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## ► To cite this version:

Alexandre Bauer, Lucie Develay, Sébastien Motreuil, Maria Teixeira, Nelly Debrosse, et al.. Differences in specificity, development time and virulence between two acanthocephalan parasites, infecting two cryptic species of *Gammarus fossarum*. 2024. hal-04455823v3

**HAL Id: hal-04455823**

**<https://hal.science/hal-04455823v3>**

Preprint submitted on 26 Jun 2024

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# Differences in specificity, development time and virulence between two acanthocephalan parasites, infecting two cryptic species of *Gammarus fossarum*

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## ABSTRACT

Multi-host parasites can exploit various host species that differ in abundance and susceptibility to infection, which will contribute unequally to their transmission and fitness. Several species of acanthocephalan manipulative parasites (among which *Pomphorhynchus laevis* and *P. tereticollis*) use various amphipod species of the genus *Gammarus* as intermediate hosts. Many *Gammarus pulex* and *G. fossarum* cryptic lineages are living in sympatry in European rivers, questioning the spectrum of intermediate hosts that acanthocephalans can use, and their relative contribution to their life cycles. In this work, the respective roles of parasites species (*P. laevis* and, for the first time, *P. tereticollis*) and sympatric host cryptic species (the *G. fossarum* species complex) were studied experimentally on two traits: host susceptibility to infection and parasite virulence. Differences were found, both in terms of infectivity and virulence, between the cryptic hosts and between the two parasite species. We confirm that these acanthocephalans, previously considered as generalists, show specificities among their sympatric hosts. Differences in field prevalence and susceptibility after experimental exposures were more pronounced between cryptic *G. fossarum* species for *P. tereticollis* than for *P. laevis*. The mortality of infected individuals increased significantly after several weeks of development of both parasite species. *P. tereticollis* was less virulent than *P. laevis*, perhaps due to differences in host exploitation, since we evidenced that *P. tereticollis* had a much slower growth rate.

**Keywords:** experimental infection, *Gammarus fossarum*, *Gammarus pulex*, host specificity, infectivity, multi-host parasite, *Pomphorhynchus laevis*, *Pomphorhynchus tereticollis*, prevalence

## Introduction

Multi-host parasites are facing hosts of different qualities, which can contribute unequally to their transmission (Rigaud *et al.*, 2010). Key hosts, i.e. species that contribute much more than other potential host species to the parasite maintenance within the community, are often characterized by high abundance, high susceptibility to infection, and high number of propagules produced per infected individual (Marm Kilpatrick *et al.*, 2006; Streicker *et al.*, 2013; Manzoli *et al.*, 2021). For the management of infectious diseases, understanding the way parasites and pathogens use their multiple hosts is still challenging (Fenton *et al.*, 2015), particularly for epidemiology (Carrau *et al.*, 2021). With the advent of molecular taxonomy, cryptic diversity – represented by morphologically homogeneous lineages, genetically divergent enough to be considered as different species and thus forming “species complexes” – discovered in many animal and plants species revolutionized the study of interactions between species in general, and more particularly host–parasite relationships (Pérez-Ponce de León and Nadler, 2010; Pinacho-Pinacho *et al.*, 2018). Indeed, cryptic diversity was found in most parasite groups and many of these parasites, initially presumed to be generalists, were shown in fact to have a narrower host spectrum when genetic divergence was considered (Wang *et al.*, 2006; Janzen *et al.*, 2009; Mlynarek *et al.*, 2013; Escalante *et al.*, 2016; Pérez-Ponce de León and Poulin, 2018; Zittel *et al.*, 2018). Interestingly, cryptic diversity may also be found in hosts of a given parasite. Here we will focus on the effect of cryptic diversity in European gammarids host-parasite interactions. Over the years, these freshwater amphipods have become a model for studying cryptic diversity and a high number of cryptic lineages was found for *Gammarus fossarum*, *G. balcanicus* and *G. roeselii* (Müller, 2000; Lagrue *et al.*, 2014; Mamos *et al.*, 2016; Grabowski *et al.*, 2017; Copilaş-Ciocianu *et al.*, 2020; Wattier *et al.*, 2020). Parasite infection and distribution patterns have been studied in light of these highly cryptic divergences, e.g. microsporidia (Quiles *et al.*, 2019, 2020, 2021), or acanthocephalans (Westram *et al.*, 2011; Galipaud *et al.*, 2017). Westram *et al.* (2011), based on a field study in Swiss rivers, showed that two cryptic lineages of *G. fossarum* (*Gf* type A and *Gf* type B, lineages defined by Müller, 2000) can be infected by several species of acanthocephalans, including *Pomphorhynchus tereticollis* and *Polymorphus minutus*, with higher prevalence in *Gf* type B. Galipaud *et al.* (2017) showed in a field survey in Eastern France that infection levels by *P. tereticollis* in *G. roeselii* are lower than in two other *G. pulex/fossarum* lineages, but stronger for *Pomphorhynchus laevis*. They also found highly variable prevalence among *G. fossarum* molecular operational taxonomic units (MOTUs). The *Gf*-III MOTU (defined by Lagrue *et al.*, 2014) showed higher prevalence of *P. tereticollis* than all other MOTUs and *Gf*-II a higher prevalence of *P. laevis*. The *Gf*-VII host MOTU was poorly infected, suggesting resistance to acanthocephalans for this cryptic species.

