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Opportunities (and challenges) in dairy cattle cognition research: A key area needed to design future high welfare housing systems

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ABSTRACT

The ability of dairy cattle to adapt to husbandry systems and management routines is crucial for ensuring higher welfare and efficient production. However, this ability can be compromised by our limited knowledge of their cognitive abilities, which may result in suboptimal husbandry and management standards. In this narrative review, we highlight three topics of cattle cognition research that are currently understudied, and yet key to developing future high welfare dairy cattle housing systems: 1) transmission of information from cow to calf, 2) mechanisms to attenuate fear, and 3) cognitive processes involved in the human-cattle relationship. We review the currently available literature on all three topics and highlight promising research areas from an animal husbandry point of view. We conclude that future studies should focus on elucidating what, and how much, calves learn from their dam during prolonged cow-calf contact in dairy cattle systems. Such information could constitute an important part of the discussion of whether to keep cows and calves together for a longer time after calving in the dairy industry. Fear in the cattle group might be lowered by the use of calm companions and future studies could uncover if attenuation of fear might even be induced by conditioning positive experiences of cattle with unrelated stimuli such as odours. Lastly, the human-cattle relationship might benefit from utilising the already established training regimes from other species, for example positive reinforcement training or target training, which may have the potential to decrease risk of injury during handling for both the cow and the handler.

1. Introduction

Commercial dairy production systems require cattle to obtain information about their physical and social environment and to adapt when their environment changes (reviewed in Marino and Allen, 2017; Rørvang and Nawroth, 2021). Dairy cattle, in general, have been shown to quickly adapt to novel environments, such as when learning how to use an automated milking system (e.g., Jacobs and Siegford, 2012), or when accessing automatic feeders (e.g., Collis, 1980). Cattle's ability to learn about and adapt to their physical and social surroundings is thus crucial for the functionality of the production system, for animal welfare and the safety of the handlers involved. In spite of this, knowledge of the cognitive abilities of cattle is still very limited (George and Bolt, 2021; Marino and Allen, 2017; Nawroth et al., 2019). This lack of knowledge makes it likely that commercial housing systems and management routines are only partially adapted to the behavioural and cognitive repertoire of cattle. An example of this is the presence of oral stereotypies such as tongue rolling and bar biting (reviewed in Radkowska et al., 2020; Redbo, 1992), which are believed to be caused by insufficient opportunities to express natural behaviours (e.g., grazing, rumination, lying down ruminating, Redbo, 1992). Cattle are motivated to work for access to items or areas that many current husbandry systems are lacking e.g., access to an automatic brush (McConnachie et al., 2018), and pasture (von Keyserlingk et al., 2017; Charlton et al., 2013). Providing cattle with opportunities to utilise their cognitive abilities such as opening gates to obtain resources (also known as contra-freeloading, Jensen, 1963; Osborne, 1977) could improve their welfare in terms of providing a sense of control over their environment, or offer an outlet from boredom (Mandel et al., 2016; Wechsler and Lea, 2007). This collectively highlights the need for housing systems and management routines that are better suited for the behavioural and cognitive repertoire of cattle, and in order to provide such future systems it is

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important to understand the breadth of the cognitive capacities of cattle. Our current lack of knowledge raises challenges, but it may also be viewed as an opportunity for developing better and improved housing systems and management routines in the future.

