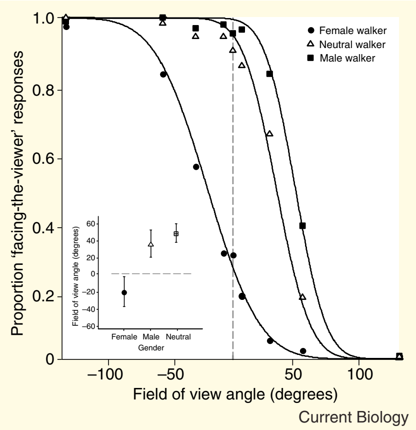

Current Biology

Figure 2. Proportions 'facing the viewer' answers as a function of perspective information, represented by field-of-view angle.

Negative scores denote perspective cues to looming and positive scores perspective cues to retreat. The dashed grey line indicates the perspective-cue neutral point (orthographic projection). Female walkers (filled circles) elicited mainly perceptions consistent with retreat. Neutral (open triangles) and male walkers (filled squares) elicited mainly perceptions consistent with approach. The means of the Gaussian functions fitted to each set of data (inset, bottom left) show that judgements of the orientation of the walkers could not be predicted on the basis of the perspective cues incorporated into each stimulus. Bars indicate 95% confidence intervals about each mean.

approach even when there were unambiguous perspective cues to retreat. Conversely, the mean of the function fitted to judgements of the female walker is below the neutral point, consistent with female walkers appearing to retreat even when there were unambiguous perspective cues to approach. These effects were independent of observer gender. The results demonstrate that the perceived direction-of-facing of an otherwise ambiguous point-light figure (see Supplemental data available on-line) is related to the perceived gender of the figure.

Humans, like many other species, are fundamentally social animals and have evolved mechanisms allowing them successfully to work in large social groups [8]. Our data suggest that biological motion is an important cue for social organisms trying to operate in environments where other cues as to the actions or intentions of other organisms may be ambiguous. Whilst the precise role of local cues in mediating these effects requires further explication, it is tempting to speculate that the orientation biases reported here reflect the development of perceptual mechanisms that weigh in the probable cost of *misinterpreting* the actions and intentions of others. For example, a male figure that is otherwise ambiguous might best be perceived as approaching to allow the observer to prepare to flee or fight. Similarly, for observers (especially infants) the departure of females might signal also a need to act, but for different reasons.

Supplemental data

Supplemental data are available at http://www.current-biology.com/cgi/content/full/18/17/R728/DC1

Acknowledgments

We thank David Burr for reading of the manuscript and John Campbell for support. We thank also two anonymous reviewers for useful comments and suggestions.

References

1. Johansson, G. (1973). Visual perception of biological motion and a model for its analysis. Percept. Psychophys. *14*, 201–211.
2. Blake, R. (1993). Cats perceive biological motion. Psychol. Sci. *4*, 54–57.
3. Hermann, L.M., Morrel-Samuels, P., and Pack, A.A. (1990). Bottlenosed dolphin and human recognition of veridical and degraded video displays of an artificial gestural language. J. Exp. Psychol. Gen. *119*, 215–230.
4. Dittrich, W.H. (1993). Action categories and the perception of biological motion. Perception *22*, 15–22.
5. Kozlowski, L.T., and Cutting, J.E. (1977). Recognizing the sex of a walker from a dynamic point-light display. Percept. Psychophys. *21*, 575–580.
6. Dittrich, W.H., Troscianko, T., Lea, S.E.G., and Morgan, D. (1996). Perception of emotion from dynamic point-light displays represented in dance. Perception *25*, 727–738.
7. Vanrie, J., Dekeyser, M., and Verfaillie, K. (2004). Bistability and biasing effects in the perception of an ambiguous point-light walker. Perception *33*, 547–560.
8. Allison, T., Puce, A., and McCarthy, G. (2000). Social perception from visual cues: role of the STS region. Trends Cogn. Sci. *4*, 267–278.
9. Troje, N.F. (2002) Decomposing biological motion: a framework for analyses and synthesis of human gait patterns. J. Vision *2*, 371–387.

