Fig. 1 Tropical Tales–children's audio story about a child finding a cure for leishmaniasis. Photo Copyright Eimear Kavanagh.

Fig. 2 Bed-In event in Liverpool; Bednets not Bombs, protest about lack of funding for insect vector and bed nets research. Photo Copyright Rod Dillon.

provided for military activity. My partner Viv Dillon and I spent the day in bed covered with a mosquito net (Fig. 2). The installation included a video projected onto the bednet, containing footage of sand flies and mosquitoes together with fighter aircraft, overlayed with sounds of warfare, insects, children, and electrical laboratory equipment.

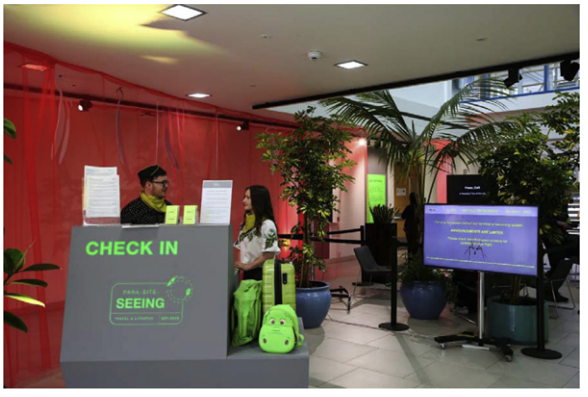

Fig. 3 Parasiteseeing; The Departure Lounge. An art show about travels from the perspective of *Leishmania*. Photo Copyright Erika Stevenson.

The final example was an interactive art show called 'Parasite-seeing; the Departure Lounge'. Artist Jen Southern and myself were commissioned by Dundee University LifeSpace Science Art Research Gallery UK and the Wellcome Centre for Anti-infectives Research. In this show, we exploited the known concept of an airport travel lounge and transformed it into a place where the audience were invited to imagine life from the perspective of a travelling *Leishmania* parasite. The interactive exhibition started with visitors checking in at a check-in desk with a *Leishmania* passport that they were instructed to stamp as they walked through the exhibition (Fig. 3). Final boarding took place in a model area of a sand fly gut, with the final exit being illustrated by a poem about a new anti-leishmanial drug developed at the Wellcome Centre. The exhibition took in many facets of research on *Leishmania*, including historical aspects with many elements of social media following *Leishmania* travels in the wild and in the lab including a twitter feed from @ldBOb72 a *Leishmania* parasite.

Disclosure of interest The authors declare that they have no competing interest.

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The trypanosome journey in the tsetse fly

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Trypanosoma brucei is a flagellated parasite responsible for sleeping sickness in central Africa. It is transmitted from one host to another via the bite of the tsetse fly (*Glossina* genus), which is the major mode of contamination. The tsetse fly (Fig. 1), both male and female, feeds exclusively on blood and exhibits unique features such as viviparous reproduction and lactation. It should be considered as a real host for trypanosomes, since the parasites differentiate and proliferate in several fly tissues such as the gut, the proventriculus, and the salivary glands. Trypanosomes adapt to these various environments by modifications in their cell surface composition, metabolism, and morphogenesis. One of the most prominent characteristics of trypanosomes is the presence of a flagellum that is attached to the cell body and drives parasite movement, but also dictates cell morphology. Its length varies according to the life cycle stage, ranging from 3 to 30 μ m. This organelle is essential for parasite survival. Here, we will discuss the different aspects of trypanosome development in the tsetse fly, with focus on flagellum function.

The disease and the parasite Human African Trypanosomiasis is a disease characterised by two phases, one with rather unspecific symptoms such as bouts of fever, headaches, weakness or lymphadenopathy, and a second one with severe neurological symptoms including disruption of the sleeping pattern, hence the historical name of the disease, sleeping sickness. It is due to a parasitic protist called *Trypanosoma brucei*, with only two subspecies being responsible for human infections: *T. b.*

Fig. 1 The tsetse fly.

gambiense (98% of the cases) and *T. b. rhodesiense*. Under the microscope, this extracellular parasite exhibits a long motile flagellum that is attached to the cell body. It performs multiple functions such as motility, morphogenesis and adhesion to specific tissues. The parasite possesses a typical eukaryotic nucleus (35 Mo) and a single mitochondrion whose large genome is condensed in a structure called the kinetoplast. The parasite escapes the host immune response thanks to a sophisticated process of antigenic variation. The disease is exclusively encountered in sub-Saharan Africa because the parasite is transmitted by the bite of the tsetse fly (Fig. 1), an insect that is not found outside this region.