Cattle have evolved a rich behavioural and cognitive repertoire, and have adapted to being under human care over the course of domestication. Social interactions with conspecifics and with humans are part of everyday life for dairy cattle in loose housing systems. Early experiences in a calf's life are often crucial for its further development (e.g., von Keyserlingk et al., 2009), and thus providing proper early life experiences is important for production (reviewed in Jensen, 2018). In intensive commercial dairy housing systems, cow and calf are often separated shortly after the birth of the calf (von Keyserlingk and Weary, 2007; Vasseur et al., 2010). In such systems, calves are often moved to individual pens, where they are raised during the milk-feeding period, which has previously been shown to be beneficial for weight gains (Maatje et al., 1993), to lower the incidence of disease (Tomkins, 1991), and to reduce cross-sucking (Van Putten, 1982). This management style is markedly different from what would happen in the wild (e.g., in groups of feral cattle) or in extensive management systems, where calves live in social groups forming attachments to both adult cows, and other calves (Kilgour and Dalton, 1984; Vitale et al., 1986). Depriving calves of access to peers can have a negative impact on their welfare and later productivity. For example, recent studies point to negative effects of individual housing on feed intake and weight gains (Bernal-Rigoli et al., 2012; Costa et al., 2015), but also behavioural problems (Jensen and Larsen, 2014). Individual housing has also been shown to cause cognitive deficits in milk fed calves (Gaillard et al., 2014; Meagher et al., 2015), indicating impaired behavioural flexibility which may influence the animal's ability to adjust to variable environments on the dairy farm. Raising calves with access to their dams (or peers) can have additional benefits, as older individuals often have more experience interacting with their environment (e.g., Costa et al., 2016a) - an experience that could be of benefit for younger and more naïve individuals.

Cows are subjected to a myriad of handling events throughout lactation, such as when they are moved to the maternity area before partition, during milking, and veterinary treatments, or when regrouped to a new pen or moved to pasture. Handling cattle can however be a dangerous job (Douphrate et al., 2012) and research indicates that many injuries to both humans and cattle in the dairy industry happen in relation to manual livestock handling (Pinzke and Lundqvist, 2007; Douphrate et al., 2006; Boyle et al., 1997; Pratt et al., 1992). Areas found to be especially associated with a high injury risk are situations where humans and cattle interact directly such as during moving (Erkal et al., 2008; Rasmussen et al., 2000) and hoof trimming (Boyle et al., 1997). In a Swedish study examining injuries to stock people and impeded ability to work in 2004, 5000 incidents were reported with 30% occurring on dairy farms (Douphrate et al., 2006). Lindahl (2014) further reported that dairy farms in Sweden suffered most injuries compared with the rest of the agricultural sector and that these injuries were often severe with long periods of leave or even fatal. From the US, Layde et al. (1996) reported that cattle were involved in the majority of animal-related injuries, and Douphrate et al. (2006) further reported that the risk of livestock handling injuries increased on larger operations (> 10 workers). With the current trend toward increasing farm size worldwide (Barkema et al., 2015), this incident rate can be expected to rise. The main underlying reason for the many accidents on farms is believed to be fear reactions from the animal (Boyle et al., 1997; Lindahl, 2014). While fear in cattle contributes negatively to both animal welfare and productivity (Hemsworth and Coleman, 1998) it also increases the risk of injury to handlers. Hence, there is a clear need for optimising human animal interactions to reduce both, human and animal injuries.

The focus of this narrative review is to approach the available knowledge on dairy cattle social cognition from an animal husbandry point of view on three distinct topics derived from the issues reported above: the transmission of information from cow to calf, potential general mechanisms to attenuate fear in cattle, and the human-cattle relationship during handling and management processes. Subsequently, we will also highlight the challenges and possibilities within each topic in commercial dairy cattle production. From this knowledge, we further aim to propose future key research questions, which hold potential to improve the functionality of the current housing/management systems, ultimately benefitting both animal welfare and human safety. The review focuses on dairy production systems, but the suggested focus areas might also be relevant to beef cattle systems.

2. Vertical transmission of information from cow to calf

In commercial dairy production it is common practice to remove the calf from the dam within the first few days after birth (reviewed in Flower and Weary, 2003). This practice is of increasing public concern (Busch et al., 2017) and as a result, several new housing systems with increased or prolonged cow-calf contact have been studied (e.g., Mutua and Haskell, 2022; Johnsen et al., 2021; Meagher et al., 2019; Wenker et al., 2022). Further research on the potential welfare benefits of cow-calf contact systems is needed (Weary and von Keyserlingk, 2017; Wenker, 2022) to ensure better alignment of dairy farming with public values but also to ensure feasibility of these systems for the cow, the calf, and the farmer. Although this area of research is relatively new, the number of studies is growing, with indications of welfare benefits despite the loss of sellable milk (Meagher et al., 2019).