[1]Laboratory of Perceptual Processing, Department of Psychology, Southern Cross University, Coffs Harbour, NSW 2450, Australia. [2]Laboratory of Experimental Psychology, University of Leuven, Tiensestraat 102, B-3000, Leuven, Belgium. [3]Department of Psychology and School of Computing, Queen's University, Kingston, Ontario, K7M 3N6, Canada. [4]Laboratory of Cognitive Neuroscience, Brain-Mind Institute, Ecole Polytechnique Fédérale de Lausanne, 1015 Lausanne, Switzerland.
*Email: rick.vanderzwan@scu.edu.au

Tardigrades survive exposure to space in low Earth orbit

K. Ingemar Jönsson[1,*], Elke Rabbow[2], Ralph O. Schill[3], Mats Harms-Ringdahl[4] and Petra Rettberg[2]

Vacuum (imposing extreme dehydration) and solar/galactic cosmic radiation prevent survival of most organisms in space [1]. Only anhydrobiotic organisms, which have evolved adaptations to survive more or less complete desiccation, have a potential to survive space vacuum, and few organisms can stand the unfiltered solar radiation in space. Tardigrades, commonly known as water-bears, are among the most desiccation and radiation-tolerant animals and have been shown to survive extreme levels of ionizing radiation [2–4]. Here, we show that tardigrades are also able to survive space vacuum without loss in survival, and that some specimens even recovered after combined exposure to space vacuum and solar radiation. These results add the first animal to the exclusive and short list of organisms that have survived such exposure.

The experiment was conducted within the Biopan-6 experimental platform provided by the European Space Agency (ESA) during the FOTON-M3 mission in September 2007. During ten days at low Earth orbit (258–281 km above sea level) samples of desiccated adult eutardigrades of the species *Richtersius coronifer* and *Milnesium tardigradum* were exposed to space vacuum and two different UV-radiation spectral ranges: UV-A and UV-B ($UV_{A,B}$, 280–400 nm), and the full UV range from vacuum-UV to UV-A (UV_{ALL}, 116.5–400 nm). The experiment included three sets of flight samples: samples exposed to space vacuum (SV) only, samples exposed to space vacuum and $UV_{A,B}$, and samples exposed to space vacuum and UV_{ALL}. All samples were also exposed

