape trap tubes: Martin-Ordas, Call, & Colmenares, 2008; dolphin underwater modality apparatus: e.g., Herman, 2010), rather than by examples of previous enrichment for these taxa. Clark and Smith (2013) "point toward an area of research which has thus far been overlooked in zoos—in the middle-ground between highly complex and controlled laboratory tasks, and relatively simple food/object enrichment" (p. 808). Clark and Smith (2013) found that chimpanzees exhibited more problem-solving behaviors and spent significantly more time engaged in social play when the maze was present; the maze was also used significantly more when it contained wooden tokens (which could not be physically accessed) compared with food items (nuts, which could be physically accessed). On the basis of these results, Clark and Smith (2013) felt there was some evidence for cognitive enrichment, but a small sample size (six individuals) made it difficult to draw strong conclusions. Clark et al. (2013) found that a group of six male dolphins spent significantly more time underwater when the underwater maze was present; it challenged cognitive skill through the stimulation of new problem-solving strategies and also stimulated social play. The maze was also used significantly more when it contained a rubber ball that could not be removed, in comparison to a gelatin ball that could be removed (and played with). On the basis of these results, Clark et al. (2013) concluded that the maze task was a form of cognitive enrichment, but once again, a small sample size raises caution and warrants further research.

Cognitive research as enrichment. Most examples of cognitive enrichment described thus far (with the exception of broad environmental enhancements, *sensu* laboratory settings, Kramer et al., 2004; Milgram et al., 2006) have intended to enhance welfare via a specific cognitively challenging task. Researchers in zoos and some laboratories have recently begun to question whether experiments primarily designed to test cognitive skill may also have the secondary benefit of enhancing welfare (MacDonald & Ritvo, 2016). Testing cognitive skill using discrimination tasks via a computer touchscreen (the term "computer-game-task", CGT for short, will be used for consistency) is gaining popularity in zoos (Bennett, Perkins, Tenpas, Reinebach, & Pierre, 2016; Leighty & Fragaszy, 2003; Ross, 2010). By incorporating CGTs into modern exhibit design, comparative research on gorillas (*Gorilla gorilla gorilla*), chimpanzees and Japanese macaques (*Macaca fuscata*) is currently being undertaken within the same zoo facility, integrating cognition, welfare and public engagement with science (Egelkamp, Hopper, Cronin, Jacobson, & Ross, 2016).

Washburn and Rumbaugh (1992) found that lab-housed rhesus macaques voluntarily used CGTs (with a joystick) for over nine hours a day, even when a variety of other manipulable objects were available; over-grooming, aggression and stereotypical behavior were replaced by CGT-use in the activity budgets of subjects. Furthermore, these CGTs were more effective at reducing behavioral indicators of distress than plastic "toys" or cage-mates. In contrast, Whitehouse, Micheletta, Powell, Bordier, and Waller (2013) found that participation in CGTs had no significant effect on self-directed behavior (SDB) in socially-housed Sulawesi macaques (*Macaca nigra*) in a custom-built research center within a zoo. In the laboratory, participation in CGTs was linked to a reduction in salivary cortisol (i.e., a measure of stress) and reduction in SDB in socially-housed guinea baboons, *Papio papio* (Fagot, Gullstrand, Kemp, Defilles, & Mekaouche, 2014). These discrepant results call for more research on the welfare effects of monkeys using CGTs.

In contrast to monkeys, the link between CGT-use and well-being in great apes appears to be less straightforward. SDB is commonly used as an indicator of compromised well-being in primates because it is linked to anxiety-inducing situations such as social crowding and tension (Aureli & de Waal, 1997; Maestripieri, Schino, Aureli, & Troisi, 1992). Furthermore, a reduction in SDB has been observed in primates following the administration of anxiolytic (anxiety-reducing) medications (Schino, Troisi, Perretta, & Monaco, 1991). In great apes, SDB has recently been linked to participation in relatively more complex tasks, making errors in tasks (Yamanashi & Matsuzawa, 2010), and/or when the outcome of a touchscreen cognitive task is uncertain (Elder & Menzel, 2001; Itakura, 1993; Leavens, Aureli, Hopkins, & Hyatt, 2001). A recent study by Wagner, Hopper, and Ross (2016) found that zoo-housed Western lowland gorillas and chimpanzees performed more SDB when they made an error on a task, regardless of the perceived level of task difficulty.