Cattle, as group-living animals, rely on social information in their daily life. Work done on other species provides some evidence that the severing of the maternal bond at birth can be detrimental to behavioural development (rats: Lévy et al., 2003; Melo et al., 2006), and studies on dairy calves suggest that either prolonged contact with another calf (Gaillard et al., 2014) or the dam (Meagher et al., 2015) improves the flexibility of learning. To our knowledge, no work has investigated other potential benefits of prolonged maternal contact. There is thus a risk that dairy calves do not develop proper learning skills when they are isolated at an early age, and as a result, may lack key abilities to optimally adapt to changes in the commercial housing system later on.

We here suggest as an additional important topic the role that the dam plays in the transmission of information to her offspring. The studies available on social learning skills of cattle, in general, indicate that the cognitive mechanisms involved are mainly social facilitation and stimulus enhancement (Rørvang and Nawroth, 2021) – skills relevant for exploring new food resources (Howery et al., 1998; Pfister et al., 2002). Whether cattle can also rely on higher social learning mechanisms (i.e., goal emulation (Boesch and Tomasello, 1998) and imitation (Galef, 2013; Nicol, 1995)) is relatively unexplored. To our knowledge, only one study has attempted to investigate this research topic by confronting cows with a spatial detour task. Half of the cows had the route to the reward demonstrated by another cow (observers), whereas the other had no demonstration (controls). Observers were not more successful or faster to detour than controls, but successful observers tended to be faster than successful controls. Results therefore indicate that the learning mechanisms involved were more likely social transmission mechanisms, such as stimulus enhancement (Stenfelt et al., in press). Social transmission skills (which can be defined as the cognitive processes that involve a simple transfer of information and/or behaviour between individuals of the same or different species, Rørvang et al., 2018a) could be beneficial in a commercial setting when cows, for example, have to learn how to operate automatic feeding bins or other automatic fixtures in their environment. Although in many instances the mechanisms associated with the transfer of social information remain unclear (reviewed in Rørvang et al., 2020), there is some evidence that social facilitation and enhancement effects can lead to a faster adaptation to novel situations (e.g., Costa et al., 2014; De Paula Vieira et al., 2012; Stenfelt et al., 2022). Such examples may include learning how to use automatic cattle brushes or feeding bins – where watching another cow interacting with the fixture/apparatus will result in an increased motivation to engage with the item themselves, which can ultimately lead to faster acquisition of the task by the naïve cow via individual associative learning. From that perspective, the ability to acquire information from peers is beneficial for the dairy cow: social transmission results in increased grazing time (Phillips, 2004), and feed intake (Babu et al., 2003, 2004; Jensen et al., 2015). There is a plethora of evidence suggesting that dairy calves benefit greatly, including cognitively, when provided social contact early in life (see review by Costa et al., 2016b). Acquiring information from peers can shape behavioural flexibility (Gaillard et al., 2014; Meagher et al., 2015), but what remains unclear are whether there are additional benefits when maternal contact is also provided. We, therefore, encourage studies on the long-term effects of cow-calf and calf-calf contact in early life on calves' ability to adequately rely and act upon social information in the short and the long term, i.e., later in life.