The tsetse fly *Glossina* flies have unique biological peculiarities. In contrast to most insects, they are not oviparous. Mating occurs from five days after birth and larval development takes place into the female uterus. After 14 days, the female lays a single pupa that is lightly buried in the ground. Development continues for 28 days before hatching and emergence, which is completed in only a few minutes. Like other insects, the tsetse fly is often termed a vector, but it should be considered as real host for at least two reasons. First, trypanosomes undergo a long trip in the tsetse fly, developing in a very precise order in different tissues with a lot of specific morphological, genetic, and biochemical adaptations. Second, trypanosomes are likely to have been parasites of insects well before affecting other organisms. The term of vector is probably more appropriate in the case of mechanical transfer of pathogens from one host to the other, as observed with the bite of tabanids and the transmission of *Trypanosoma evansi*, for example. This parasite is lacking several mitochondrial genes normally encoded on kinetoplast DNA and is unable to develop in the tsetse fly, yet can be passively transferred from one host to the other. Finally, it should be pointed out here that, although the presence of trypanosomes can affect the tsetse fly, the insect itself does not suffer from sleeping sickness. Therefore, it is preferable to say that the tsetse fly transmits trypanosomes, and not the disease. In the laboratory, tsetse flies are bred in netted cages and fed with heated sheep blood using a membrane to mimic the presence of the skin. Flies do not feed directly on blood.

Trypanosomes in the tsetse fly Trypanosomes are ingested with blood when the fly feeds on an infected host and reach the crop where they have to resist dehydration. Next, the "paste" containing blood and trypanosomes is moved to the gut. The parasites differentiate to adapt to this new environment, where they have to face digestive enzymes and exhibit new molecular, biochemical, and metabolic features. They proliferate in the posterior midgut and then need to migrate to the proventriculus. This is a challenging trip for a trypanosome. If we compare with humans, it would be equivalent to swimming seven kilometres in a highly viscous environment like jelly... This is achieved by active forward motility, with the beating flagellum driving migration [1]. The parasite next moves to the salivary glands, a process also likely to be governed by the flagellum. However, this could not be experimentally proven given the failure of motility mutants to reach the proventriculus. None of these parasite stages are able to infect mammals. Once trypanosomes arrive in the salivary glands, they therefore need to differentiate in an infective stage. For this, they attach to the epithelium of the salivary glands before starting the differentiation process. This prevents them from being released prematurely with the saliva. This adhesion takes place via the flagellum, which develops unique and complex membrane extensions that wrap around microvilli of the fly epithelial cells. The parasite then undergoes an asymmetric division, with the daughter cell inheriting the old flagellum, which remains attached to the epithelium and the other daughter inheriting the new flagellum, which adopts different morphology and biochemical composition [2]. This latter cell differentiates to the infectious stage and is released in the saliva. It is now ready to infect a new host.

Trypanosomes in mammalian hosts After landing on skin, the tsetse fly does not find immediately blood vessels for feeding. Rather, it probes by scratching and dilacerating tissues. During this process, the fly injects saliva and, if it contains trypanosomes, these are delivered in the skin. It was long accepted that trypanosomes rapidly move to the lymph, then to the blood, where they would spend most of their time before reaching the nervous system. However, recent development in imaging techniques allowed researchers to visualise parasite progression in mouse models. Strikingly, trypanosomes are mostly present in the skin, including in cases where they were not detected in the blood. They are highly motile, possibly to escape phagocytic cells. Moreover, skin trypanosomes have been shown to infect naïve tsetse flies, demonstrating their role in parasite transmission [3,4]. Analysis of skin biopsies from human patients coming from endemic areas for human African trypanosomiasis revealed the presence of trypanosomes, suggesting that the same phenomenon could occur in humans [3]. This is an amazing finding that could change the paradigm of African trypanosomiasis given the fact that diagnosis is based on the detection of parasites in the blood. This means that trypanosome carriers might go undetected and could contribute to parasite transmission. This could be highly significant in the current context of HAT elimination [5].

Conclusion Trypanosomes show remarkable adaptations to live within different tissues of the tsetse fly with the final aim to ensure their transmission to mammalian hosts. The flagellum is a key organelle to this success, as it drives motility but also controls cell morphogenesis, which is suited to each particular tissue where the parasite develops. Cilia and flagella are known to function as sensory organelles in other organisms and it would not be surprising to see it exploited by trypanosomes to detect their environment [6].