Despite the link between CGT-use and anxiety, CGTs originally developed to test primate cognition in a formal laboratory setting (e.g., Rumbaugh, Richardson, Washburn, Savage-Rumbaugh, & Hopkins, 1989) have also been reported as "enriching" for zoo chimpanzees (Bloomsmith, Baker, Lambeth, Ross, & Schapiro, 2000; Ross, Bloomsmith, Baker, & Hopkins, 2000) and orangutans (*Pongo pygmaeus*, Tarou, Kuhar, Adcock, Bloomsmith, & Maple, 2004). Positive effects include high engagement with tasks and increased activity level after task exposure. Yamanashi and Hayashi (2011) reported that laboratory-housed chimpanzees participating in cognitive research (using CGTs) had comparable levels of foraging/feeding and resting to wild chimpanzees, and also spent significantly longer foraging/feeding than non-experimental chimpanzees at the same facility. Herrelko, Vick, and Buchanan-Smith (2012) found that, during the introduction of a new cognitive testing program (using CGTs) to zoo chimpanzees, SDBs increased when visual access to keepers was restricted, but not when the task changed in nature (i.e., level of difficulty).

Cognitive research (and thus cognitive tasks as enrichment) are relatively lacking for non-primate taxa. However, Clark (2013) reviewed the field of marine mammal (primarily bottlenose dolphin and

California sea lion, *Zalophus californianus*) cognition and proposed that knowledge of various species' cognitive skills could and should be used to develop appropriate cognitive enrichment. Cognitive research on other species could be applied in a similar fashion; for example we have a growing knowledge of the cognitive skills of elephants, *Elephas maximus*, *Loxodonta africana* (Foerder, Galloway, Barthel, Moore, & Reiss, 2011; Perdue, Talbot, Stone, & Beran, 2012; Plotnik, Lair, Suphachoksahakun, & de Waal, 2001), giant pandas, *Ailuropoda melanoleuca* (Dungl, Schratter, & Huber, 2008; Perdue, Snyder, Pratte, Marr, & Maple, 2009) and black bears, *Ursus americanus* (Johnson-Ulrich et al., 2016; Vonk & Beran, 2012; Vonk, Jett, & Mosteller, 2012). There has also been substantial work on the cognition (mainly physical cognition) of corvid birds (Clayton & Emery, 2005; Taylor, 2014). Benson-Amram, Dantzer, Stricker, Swanson and Holekamp (2016) reported that in mammalian carnivores, brain size (volume) is a strong predictor of problem-solving ability. The authors presented 140 individuals of 39 different zoo-housed species with a novel problem-solving task (a mesh puzzle box containing food), finding that species with larger brains were more successful at opening the box. This research could be used in future to prioritize puzzle-based cognitive enrichment to species that may be more likely to express novel problem-solving skills.

Theoretical and Practical Issues with Cognitive Enrichment

So far I have shown that attempts at cognitive enrichment are varied, with notable differences between laboratories, farms, and zoos. This should be expected, given the different species housed, different environments, and unique research goals of each setting. However, a number of theoretical and practical issues emerge from this corpus, regardless of the study system. These are: (i) providing appropriate challenges to animals; (ii) measuring the cognitive component of enrichment (i.e., assessing if it can be accurately defined as "cognitive" enrichment as opposed to another type of enrichment); (iii) group (social) effects, (iv) assessing welfare outcomes of challenge, and (v) perceptions of cognitive enrichment by visitors, animal caretakers and facility management. I shall focus on these issues now.

Appropriate challenges for captive animals. Korte, Olivier, and Koolhaas (2007) argue that animals are adapted to respond to challenge and they therefore require it in order to function normally. Korte et al. (2007) call this the "allostasis concept"; this is an alternative to the concept of homeostasis where systems should always be held in balance. In order to make challenge "appropriate," Korte and colleagues ague that if animals face chronic challenge (hyperstimulation) it causes detrimental "wear and tear" of normal biological functioning. Conversely, if animals do not face challenges frequently enough (hypostimulation) they may lose their biological strategies to respond to such challenges (a "use it or lose it" scenario). The key, therefore, is to challenge animals at a frequency that allows them to function normally.

A different approach to cognitive challenge focuses less on biological functioning and frequency of challenge, and more on level of challenge specific welfare outcomes. Based on a model by Myers and Diener (1995), Meehan and Mench (2007) propose that achieving an appropriate level of challenge requires matching the level of challenge offered to the animal to the level of cognitive skill they possess. There are four possible welfare outcomes: (i) when an animal has a high level of skill that can be applied to master a high level of challenge, a positive emotional state of satisfaction and pleasure known as "flow" can arise; (ii) when an animal does not possess high enough cognitive skill to cope with a challenge, anxiety can arise (Duncan & Wood-Gush, 1972); (iii) a combination of low skill and low challenge may result in apathy: a negative emotional state often attributed to captive animals living in environments that suppress opportunities for exploration (Myers & Diener, 1995; Wood-Gush & Vestergaard, 1989). Finally, (iv) boredom may arise when an animal possesses more cognitive skill than it can exercise on the environment because tasks are not challenging enough or challenges are nonexistent (Wemelsfelder & Birke, 1997).