Another important aspect of socially acquiring skills from the dam is learning where and how to feed or graze. As dairy production is relying on cows with an efficient feed intake and specific feeding behaviour, this particular behaviour plays a central role in the production context. We know that naïve heifers benefit from being grouped with an experienced cow in the first hours after being introduced to pasture (Costa et al., 2016a), and that calves develop preferences from their dam (or foster dam) for specific pasture locations later in life (Howery et al., 1998; Provenza et al., 1992). Social transmission skills are thus also important for the development of feeding behaviour of calves; a calf with no prior grazing experience may exploit social information from peers resulting in reduced latency to approach and touch grass and shorter learning time to graze. It is therefore also fair to argue that these mechanisms are important in developing feeding behaviour fitted to the indoor housing of dairy cows in commercial housing such as eating novel feed i.e., concentrates or straw. Hence, knowing more about how, and from whom, calves learn to feed and how this may be affected by prolonged cow-calf contact should be a future research focus.

For calves, it might also be important to acquire information about the human in the environment from the dam. Research on horses, for example shows that foals benefit from observing their mothers' reactions in potentially fear-eliciting situations, which enables them to learn when not to be scared (Christensen, 2015) and increases their acceptance of humans (Christensen et al., 2020). Calves are better able to adapt to novel circumstances when kept with companions during the milk feeding period (Bolt et al., 2017; Costa et al., 2016b; Gaillard et al., 2014; Meagher et al., 2015), and although some results are conflicting, studies indicate a reduction in stress or fear responses of the calf, when cow and calf are allowed longer contact after birth (reviewed in Meagher et al., 2019).

Studies comparing calves reared with and without their dams show that calves reared with their dams express more play behaviour and social interaction (Waiblinger et al., 2020), potentially indicating more developed social skills for later life. Higher social competence in calves reared with the dam has also been found in studies where calves were confronted with an unfamiliar cow (Buchli et al., 2017), and when heifers were integrated into the cow herd (Wagner et al., 2012). It may thus be advantageous to keep cow and calf together in order to lower fear and develop higher social competencies. Future studies could focus on such aspects, and investigate whether reduced fear reactions in the offspring may be sustained over time and across different fear-eliciting objects or situations.

3. Attenuating fear in cattle by use of conspecifics and conditioning cues

3.1. Social buffering

Dairy cattle breeds have been selected for various personality or temperamental traits to ensure a so-called workable milking temperament, described by high sociability with low intra-specific aggression and less reactivity in response to novelty and social separation (see e.g., Haskell et al., 2014). This selection is done with the aim of having tranquil and docile cows, but some situations (e.g., when exposed to novel or potentially threatening stimuli) might still make cows react fearfully. Fearful reactions in cattle are often abrupt and unpredictable, and thus can make the animals hazardous to handle (Grandin, 1996; Lindahl et al., 2016). One of the underlying reasons for cows reacting unpredictably may arise from the fact that is often not clear which stimuli or context might elicit fear in individual animals. Information on how to reduce fearful behaviour in cattle is generally lacking in cattle research, although studies of fear reactions are relatively abundant in other large mammalian species kept under human care, such as horses (Christensen et al., 2008, 2005; Rørvang et al., 2015). Fearful cows are not only a threat to human safety (Boyle et al., 1997; Lindahl et al., 2016) but fear is also detrimental to animal welfare (Broom, 2014; Mota-Rojas et al., 2020) and productivity (Hemsworth and Coleman, 1998; Mota-Rojas et al., 2020). On a larger scale, high degrees of fearfulness amongst cattle can impact the sustainability of dairy production through 1) reduced productivity and higher risk of culling, or 2) increased risk of sickness or injury which also results in a higher risk of involuntary culling, all of which reduces longevity (shorter life in the herd; reviewed in Mota-Rojas et al., 2020). Adding to this, fear reactions are often contagious in a group of animals (Griffin, 2004). Fear may thus affect animals who are not in direct contact with the fear-eliciting stimuli, and even at a distance, making individual fear reactions difficult to predict for the human handlers involved. Innovative ways to reduce fearful behaviour in cattle are thus needed in order to improve animal welfare and handler safety.

