

LETTER

Rudolph the red nosed reindeer had a low stress tolerance and suffered from stress induced psychogenic fever. A reply to Crooks *et al.* 2017

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We thank the authors (Crooks *et al.* 2017) for their well-informed and thought-provoking reply to our article on Rudolph's red nose (Van der Hoven *et al.* 2012). Crooks *et al.* stated Rudolph's red glowing nose is an advantage in foggy conditions, since red is the most visible colour in foggy conditions. As May (1939) noted that Rudolph's 'glowing' nose aided Santa Claus in his Christmas Eve preparations when a thick fog descended, Crooks *et al.* elaborated on that observation and concluded (1) Rudolph was specifically chosen because of this adaptation, to aid in navigation and (2) that his red nose was in fact caused by bioluminescence and not by our finding - cerebral and bodily hyperthermia caused by exceptional physical burden of flying with a sleigh with Santa Claus, resulting in an overworked cooling mechanism (hyperemia) in the countercurrent units in the nasal mucosa.

Stress

In comment to the bioluminescence theory some details need to be addressed. Crooks *et al.* point out that Rudolph was selected for his red nose, without being stressed. We suggest however, that he was excited due to the selecting process. May (1939) described Rudolph having a red nose even when sleeping, and in the wording of the story we note a high level of chronic stress by peer pressure as the poor reindeer is ridiculed for his peculiar nasal features. ["Ha ha! Look at Rudolph! His nose is a sight!" "It is red like a beet!" "Twice as bio! Twice as bright!" While Rudolph just wept. What else could he do? (May 1939)]



'We now hypothesize that Rudolph suffered from stress-induced chronic hyperthermia ('psychogenic fever') which caused his nose, even at rest, to be constantly red.' Reindeer (*Rangifer tarandus*), collection Natural History Museum Rotterdam; NMR 9990-002295. [Mark Prinsen]

Being selected for his leading part in the sledge team would also cause such a tremendous tension that he would be susceptible to become overheated, while the other members of the sledge team would not have been receptive to this stressful event. Their situation can be judged as a normal condition, but for Rudolph it was quite exceptional.

Furthermore, it is known that chronic psychological stress affects body temperature (Oka 2015). This condition is called 'psychogenic fever' or 'functional hyperthermia'. Chronically stressed animals display an enhanced hyperthermic response to novel stress, while past fearful experiences induce conditioned hyperthermia to the fear context. It seems very plausible to us that Rudolph suffered from chronic hyperthermia induced by chronic stress, giving rise to a constant red nose, even while resting as described by May (1939).

Altitude

We agree with Crooks *et al.* with regard to the proposed influence of high-altitude flying on the temperature regulation in reindeer. However, because of the aforementioned stress during preparation for flight and the physically hard take-off procedure, Rudolph would have initially shown his red nose, by a combination of mental and physical stress as the leading reindeer.

Flight formation and vision

Crooks *et al.* emphasize all reindeer of the sledge team have an equal work load caused by their linear formation, and thus should all have an overheated red nose. Figure 1 in Crooks *et al.* however shows a flight formation that is not linear. Rudolph is in the lead and the others are flying in pairs behind him. Therefore, he would have been the most physically challenged animal of the sledge team and, furthermore, the distribution of force generated per animal is not clear. Rudolph is also smaller than the average reindeer [*While every so often they'd stop to call names At one little deer (Rudolph) not allowed in their games (May 1939)*]. The workload on the leading animal may be much greater than for the other team members. This, together with Rudolph's small physique, leads to extra physical stress. Such individual differences in stress vulnerability are based on alterations in neural circuits/mechanisms designed to properly tune and terminate stress responses (Ebner & Singewald 2017). Perhaps the other animals were work-shy, or exhibited the same attitude as for instance some persons riding second party on a tandem bike.

Crooks *et al.* also challenge the validity of our hypothesis based on research into the eyesight of reindeer. This is indeed an interesting thought that prompts further research.

Bioluminescence

Crooks *et al.* emphasize the importance of bioluminescence as an explanation for Rudolph's navigational skills. As they admit, bioluminescence has not been described in mammals. Some research suggests this to be a possibility, for instance the cou-

pling of bioluminescent jellyfish genes to other specific genes in human-genetic disorder experiments using pig embryos (the so-called 'glow-in-the-dark' piglets; Li *et al.* 2014). But no such experiments were performed on Rudolph (and any other reindeer) as far as we know, so it could only have been the result of a spontaneous mutation. This would have been an unrealistic occurrence, as it has never been described in reindeer (*Rangifer tarandus*), nor in any other mammal.

In addition, Ince *et al.* (2012) found that the nasal mucosa of the reindeer is richly vascularized, with a vascular density 25% higher than in humans. These results highlight the intrinsic physiological properties of Rudolph's luminous red nose, which help to protect his snout from freezing during sleigh rides and to regulate the temperature of the reindeer's brain - all factors essential for flying reindeer pulling Santa Claus's sleigh under extremely low temperatures.

CONCLUSION

In conclusion, as an explanation for Rudolph's red nose, we still believe the theory of Van der Hoven *et al.* (2012) is more plausible, based on the anatomy of the nasal mucosa of the reindeer in combination with chronic stress and the expected physical exertion of towing an overweight sleigh. Furthermore, we now hypothesize that Rudolph suffered from stress-induced chronic hyperthermia ('psychogenic fever') which caused his nose, even at rest, to be constantly red.

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