It is clear that the only suitable outcome of the model above (Meehan & Mench, 2007; Myers & Diener, 1995) is the promotion of flow and/or the prevention of anxiety, apathy, and boredom. Currently, this four outcome model has not been explicitly applied to the development of appropriate challenges for captive animals. There are two main reasons why cognitive challenges are more often provided on a trial-and-error basis by researchers. First, cognitively speaking, it can be difficult to know what a chosen study species is "capable of." The field of animal cognition has heavily focused on primates (particularly great apes), as well as other "higher" charismatic mammals such as cetaceans, and birds belonging to the corvid family. The development of appropriate cognitive enrichment for well-studied taxa will be easier than for taxa whose cognitive skills have not been studied in depth. In relation to this, the reward type must also be species-appropriate. The majority of captive animal enrichment uses food rewards, but in the context of cognitive enrichment, we know that some animals are motivated to seek challenge without the need for extrinsic rewards (Clark & Smith, 2013; Clark et al., 2013; Langbein et al., 2009). For example, Clark and Smith (2013) found that chimpanzees used a pipe maze significantly more when it contained only visibly accessible tokens compared with physically accessible Brazil nuts.

The second reason why the level of challenge provided by cognitive enrichment has been fairly *ad hoc* so far is due to variation within and between animals. Different levels of cognitive skill (and thus different motivations to perform a cognitive task) will exist within a study population. For example, in a study of socially housed Guinea baboons (*Papio papio*), Fagot and Bonté (2010) found that only 75% of subjects were able to learn to use a CGT in a laboratory setting. In a study of zoo bottlenose dolphin cognitive enrichment, Clark et al. (2013) found that two out of six subjects in a group of male dolphins were "high users" and used the cognitive device (an underwater pipe maze) significantly more than their groupmates. The authors ruled out exclusion by more dominant individuals; the most dominant (and eldest) male used the device the least and showed very little motivation towards it. A group of five female dolphins tested at the same facility did not use the device at all, even after the introduction of positive reinforcement training. Similarly, Clark and Smith (2013) found that there a disparity in device use within a mixed group of six zoo chimpanzees; two males were "high users" whereas the eldest female contacted the device (a pipe maze) a negligible amount, even though three copies of the device were made available to prevent task monopolization. In great apes, motivation to participate in cognitive tasks has been linked to various personality "traits" such as boldness (Herrelko et al., 2012).

The cognitive component of enrichment. Here, I revisit our fundamental difficulty in trying to define cognitive enrichment. When can enrichment accurately be defined as "cognitive"? Buchanan-Smith, Vick, Morton, and Herrelko (2016) stated that cognitive enrichment needs to be evaluated stringently to confirm that we are actually engaging evolved cognitive skills rather than just occupying them at a low level and/or for a short period of time. Other types of enrichment such as food-based and structural enrichment are easy to define because the additions to the animal's environment are clear to us as humans. We can be fairly confident that food enrichment will stimulate foraging and feeding behaviors. Similarly, structural enrichment will stimulate locomotory behavior. The question for staff evaluating enrichment is whether these behavioral responses are significant compared with baseline. In contrast, cognitive enrichment is unique because we are adding a (hopefully) cognitively challenging task to the environment and aim to measure something we cannot physically see: cognitive stimulation. We must use the best evidence available from laboratory tests and naturalistic observations that animals will possess the skills needed to perform the task, and will be challenged by doing so. We cannot see the process of cognition being challenged and must therefore use behavioral proxies (Shettleworth, 2010).

There is currently no agreed upon "level" of cognitive stimulation (the output) that makes cognitive enrichment effective. Some elegantly designed studies in laboratories and farms have investigated transferable cognitive skill: the animal is exposed to cognitive task A, and the effect of this exposure on performance on task B is measured (e.g., Milgram et al., 2006) but there is no threshold level of performance researchers are aiming to stimulate. The effect of exposure to task A on behavior in an open-field has also been compared to the behavior of control groups with no task exposure in laboratories and farms (Puppe et al., 2007; Zebunke et al., 2013).