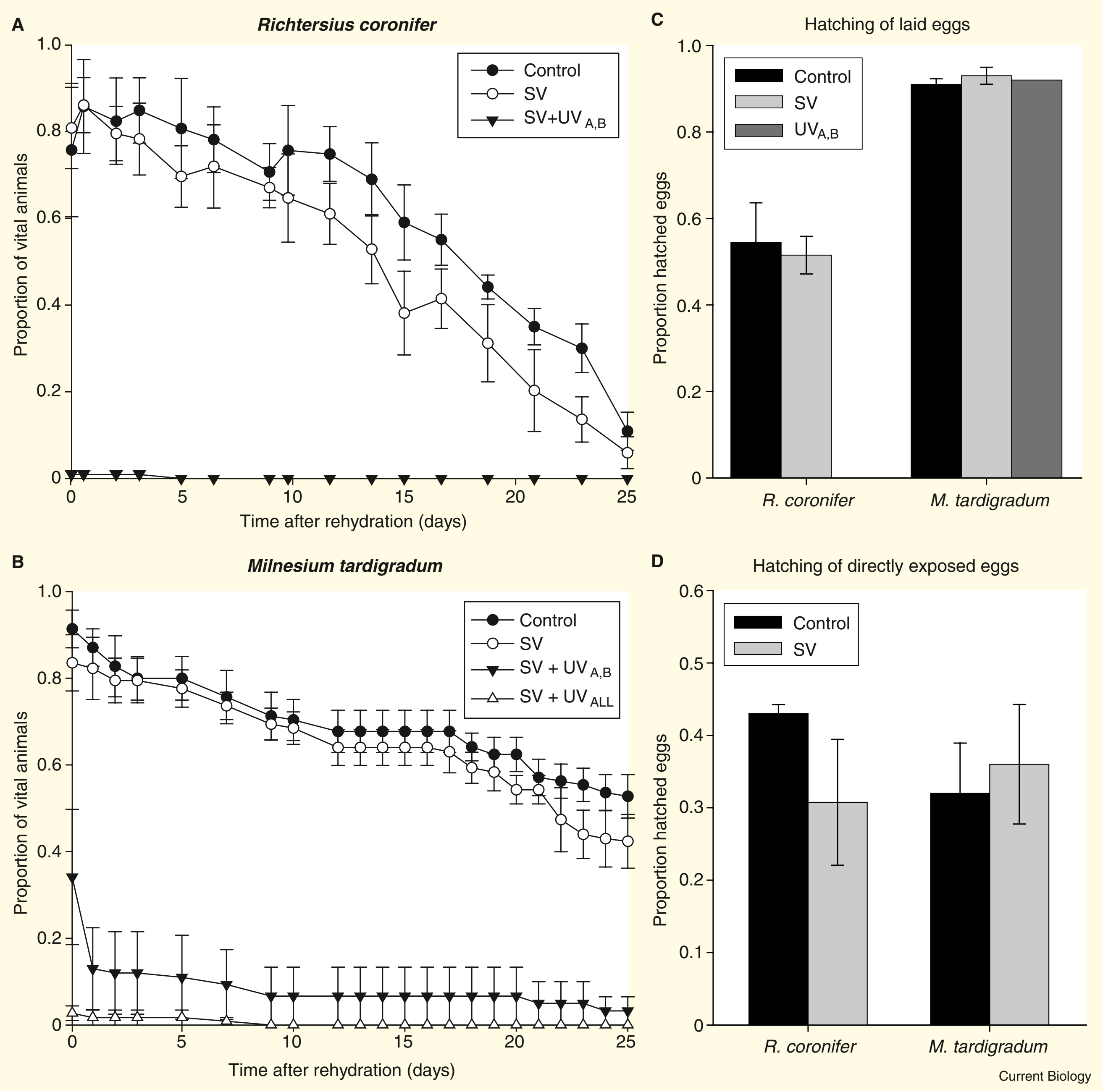

Figure 1. Survival of tardigrades and tardigrade eggs under space conditions.

(A,B) Post-flight survival in space-exposed tardigrades as a function of time after rehydration. (A) *R. coronifer*. (B) *M. tardigradum*. Tardigrades were exposed to space vacuum (SV), space vacuum and UV 280–400 nm (SV+UV$_{A,B}$), and space vacuum and UV 116.5–400 nm (SV+UV$_{ALL}$). Controls were kept under ambient laboratory conditions. Animals were recorded as vital if showing coordinated leg movements. Data represent mean ± 1 s.e.m. for four replicate samples. Time = 0 on the x-axis represents 2 hours post-rehydration. Data for SV+UV$_{ALL}$ were excluded from (A) because no specimens of *R. coronifer* in this category revived. In general, controls and vacuum-exposed tardigrades survived equally well in both species (Mann-Whitney test, $p > 0.05$ in all comparisons except for one estimate in *R. coronifer*: day 23, U = 1, $p = 0.043$). Survival of samples exposed to SV+UV$_{ALL}$ were significantly different from controls and vacuum-exposed samples in *M. tardigradum* ($p < 0.05$ in all comparisons). (C,D) Post-flight hatching success of eggs of the tardigrades *Richtersius coronifer* and *Milnesium tardigradum*. (C) Rate of hatching of eggs laid by animals exposed to space vacuum (SV) and for controls. Data represent mean ± 1 s.e.m. for 4 replicate samples, each with 9-26 freely laid eggs (*R. coronifer*) or 5–30 exuvia with eggs (*M. tardigradum*). Since only one of the UV$_{A,B}$ replicate samples produced exuvia with eggs, no standard error is given for this group. Exposure groups did not differ statistically in either *R. coronifer* (Mann-Whitney test; U = 8.0, $p = 1.0$) or *M. tardigradum* (Nested ANOVA, F(2,154) = 0.14, $p = 0.87$). (D) Rate of hatching of eggs directly exposed to space vacuum (SV) and for controls. No light-exposed eggs hatched. Data represent mean ± 1 s.e.m. for 4 replicate samples, each with 9–26 eggs (*R. coronifer*) or 16–50 eggs (*M. tardigradum*). Exposure groups did not differ statistically in either *R. coronifer* (Mann-Whitney test; U = 10, $p = 0.56$) or *M. tardigradum* (U = 7, $p = 0.77$).