Disclosure of interest The authors declare that they have no competing interest.

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Session VI. Insects in the future

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Insects on the menu

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Major challenges facing humanity Feeding the rapidly growing human population is a challenge with many facets: the need for producing 70% more food in 2050 compared to 2010 is challenging in itself. Yet, it is even more challenging in the context of environmental and population changes, nutrition crises, and health issues. Moreover, this challenge is closely connected to other challenges, including mitigation of climate change, avoiding waste by developing a circular economy, conserving biodiversity, and supporting human health (Fig. 1). These challenges can only be met when we fundamentally change the way we produce food because current food production methods face serious limitations in resources, water, land, and energy [1]. The most important issue in supplying food to the rapidly growing human population is the production of sufficient high-quality proteins. At present, this especially relies on the production of livestock. However, livestock production has a large ecological footprint in terms of land use and greenhouse gas production [2,3]. Most of this is the result of the inefficient conversion of feed-to-meat by conventional livestock, especially cattle [3]. At present, 80% of global agricultural land is used to produce livestock, and increasing the production of meat will have major negative consequences for land use and climate change. Hedenus et al. [2] concluded that a reduction in ruminant meat consumption is indispensable for meeting the maximum 2 °C target above the pre-industrial level. An excellent, sustainable, alternative to conventional meat is available in insects. Insects are the most abundant group of animals on Earth with one million species being described and an estimated 5 million species still to be discovered. More than 2000 insect species are known to be consumed by humans (https://www.wur.nl/en/Research-Results/Chair-groups/Plant-Sciences/Laboratory-of-Entomology/Edible-insects/Worldwide-species-list.htm) (Fig. 2). Their nutritional content varies between species, but in general the protein content is similar to that of conventional meat, while insects contain more unsaturated fatty acids [4]. Moreover, the high mineral content of insects in comparison to conventional meat is particularly interesting, considering the worldwide prevalence of iron and zinc deficiency. For instance, anaemia is a global public health problem affecting a quarter of the human population [5].

Fig. 1 The challenge of feeding the rapidly growing human population is closely connected to other challenges, including mitigation of climate change, avoiding waste by developing a circular economy, conserving biodiversity, and supporting human health.

Insects in a circular economy Insects can transform rest streams such as food waste or rest streams from food industry into high-value protein products. In doing so, they are valuable components of a circular economy. Recent reports show that insects can make important contributions to global food security [6] and that producing insects for food and feed has prospects for rapid commercial and societal uptake. Insect production has a much smaller ecological footprint, in terms of land and water use and greenhouse warming potential compared to the production of pigs and cattle [6–8]. This is especially due to the much better feed-to-meat conversion ratio of insects: ca. 2.2 kg feed required per kg of edible weight production for crickets, whereas this is more than 10 times higher (25 kg per kg edible weight produced) for beef [4,9]. Moreover, important feed sources for livestock production currently include fish meal and soybean meal, both obtained from a market competing between human food and animal feed. In addition, the use of fishmeal poses an increasing threat to the viability of marine and aquatic ecosystems [10]. In recent years, important developments have been initiated in the private sector that can contribute to the urgently needed changes in food production systems, i.e. the production of insects as food and feed [6,11,12]. Important developments are being made in the commercial production of insects as food and feed (www.ipiff.org). These new production systems provide an important contribution to addressing several of the main challenges that we face, including resource, land, and water scarcity [12].

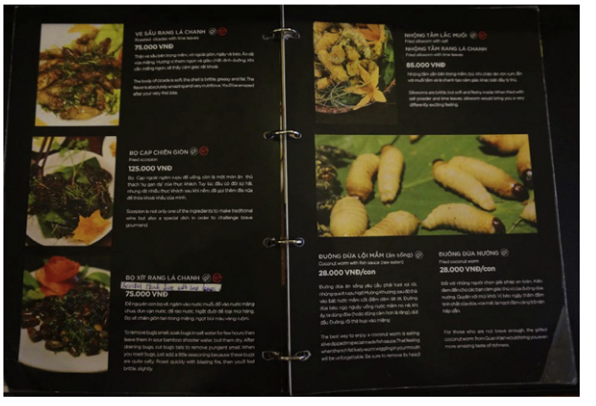

Fig. 2 Menu of a restaurant in Hanoi, Vietnam.