In zoos, the trend has been to quantify how subjects interact with cognitive tasks (e.g., types of problem-solving strategy, and changes in use over time). Unfortunately, this does not provide a sophisticated approach to enrichment evaluation. Consider this analogy: you can casually hold and manipulate a Rubik's Cube® or similar handheld puzzle, without ever needing to "solve" it or engage in the cognitive challenge it provides. Neither is high task use always the best welfare outcome; as discussed previously, Markowitz and Line (1989 found that a macaque obsessively pressed a task control switch many thousands of times in one week to obtain a food reward, rather than express more naturalistic behavior. Furthermore, animals may engage with cognitive challenge tasks for very short periods of time but still seemingly benefit from this interaction (Buchanan-Smith et al., 2016). Research is now needed to determine whether more complex or creative interaction with cognitive tasks is linked to a better welfare outcome. There is also value in studying frequency of use, perseverance, and the welfare effects of succeeding versus merely "taking part" in a task. We know that the "Eureka effect," when animals independently learn to solve problems without any demonstration or training (see below), is linked to positive emotions (Hagen & Broom, 2004; McGowan et al., 2014; Perkins, 2000), but we have little knowledge of the benefits of becoming more cognitively engaged over a longer period of time.

There are two ways in which positive reinforcement training has been used for cognitive enrichment purposes. First, I have cited examples of training animals to use cognitive tasks, when it is unlikely that animals would learn how to perform these tasks (or indeed interact with the apparatus) spontaneously. However, it has been questioned whether the process of training can dampen the level of cognitive challenge, and instead whether challenges should be developed that require spontaneous and creative problem-solving (Clark, 2011). Second, training is used as a form of cognitive enrichment itself. For example, rescue shelter cats with behavioral indicators of frustration were trained to perform a discrete task (touch paw to trainer's hand); trained cats displayed more behavioral indicators of contentment and were less prone to infection than untrained cats (Gourkow & Phillips, 2016). In that study, training was labeled as a form of "cognitive enrichment". Participating in training could be seen as a form of cognitive enrichment for animals because they must use their cognitive skills to respond to cues. However, this likely becomes much less effective when the animal is recalling already learnt behaviors. It is also difficult to tease apart the relative benefits of participating in training and interacting with a human trainer (if present).

Effects on group members. Another major, yet often overlooked practical consideration for cognitive enrichment is the effects of an animal's social environment. Traditionally, laboratory cognitive tests are performed on individuals isolated periodically from their social groups, but there are also examples of social testing (e.g., Fagot & Bonté, 2010; Fagot & Paleressompoulle, 2009; Washburn et al., 1994). Going forward, it is important to understand the effects of providing enrichment to isolated and group-housed animals to maximize its effect.

Providing cognitive challenges to isolated animals has several advantages: only one set of expensive equipment and associated staff is required, and it is possible to make detailed observations on individual subjects without distraction or disturbance from other animals. Research suggests that the isolation of primates is often a stress-provoking experience (reviewed by Fagot & Paleressompoulle, 2009). However, more recently Whitehouse et al. (2013) found that pro-social behaviors increased in Sulawesi macaques housed at a zoo-based cognition center on cognitive testing days compared to non-testing days. The authors deduced that experimental isolations for short periods can increase group welfare by mimicking natural fission-fusion behavior. Similarly, at another zoo-based cognition center, Ruby and Buchanan-Smith (2015) found that isolated cognitive testing had little effect on the stress-related behavior of brown capuchins (*Sapajus apella*). Both affiliative and aggressive social behavior increased following individual testing, suggesting that group-housed capuchins invested time and energy in the re-establishment of their social bonds following artificial group fission. A final consideration is that some primates have a perception of social inequality (there is a dearth of study for other taxa). For example, chimpanzees and capuchins have an understanding of how they are treated in comparison to others, and although tolerance to inequality has been shown, they can also respond with frustration when "unfair" treatment occurs (Brosnan & Bshary, 2010; Brosnan, Schiff & de Waal, 2005; Dubreuil, Gentile,

& Visalberghi, 2006). If the isolated group member is perceived to be receiving "special" treatment including food rewards as a part of the testing process, this could lead to group conflict.