Social buffering, which refers to the notion that the presence of a peer reduces the negative effect of a stressful event (Rault, 2012), might be an appropriate mechanism to reduce stress during handling practices. Dairy calves have been shown to vocalise less and explore more when placed in a novel room with a companion than calves placed in a novel room alone (Duve and Jensen, 2011; Færevik et al., 2006). Heifers more readily approached a human and ate more when accompanied by a companion in a novel place (Veissier and le Neindre, 1992), and the presence of conspecifics appears to reduce the behavioural responses to isolation regardless of the identity (i.e., familiarity) of the companion (Boissy and Le Neindre, 1997; Veissier and le Neindre, 1992). Recent research suggests that fear can additionally be socially attenuated in groups of animals via trained, calm companions. In horses, reducing fear within a group of three naïve horses can be achieved by adding just one calm companion (demonstrator to observer ratio 1:3) (Rørvang and Christensen, 2018). Using calm companions in groups of cows might similarly have the potential to reduce fear reactions. When groups of naïve dairy cows ($n = 3$) were tested in a fear-eliciting situation (i.e., sudden opening of a colourful umbrella as used in the horse study (Rørvang and Christensen, 2018)) with either a trained, calm companion or an untrained (i.e., not calm) companion, the naïve cows who were accompanied with a calm companion reacted less fearfully, returned faster to their feed bucket after being frightened, and had significantly lower heart rate increase during the test (Stenfelt et al., 2022, Fig. 1). Future research should investigate whether different demonstrator-to-subject ratios can also alter the efficiency of fear reduction as proven efficacy using larger groups would allow for easier transferability to on-farm scenarios. Additional information on consistency over time and across different contexts is also needed, including applied situations such as training naïve heifers to enter the automatic milking unit.

3.2. Role of conditioned stimuli on stress responses

Another important mediator in the controlling of social fear is the sensory apparatus of cows. It has been argued that visual cues are the main modality mediating attenuation of fear (e.g., Guzmán et al., 2009), but it is very likely that other senses also play a role (Nielsen, 2018).

Fig. 1. Picture from a study by Stenfelt et al. (2022). One calm companion (trained cow) successfully lowered fear in naïve groups of dairy cows in a fear-eliciting situation. The fear-eliciting situation is illustrated in the picture as a sudden opening of a red and white umbrella, while the cows were feeding from their yellow feed buckets. The demonstrator to observer ratio were 1:3 in this test. Photo courtesy: Johanna Stenfelt.

Cattle have been found to react more fearfully when exposed to olfactory cues from stressed conspecifics (Terlouw et al., 1998), and can be trained to differentiate between conspecifics based on olfactory cues alone (Baldwin, 1977). It is thus possible that cattle rely on olfaction in more contexts than we currently know (Wyatt, 2003). Research on the sensory abilities of cattle is generally sparse, highlighting a need for more knowledge on how sensory information is processed and prioritised by cows and how different senses might be utilised in attenuating fear in cow groups (Nielsen, 2018). One potential line of enquiry is to determine if cattle are able to learn to associate an odour with a pleasant situation. If cattle are able to form a conditioned response, the use of odours could potentially be used to mitigate the stressors associated with certain known stressful events, such as loading onto a transporter. Another option could be to utilise calming odours such as lavender, which has been found to lower cortisol levels in horses being transported (Heitman et al., 2018), and reduce travel-induced sickness in pigs (Bradshaw et al., 1998). To our knowledge there has been no work on this topic in dairy cattle to date.

Another aspect of conditioning, which is important to consider in the aim of lowering fear in cattle, is the possibility that fear reactions can function as conditioning stimuli. Such mechanisms have been studied in rodents (reviewed in Curzon et al., 2009) and humans (Vervliet et al., 2013). This means that when a cow is exposed to a fearful companion, she may learn to associate the experienced fear with a specific situation, object or conspecific (Olsson and Phelps, 2007). These aspects are important in cattle handling as it means that cattle may react unpredictably to certain situations, objects or persons. A cow may for example react fearfully towards an automatic feeding bin although she has no own experience from interacting with the automatic feeding bin – the reaction could be caused by watching another cow reacting fearfully near the automatic feeding bin. Future studies should thus include these aspects as they remain rather unexplored in farm animal species.