to ionizing solar and galactic cosmic radiation. Desiccated control samples were kept under ambient laboratory conditions, but otherwise treated in the same way as flight samples. After the flight, the samples were rehydrated and survival and reproductive patterns were recorded. Our experiment included exposure of both animals and eggs of the two tardigrade species (Supplemental data).

Both species of tardigrades survived exposure to space vacuum alone very well, with no significant difference in survival pattern compared to controls (Figure 1A,B). In contrast, samples exposed to the combined effect of vacuum and solar radiation had significantly reduced survival. In samples exposed to the most life-threatening conditions (UV_{ALL}), only three specimens of *M. tardigradum* survived. Among samples exposed to $UV_{A,B}$, a high proportion (68%) of the *M. tardigradum* specimens revived within 30 minutes, but subsequent mortality was high. In *R. coronifer*, only one specimen exposed to $UV_{A,B}$ revived. Thus, exposure to solar radiation had a very strong negative effect on survival.

We found no significant effect of space vacuum on egg-laying in either *R. coronifer* (Mann-Whitney test, $U = 11$; $p = 0.38$) or *M. tardigradum* ($U = 14$; $p = 0.081$). However, surviving $UV_{A,B}$ exposed animals of the latter species had a lower rate of egg laying ($U = 16$; $p = 0.017$).

Eggs laid by animals exposed to space vacuum hatched as well as eggs from control animals in *R. coronifer* (Figure 1C). The same was observed in *M. tardigradum*, in which also the $UV_{A,B}$ eggs hatched as well as controls. Also tardigrade eggs exposed directly to space conditions showed no difference in hatching rate between vacuum-exposed eggs and controls, with a similar pattern in *R. coronifer* and *M. tardigradum* (Figure 1D). No juveniles appeared from eggs exposed to solar light.

So far, only lichens [5] and bacteria [6] have been reported to survive the combined exposure to space vacuum and solar/galactic cosmic radiation, and no animal has previously been tested under these conditions. Our results, therefore, represent the first record of an animal surviving simultaneous exposure to space vacuum and solar/galactic radiation. Space vacuum did not affect either survival or reproduction, confirming that the cells of tardigrades, including developing eggs, can tolerate even the most extreme dehydration, at residual water levels well below one mass percent. At such low water contents, the configuration of DNA is expected to change, resulting in damage to cellular components, such as DNA [7,8].

Tardigrades exposed to solar radiation had a very low survival and fitness, and in line with studies in bacteria [6] most specimens were killed by exposure to the unfiltered solar radiation. However, remarkably, some animals of *M. tardigradum* survived exposure to both space vacuum and solar radiation, in particular among samples protected from UV-C and vacuum-UV. How these animals were capable of reviving their body after receiving a dose of UV radiation of more than 7000 kJm^{-2} under space vacuum conditions which presumably increase UV sensitivity remains a mystery.

The mechanisms behind the tolerance of tardigrades to extreme desiccation and radiation have not been revealed and represent an exciting challenge for future research. Special configurations of DNA and other cellular components that prevent damage are probably involved, but also an efficient system to repair damaged DNA [9], as recently suggested by studies in desiccation and radiation tolerant rotifers [10].