The opposite approach to cognitive enrichment is to provide a task or tasks to the social group as a whole. Practically speaking, isolation requires extra time for capture and transport of animals to a separate testing area, and so the number of subjects that can receive challenge per day may be limited. However, group testing also has practical limitations. In large groups it can be difficult to assess which individual/s are using the task and to monitor their progress. Despite these limitations, a series of studies by Fagot and colleagues on guinea baboons (Fagot & Bonté, 2010; Fagot & Paleressompoulle, 2009; Fagot et al., 2014) demonstrate that group-testing is achievable and can have significant positive welfare outcomes. A troop of approximately 26 individuals were allowed free access to a CGT (with a food pellet reward) 24 hrs per day, and individual access to the booth was controlled by baboons wearing microchip implants. Interaction with the CGT was associated with increased activity levels, significantly lower salivary cortisol (a measure of stress), and more pro-social behavior. However, hundreds to thousands of trials were performed by the troop on a daily basis along with extremely high reported levels of engagement, raising the question of whether baboons became "obsessed" with the task at the expense of other activity.

Allowing cognitive challenge to take place in a social setting can also facilitate richer response outcomes; for example, group-tested rhesus macaques developed sophisticated social response strategies such as "playing dumb" (Drea & Wallen, 1999). However, Clark and Smith (2013) found an intriguing link between cognitive task presence and rough-scratching (an indicator of anxiety *sensu* Baker & Aureli, 1997; Maestripieri et al., 1992) in socially tested zoo chimpanzees. Subjects scratched themselves more when the task was present but not while using it, suggesting that they found observing task-use by groupmates stressful. In this Special Section, Daoudi, Badihi, and Buchanan-Smith (2017) ask whether principally, social housing itself can be a form of cognitive enrichment. The authors found that when naturally sympatric tufted capuchins (*Sapajus apella*) and squirrel monkeys (*Saimiri sciureus*) were housed together in the same zoo exhibit, they chose to separate themselves spatially but may still provide each other with naturalistic cognitive challenges.

Welfare assessment. Animal welfare assessment is an incredibly complex undertaking; baseline assessment requires specialist knowledge of welfare indicators in that species, let alone repeated assessments in response to environmental manipulations such as enrichment. An enduring problem for all enrichment attempts, cognitive and otherwise, is a dearth of validated welfare indicators for many species. In other words, few behavioral, physiological or other health signals have been experimentally linked to good and poor welfare (Keeling, Rushen, & Duncan, 2011). Welfare indicators for captive primates have been well-studied compared to other taxa, originally stemming from laboratory research (e.g., Wolfe-Coote, 2005) and filtering through to zoos. In all captive animals, there has been a focus on negative behavioral indicators such as SDB and other abnormal behavior (Yeates & Main, 2008). However, as animal management standards improve, it is important to acknowledge that captive populations often have far lower levels of stereotypical and abnormal behaviors than populations several decades ago, and we should respond to this change by measuring more positive indicators (Mellor, 2015).

According to the four outcome model (Meehan & Mench, 2007), the most cogent strategy to assess cognitive enrichment going forward is to focus on the measurement of four key welfare indicators: anxiety, boredom, apathy, and flow. Poor or reduced welfare has routinely been measured in primates using SDB as a proxy for anxiety (Aureli & de Waal, 1997; Baker & Aureli, 1997; Maestripieri et al., 1992), but non-handed taxa such as ungulates are unable to perform high levels of SDB and therefore other indicators of poor welfare need to be validated for these species. Boredom is notably difficult to measure in nonhuman animals because it is linked to both high levels of activity (Wemelsfelder, 1993) and inactivity (Dawkins, 1990). It thus risks confusion with apathy, which also currently lacks study. This type of fundamental animal welfare research ideally needs to be undertaken before enrichment attempts are made; otherwise it is difficult to draw valid conclusions from the behavioral changes observed in response to enrichment.

The most understudied welfare indicator in animals is flow. To date, flow has been reported only in humans (Csikszentmihalyi, 1988) but could have real applications to nonhuman animals if we continue to embrace the concept of positive affective states in animals (Yeates & Main, 2008). Csikszentmihalyi (1990) stated: "The best moments in our lives are not the passive, receptive, relaxing times… The best moments usually occur if a person's body or mind is stretched to its limits in a voluntary effort to accomplish something difficult and worthwhile" (p. 3). Because flow is facilitated by being absorbed in a task, Clark (2011) suggested it could be inferred in cognitive enrichment studies by measuring how easily an animal is "distracted" from a cognitive task.