4. The human-cattle relationship

4.1. How cattle perceive and interact with humans

In dairy cattle farming systems, cows interact with humans on a daily basis. It should be noted that cattle are able to discriminate between humans from an early age (de Passillé et al., 1996; Munksgaard et al., 1999; Rybarczyk et al., 2001). It is thus important to establish a good human-animal relationship from the very beginning of the calf's life, which may even last for the entirety of the production cycle (Breuer et al., 2003; Rushen et al., 1999). Several studies have investigated the human–cattle relationship and highlighted ways to improve it. For example, Lange et al. (2020) and Lürzel et al. (2016) investigated the effects of gentle stroking of heifers and found that avoidance distance decreased when heifers had been stroked by a human as calves (Lürzel et al., 2016), while the exact manner of stroking applied seems less relevant in the promotion of positive affective states in cattle (Lange et al., 2020). Early handling also seems crucial for later acceptance (i.e., allowing the human within close proximity) of dairy cows to humans, e.g., Jago et al. (1999) found that handling in the first two days after birth resulted in calves readily approaching and interacting with an unknown human regardless of any later interactions with humans. Breuer et al. (2003) found that negative tactile handling leads to both a behavioural and a physiological acute and chronic stress response in dairy heifers. While most of these have focused exclusively on how tactile stimulation can affect the human-animal relationship, humans and cattle can also interact via other modalities using, for example, olfactory or acoustic stimuli. Cattle are able to detect similar and also higher sound frequencies than humans (Heffner and Heffner, 1992, 1983) and their sense of smell plays a central role in both social and sexual behaviour (Wyatt, 2003). It is therefore likely that cattle gather much more information from human handlers than is currently considered. Research from horses, for example, shows that horses handled by calm and positive humans show lower heart rates and lower cortisol concentrations (reviewed in Rørvang et al., 2020) and recent research already hints that cattle may be able to recognise human stress-related chemosignals (Destrez et al., 2021). If cattle are able to associate these signals with negative human-animal interactions, they may consequently change their behaviour. Hence these results should be explored further on larger samples and other breeds (only Charolaise were tested in Destrez et al., 2021) to be able to make a final conclusion on the common saying that cows can smell a person's bad mood.

4.2. Facilitating positive interactions

Although fearful or aggressive animals are believed to be the main cause of animal-handling injuries and have been intensively studied (Boyle et al., 1997; Lindahl, 2014), the possibility of facilitating positive human-animal interactions by applying learning theory to train cows has received sparse attention (but see: Lomb et al., 2021). In other domestic animal species, there is considerable work on mapping how the animal reacts to cues from humans and conspecifics in order to avoid risky situations. Horses, for example, can be habituated to otherwise fear-eliciting situations (Christensen et al., 2008) and positive reinforcement training is an efficient tool to lower stress in numerous situations across different animal species (e.g., horses: Dai et al., 2019, lions: Callealta et al., 2020, primates: Perlman et al., 2012, ring-tailed lemurs: Spiezio et al., 2017). Positive reinforcement training has also become common in biomedical research, ensuring reliable experimental results and welfare of the laboratory animals (Laule et al., 2003; Scott et al., 2003), and recently this technique has also been increasingly implemented in modern zoos, enhancing animal husbandry standards and welfare (e.g., Laule et al., 2003, Laule and Whittaker, 2007). These approaches have only been applied to cattle to a limited extent, although cattle are routinely handled, and have to 'behave' within farm routines. The North American cattle handlers Bud Williams (who proposed the "Low-stress cattle management" principles in the 90′ies, Williams, 2012) and Dylan Biggs (teaching the "Low-stress principles", Biggs, 2013) have anecdotally pointed to such concepts indirectly when stressing the importance of the stock person spending time walking through the herd, in order to reduce the size of the flight zone (i.e. habituate cattle to the presence of the human, Stookey and Watts, 2014). In addition to this practical viewpoint, research has also pointed to cows' general trainability. For instance, cows can easily learn to follow a target using positive reinforcement training (Rørvang et al., 2018b). Such a training principle could be useful in many ways while handling cattle, especially in situations where it is beneficial to distance the human from the cow such as during moving for various purposes including loading for transport (Rasmussen et al., 2000), which has also proven an efficient method in horses (Dai et al., 2019). Another example is a study by Lomb et al. (2021), showing that heifers that have been trained using a combination of positive reinforcement and counterconditioning readily tolerated a painful procedure. Chen et al. (2016) also showed that positive reinforcement training is beneficial during restraining of cattle. The authors also noted that the training also reduced avoidance behaviour both during the procedure and after the procedure. Adding to this, there is evidence to suggest that while training will reduce fear in cattle, it may also enhance the quality of the relationship between handler and cow (Ceballos et al., 2018; Lürzel et al., 2016), which could even be generalised to other handlers. Much more information thus remains to be uncovered on this topic, and future studies should focus on mapping which already established training regimes are useful for cattle, and in which context. Studies should also include investigations of potential long-term effects this may have on the human-animal relationship, and whether this can be generalised to other human handlers.