Supplemental data

Supplemental data are available at http://www.current-biology.com/cgi/content/full/18/17/R729/DC1

Acknowledgments

K.I.J. was supported by the Crafoord Foundation, the Trygger Foundation, and Kristianstad University. The part of the study performed in Stuttgart was enabled by the project FUNCRYPTA (0313838A), funded by the German Federal Ministry of Education and Research, BMBF. We thank Eva Zettler, Andy Reuner and Steffen Hengherr for help with the *M. tardigradum* culture, and Bengt Svensson, Mörrums Finmekano AB, for technical assistance in developing the TARDIS hardware. We are also very grateful to the European Space Agency for providing the logistic opportunity to realize the TARDIS project.

References

1. Horneck, G. (2003). Could life travel across interplanetary space? Panspermia revisited. In Evolution on Planet Earth: The Impact of the Physical Environment, L.J. Rothschild and A.M. Lister, eds. (London: Academic Press), pp. 109–127.
2. Jönsson, K.I., Harms-Ringdahl, M., and Torudd, J. (2005). Radiation tolerance in the tardigrade *Richtersius coronifer*. Int. J. Rad. Biol. *81*, 649–656.
3. May, R.M., Maria, M., and Guimard, J. (1964). Actions différentielles des rayons x et ultraviolets sur le tardigrade *Macrobiotus areolatus*, à l´état actif et desséché. Bull. Biol. France Belgique *98*, 349–367.
4. Horikawa, D.D., Sakashita, T., Katagiri, C., Watanabe, M., Kikawada, T., Nakahara, Y., Hamada, N., Wada, S., Funayama, T., Higashi, S., *et al*. (2006). Radiation tolerance in the tardigrade *Milnersium tardigradum*. Int. J. Rad. Biol. *82*, 843–848.
5. Sancho, L.G., de la Torre, R., Horneck, G., Ascaso, C., de los Rios, A., Pintado, A., Wierzchos, J., and Schuster, M. (2007). Lichens survive in space: results from the 2005 LICHENS experiment. Astrobiology *7*, 443–454.
6. Horneck, G., Rettberg, P., Reitz, G., Wehner, J., Eschweiler, U., Strauch, K., Panitz, C., Starke, V., and Baumstark-Kahn, C. (2001). Protection of bacterial spores in space, a contribution to the discussion on panspermia. Orig. Life Evol. Biosph. *31*, 527–547.
7. Frankenberg-Schwager, M., Turcu, G., Thomas, C., Wollenhaupt, H., and Bücker, H. (1975). Membrane damage in dehydrated bacteria and ist repair. In Life Sciences and Space Research XIII, P.H.A. Sneath, ed. (Berlin: Akademie-Verlag), pp. 83–88.
8. Dose, K., Bieger-Dose, A., Labusch, M., and Gill, M. (1992). Survival in extreme dryness and DNA-single-strand breaks. Adv. Space Res. *12*, 221–229.
9. Jönsson, K.I. (2007) Tardigrades as a potential model organism in space research. Astrobiology *7*, 757–766.
10. Gladyshev, E., and Meselson, M. (2008). Extreme resistance of bdelloid rotifers to ionizing radiation. Proc. Natl. Acad. Sci. USA *105*, 5139–5144.

[1]Department of Mathematics and Science, Aquatic Biology and Chemistry Group, Kristianstad University, SE-291 88 Kristianstad, Sweden. [2]Institute of Aerospace Medicine, Radiation Biology Division, DLR, Linder Höhe, 51147 Köln, Germany. [3]Department of Zoology, Biological Institute, Universität Stuttgart, Pfaffenwaldring 57, 70569 Stuttgart, Germany. [4]Department of Genetics, Microbiology and Toxicology, Stockholm University, SE-106 91 Stockholm, Sweden.
*E-mail: ingemar.jonsson@hkr.se