An understudied method of welfare assessment for captive animals, but one that could have particular relevance to cognitive enrichment, is cognitive bias testing. Animal emotional state, or "affect" cannot be measured directly, but an experimentally measurable bias in the judgment of ambiguous stimuli has been associated with emotional state in both humans and animals (Hallion & Ruscio, 2011; reviewed by Mendl, Burman, Parker, & Paul, 2009). Typically, an animal is trained to associate one stimulus cue with a positive outcome, and another with a negative outcome. An ambiguous (intermediate) stimulus cue is then introduced, and the animal's response to this cue is recorded as "optimistic" or "pessimistic" depending on whether they respond in the previously trained positive or negative manner. In addition to humans, cognitive bias has been measured in many laboratory species using this paradigm, including rats, dogs, rhesus macaques, and starlings (*Sturnus vulgaris*) (reviewed by Mendl et al., 2009). In recent work undertaken on rhesus macaques, Perdue (2017, this issue) highlighted methodological issues with cognitive bias testing that may need ironing out before future application.

The application of cognitive bias testing to animals outside the laboratory and farm settings has been performed for only a handful of species, but evidence suggests that it is certainly feasible for animals that can be trained to discriminate stimuli (Bethell, 2015). For example, Clegg, Rödel, and Delfour (2017) recently demonstrated that zoo-housed bottlenose dolphins that perform more social affiliative behavior judge spatially ambiguous cues more optimistically. Bateson and Nettle (2015) measured mood differences in three chimpanzees living in a sanctuary using a simple version of the judgment bias paradigm described above, where subjects were trained to touch different colored paper cones concealing nut rewards. More research is needed to determine how cognitive bias testing can be used as a welfare indicator, particularly in a zoo setting. McGuire, Vonk, Fuller, and Allard (2017, this issue) attempted to measure changes in the welfare of zoo-housed gorillas using cognitive bias testing, in response to changing availability of browse material (e.g., branches from which to forage from). The authors found that overall, the gorillas failed to learn the ambiguous cue paradigm that they used successfully and that individuals had preferences for different stimuli, leading them to question the suitability of the ambiguous cue paradigm for gorillas or these test subjects at least. However, these researchers have successfully used other methods for assessing cognitive bias in both gorillas and an American black bear in the same zoological setting (Vonk, pers. comm.)

Perceptions of cognitive enrichment. As indicated earlier, the last published meta-analysis on types of enrichment across captive animal settings was performed in 2007 (de Azevedo et al., 2007); therefore, a decade later, it is not entirely clear how much cognitive enrichment is currently being performed. When an updated meta-analysis is performed, key differences in terminology (for example "challenge" *versus* "enrichment") across captive settings should be taken into account to identify all relevant literature.

It is my belief that within zoos, most cognitive enrichment attempts are scientifically un-documented. In other words, cognitive challenges are actively used as a management tool but do not attract as much empirical research as other enrichment types and therefore lack publication, peer review, critique, and evolution. The current trend of evaluating cognitive research in a zoo setting is the exception. As cognitive research centers within zoos increase in popularity, staff face increasing pressure to assess the welfare outcomes of cognitive testing. So far the results have been broadly positive (e.g., Hopper, Shender, & Ross, 2016; Ruby & Buchanan-Smith, 2015; Whitehouse et al., 2013) but may represent early positive publication bias.

The reason for a lack of research on cognitive enrichment may stem from some negative or neutral perceptions by zoo staff. Visitor perceptions of cognitive enrichment are broadly positive (Perdue, Clay, Gaalema, Maple, & Stoinski, 2012b) but zoo directors, curators and care staff ultimately control the types of enrichment implemented. A perception study of zoo staff is lacking but, from my own experience of working in zoos in the UK and USA for the past 16 years, the *current* approach to cognitive enrichment (in future cognitive enrichment could become more naturalistic) does not suit the ethos of many zoos that prefer large-scale naturalistic and inexpensive environmental enrichment. In order to make valid conclusions about the effect of a cognitive task, cognitive enrichment requires a moderate to high degree of experimental control. This is not always possible in zoos that are not strongly research-driven. In future, cognitive enrichment is very likely to incorporate computer technology and therefore staff perceptions of, and skills with, technology are key considerations. Following a high initial cost, Bennett et al. (2016) proposed that the ongoing running cost of technology-based cognitive enrichment will be low and even suggested it will be comparable to traditional puzzle-feeders, but this remains to be demonstrated.

Future Directions

To consolidate this review, I will outline two future directions of cognitive enrichment in a zoo setting: (1) computerized tasks and (2) exploration and problem-solving as welfare outcomes of cognitive challenge.

Computerized tasks. The problems caused by the “cognitive” aspect of cognitive enrichment were outlined above: it cannot be guaranteed that a cognitively challenging task (as perceived by humans) will stimulate cognitive skill, and use of a task may be passive (verging on boring) rather than cognitively stimulating. In simple terms, it cannot be taken for granted that a task will be perceived or used by an animal, as intended by the human designer. The incorporation of computer technology into cognitive enrichment may help ameliorate some of these issues, as explained below.