Based on the capacity of cattle to learn and remember information about different humans, it might be intriguing to ask if cattle could possess the ability to use social information from heterospecifics, such as humans. To the best of our knowledge, it remains unknown if information can be socially transmitted from humans to cattle (reviewed for farm animals by Nawroth et al., 2019). These aspects thus remain to be investigated and highlight the potential of adjusting procedures during handling practices.

5. A note on science communication and knowledge transfer

In addition to future research, we also want to stress the importance of communicating knowledge derived from both applied and basic research on the cognitive capacities of cattle to various stakeholders, such as industry partners. As the industry is the end-user of this information, making information accessible and understandable to a variety of stakeholders is important if we want to safeguard implementation of this knowledge in husbandry and management procedures. Although initiatives aiming to improve cattle handling (the "Low-stress cattle management", proposed by Guy Williams, 2012) do exist, collaboration between practitioners and researchers needs to be increased on this topic, as otherwise this can pose a risk both to the practical applicability of the research and the scientific foundation of practical knowledge. We, therefore, encourage researchers and practitioners to bridge this gap further to safeguard a successful implementation of scientific findings alongside practical initiatives.

Communicating both the abilities, but also the limitations, of cattle cognition will help ensure that human expectations of cattle's ability to adapt to husbandry systems and routines match their actual mental capacities. Future research projects should thus include a stronger dissemination of results from cognitive research in farm animal cognition.

6. Conclusion

Research on the cognitive abilities of dairy cattle is an understudied area, although there may be unexploited potential to use such information in various aspects of dairy cattle housing, and management. We here exemplarily outlined three central aspects: 1) vertical transmission of information between cow and calf, 2) attenuation of fear via social buffering and the usage of conditioning cues such as odours, and 3) improving the human-cattle relationship by enforcing positive interactions via positive reinforcement training. Future studies should focus on elucidating what and how much calves learn from their dam during prolonged cow-calf contact in dairy cattle. Such information could be a prominent part of the discussion of whether to keep cows and calves in the dairy industry together for a longer time after calving. Fear in the cattle group might be lowered by the use of calm companions and future studies could uncover if attenuation of fear might even be induced by conditioning positive experiences of cattle with unrelated stimuli such as odours. Lastly, the human-cattle relationship might benefit from utilising the already established training regimes from other species, for example positive reinforcement training or target training, which may have long-term effects on the animals and humans involved. Cattle welfare, productivity, farm staff safety and sustainability of dairy and meat production could benefit from future advances in cattle cognitive research, and we hope this review will assist in paving the way for future research endeavours.

CRediT authorship contribution statement

MVR & CN: Conceptualization, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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