Laboratory CGTs are traditionally designed to test a specific cognitive skill or set of skills, and are standardized so that performance can be compared within and between subjects under controlled conditions. However, some computerized laboratory tests have also been designed to be highly responsive to individual users, allowing researchers to meet the maximum capabilities of their subjects, but without pushing them into detrimental responses such as learned helplessness or perseverative behavior (Kim-McCormack et al., 2016). Pushing animals to their cognitive threshold may eventually allow us to stimulate a state of “flow.” If we can build upon the laboratory approach to customizable cognitive challenges by adding a “welfare safety barrier,” in other words measuring welfare simultaneously during challenge to ensure the level of that challenge does not become too high (causing frustration or stress) or too low (causing apathy or boredom), we will be closer to stimulating flow in nonhuman animals than ever before.

Developing customized tasks will be an exciting and significant step forward for cognitive enrichment, but also a significant undertaking for researchers, giving credence to what Meehan and Mench (2007) dubbed “the challenge of challenge” (p. 1). An important future research question is whether cognitive challenge should begin at the highest, intermediate, or a random level. It is important to ensure that animals do not to start with a version of a task so easy that they gradually learn the solution rather than being challenged, or feel excluded by the task because it is too difficult. Perhaps researchers could follow the model of many human computer games beginning with several “training” levels, so that animals can learn the rules of the task, ensuring that it maintains interest and balances the feelings of satisfaction and challenge.

Habituation is an enduring problem in enrichment (Young, 2013), and computers can help to provide more frequently changing stimuli than more traditional enrichment items (Tarou et al., 2004). To this end, it is worth examining whether animals are more engaged by cognitive challenges over the long term if they are given choice over which tasks to work on, accommodating weekly, or daily or even hourly changes in motivation levels. As I stated in the Introduction, "control" over something in the environment is a common feature in various authors" definitions of cognitive challenge/cognitive enrichment (Carlstead & Shepherdson, 2000; Clark, 2011; Zebunke et al., 2013). Zoo-based research suggests that increased control over access to different enclosure areas is beneficial for polar bears (*Ursus maritimus*; Ross, 2006) and giant pandas (Owen, Swaisgood, Czekala, & Lindburg, 2005). Sambrook and Buchanan-Smith suggest that for captive animal enrichment, controllability appears more important than complexity although they focus on the characteristics of novel objects. Furthermore, Perdue, Evans, Washburn, Rumbaugh, and Beran (2014) demonstrated that capuchin monkeys and rhesus macaques "choose to choose," in the sense that they will choose the order in which they complete various psychomotor and cognitive tasks on a computerized system.

As a final point in my manifesto for computer technology in zoos, it has been shown that a variety of non-primate species can be trained to use computerized screens. For example, animals trained to use a touchscreen using their nose (American black bear, *Ursus americanus*: Vonk et al., 2012; dog, *Canis lupus familiaris*: Range, Aust, Steurer, & Huber, 2008) and tongue (sun bear, *Helarctos malayanus*: Perdue, 2016). Dolphins can make selections from a computerized "menu" by directing their echolocative clicks towards projected symbols rather than making physical contact with the screen (Amundin et al., 2008). Even very small, nocturnal primate species can be trained to use touchscreens: Joly, Ammersdörfer, Schmitke, and Zimmermann (2014) reported that it took less than 25 days to train naïve grey mouse lemurs (*Microcebus murinus*) to use touchscreens in a nocturnal set-up.

Finally, computer technology can also be used to log subjects' responses to enrichment and, therefore, assist enrichment evaluation. To date, most cognitive tasks in zoos have been installed vertically against a wall, and it has been difficult for researchers to observe or film task use "over the animal's shoulder" (e.g., Clark & Smith, 2013; Clark et al., 2013). Recording the type, frequency, and duration of contacts to a device can be incredibly time-consuming when manually coded from video footage; there is also a potential issue of observer scoring bias. If data could be recorded automatically (for example in primates: Paxton Brown, Basile, & Hampton, 2013) it would increase accuracy, reduce observer bias, and reduce processing time; therefore, modifications to an individual's level of challenge (i.e., making the task more or less difficult) could be performed faster and enrichment could become more responsive. In their review of technological applications to animal welfare, Whitham and Miller (2016) noted that automated assessments are particularly useful for shy or elusive species, or times when human observers are not present (e.g., overnight).

Competence and agency. In order to offset the highly artificial concept of computerized tasks, and to prevent animals from sitting in front of computer screens for significant parts of the day, my second approach to future cognitive enrichment encourages the stimulation of broad environmental exploration and problem-solving. It has recently been shown that physical activity can be incorporated into cognitive challenge. Hopper et al. (2016) found that increased physical activity (locomotion across the exhibit) in zoo chimpanzees could be achieved as a by-product of a cognitive token exchange study, by positioning the token stations around the exhibit. Sakuraba, Tomonaga, and Hayashi (2016) found that moving food rewards away from the touchscreen encouraged a physically disabled chimpanzee to increase locomotion.

Ŝpinka and Wemelsfelder (2011) recently proposed a new framework to assess the relationship between cognitive challenge and animal welfare, which may be particularly useful for increasing activity levels and for animals that do not perform a great deal of abnormal behavior. They proposed that "competence" and "agency" are two types of behavior that are integral to engaging with novel challenges. Competence refers to the range of cognitive skills an animal uses to deal with current, novel challenges. This includes inspective exploration (responding to novel situations: Berlyne, 1960; White, 1959) and problem-solving. Agency refers to an animal's ability to gather knowledge and enhance skills for future use (White, 1959). This includes inquisitive exploration (seeking out new challenges: Berlyne, 1960) and play behavior, which allows animals to "train for the unexpected" (Ŝpinka, Newberry, & Bekoff, 2001).

Ŝpinka and Wemelsfelder (2011) suggested that competence and agency have three overarching benefits for animal welfare. First, exploration, problem-solving and play are intrinsically rewarding behaviors; for example, they will be performed without an external reward such as food (Harlow, 1950; Wood-Gush & Vestergaard, 1991; Yeates & Main, 2008). Second, as competence and agency increase, behaviors associated with positive excitement can increase (Hagen & Broom, 2004; Langbein et al., 2004). Third, increased competence has also been linked to increased physical health in the long term (Ernst et al., 2005). Morimura (2006) suggested that cognitive enrichment for chimpanzees should focus on ensuring that chimpanzees can exert their high cognitive skills onto their surroundings: "Assuring the exertion of cognitive competence is comparable to satisfying the individual's desire to do something on its own way [*sic*] in various contexts of daily life" (p. 387).

Technology can be incorporated into broader environmental challenges. For example, Krebs and Watters (2017, this issue) provided a male eastern black rhinoceros (*Diceros bicornis michaeli*) with a mechanical feeding ball, based on the design of a commercial feeding toy for dogs. This allowed a feeding challenge over the entire exhibit (anywhere the ball can roll) and, thus, introduced an interesting and seldom-studied temporal component to cognitive challenge. In order to stimulate competence and agency, cognitive challenges could be provided over the wider environment and be more "naturalistic" in the sense of providing for an animal's motivations to explore widely. Most zoo staff aim to encourage wide exploration by offering scattered food and scent trails; the progression now is to provide more cognitively stimulating problems over a wider area, in additional to quantifying exploratory patterns to assess if they can become more complex. Perhaps tasks requiring navigation between several stations, rather like a "treasure hunt" could be designed. This is an entirely new approach to cognitive enrichment, which could draw heavily on the study of spatial cognition (Poucet, 1993), and tying into the laboratory research already performed on the effect of physical exercise on brain function.

Conclusions

This review serves to highlight that there are many approaches to captive animal cognitive enrichment, and we are yet to reach a consensus on a definition. Cognitive enrichment appears to be the least studied form of enrichment, which may be due to the difficulties of study or underlying negative or neutral perceptions by animal staff. In the attempts so far, there has been a bias towards charismatic species whose cognitive skills have been most studied in a laboratory setting; these include primates (particularly great apes), dolphins, and corvids. In defense of this bias, cognitive enrichment should be approached with caution rather than haphazardly, to ensure that the level of cognitive challenge is appropriate, and we are best equipped to do this for well-studied species.

I have discussed how technological advances can help us to design cognitive challenges that are practical, flexible and responsive to individual motivations, as well as robust against habituation. The enduring task for welfare researchers is to ensure that the behaviors they measure as a response to cognitive enrichment are valid indicators of positive and negative welfare. Flow, competence, and agency are novel concepts in animal welfare but appear to be promising in relation to cognitive enrichment. This field is emerging and full of potential, with exciting opportunities for multidisciplinary collaboration. For the time being, we should remain open-minded in terms of suitable approaches to cognitive enrichment, and always be critical of what we, as humans, believe is cognitively enriching for animals.

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