These field results suggest some degrees of parasite specificity among *G. fossarum* cryptic lineages. However, the variations in prevalence observed between acanthocephalan species in the field may be due to at least three factors: (i) a difference in hosts susceptibility to infection, thus reflecting specificity as commonly accepted (Poulin and Keeney, 2008); (ii) a difference in parasite virulence between different

hosts that can lead to an artificial deficit of some host-parasite combinations in the field and the absence of parasite accumulation in older hosts (Rousset *et al.*, 1996); and (iii) a difference in behavioural manipulation leading to a difference in predation rates. Indeed, acanthocephalan parasites use gammarids as intermediate hosts, and change their host's antipredator behaviour in a way that increases the probability of predation, and thus the parasite's chances of being transmitted to the final host (Moore, 1983; Moore and Gotelli, 1996; Lagrue *et al.*, 2007; Dianne *et al.*, 2011; Jacquin *et al.*, 2014; Fayard *et al.*, 2020). Therefore, as noticed by Poulin & Keeney (2008) and Poulin & Maure (2015), experimental infections alone can allow to fully disentangle the causes of differences in prevalence observed in nature, provided experiments are ecologically relevant. For example, Bauer & Rigaud (2015) showed in a laboratory infection experiment that, while higher prevalence in *P. laevis* are observed in the field, *G. roeselii* is less susceptible to infection by *P. laevis* than *G. fossarum* in experimental conditions. The discrepancy between field and the lab may be due to the lowest behavioural manipulation induced in *G. roeselii* (Bauer *et al.*, 2000), but the mortality induced by the parasite infection (virulence outside predation probability) was not evaluated. Galipaud *et al.* (2017) showed that there was a difference in parasite-induced mortality in the field (inferred indirectly from the absence of parasite accumulation in older hosts, see Rousset *et al.*, 1996), and that this mortality was variable between host species. This suggests that parasites express either differential virulence or differential manipulation, depending on the hosts they infect, but these two causes of mortality cannot be disentangled in a field study.

We investigated here the roles of two of these factors (namely, host susceptibility to infection and parasite virulence) in the interactions within a community of sympatric hosts and parasites. To this end, we experimentally infected several species of gammarids, including the *G. fossarum* cryptic species complex, with two sympatric acanthocephalan parasites, *P. laevis* and *P. tereticollis*. It should be noted that this infestation by *P. tereticollis* is, to our knowledge, the first experimental laboratory infection attempt with this species. Comparisons of the respective successes of experimental infections between the different host lineages exposed to the parasites made it possible to test whether they are differently susceptible to the parasites. Monitoring of survival during the whole parasite ontogeny was also carried out. Several costs may reduce the survival of individuals exposed to infection by acanthocephalans. First, the cost of the penetration of acanthors (early parasite larval stage) into the host digestive wall after ingesting the eggs; second the cost of resistance to infection; or third the cost of harbouring a developing parasite that grows from the acanthor to acanthella to cystacanth stages, multiplying its size by at least a factor of 10. The study of the survival of infected gammarids in the laboratory will allow assessing the virulence of the parasites during their development.

## Methods

### Gammarids sampling

The gammarids were collected at the beginning of January 2020 in the Albane river, between the Belleneuve and Trochères villages (47°21'25.6"N 5°15'53.6"E and 47°20'34.0"N, 5°18'22.3"E, respectively). A batch was also collected in a small tributary stream of the Suzon River (47°24'12.6"N, 4°52'58.2"E). This last population, consisting of c.a. 97% of *G. pulex* (Labaude *et al.*, 2015), has repeatedly been shown to be particularly sensitive to *P. laevis* in laboratory infections (Cornet *et al.*, 2009a; b; Franceschi *et al.*, 2010a; Dianne *et al.*, 2011, 2012, 2014; Bauer and Rigaud, 2015; Labaude *et al.*, 2020). It therefore served as a control for parasite 'quality' in the present experiment (Supplementary figure 1 shows the results for these 'positive controls').

Back to the laboratory, the amphipods were placed at 15±1°C with a 12h/12h light/dark cycle in 37 × 55 × 40 cm tanks filled with water from the field, progressively replaced by 'lab' water used in the experiments. This lab water was made by mixing equal volumes of water from the rivers of origin of the amphipods and adding progressively dechlorinated and sterile tap water (passed on activated carbon filter and a UV ramp). Only male individuals were kept, following Franceschi *et al.* (2008). Naturally parasitized individuals were not used. The amphipods were kept in collective tanks in batches of maximum 500 and fed *ad libitum* with conditioned dead elm leaves. The water was partially renewed regularly. Leaves were conditioned to develop a biofilm of micro-organisms, necessary for the nutrition of the gammarids (Bärlocher and Kendrick, 1975), by soaking autoclaved leaves in aerated lab water (therefore containing the micro-organisms present in the river) for about 7 days before distribution. Animals were thus acclimatized to experimental conditions for three weeks before the infestation procedure. This quarantine gave time for some *P. laevis* natural infections to develop since the amphipods may have ingested acanthocephalan eggs before their capture. However, since *P. tereticollis* grows more slowly than *P. laevis* (a data unknown before this work was undertaken, see results), it turned out that this quarantine was not long enough and some *P. tereticollis* natural infections emerged during our experiment. Fortunately, these natural infections could be detected before the experimental infections, allowing us to distinguish them from experimental ones, and were analysed separately (see results).

### Sampling of parasite eggs and genotyping

Chubs (*Squalius cephalus*), definitive hosts in which *Pomphorhynchus* reproduce, were sampled by electrofishing in the Albane River, at the same stations where amphipods were captured (prefectural authorization of capture no. 162, February 13, 2020). The fish were euthanised in the laboratory with eugenol (Chanseau *et al.*, 2002), dissected, and the female parasites were sampled from the digestive tract

of the hosts. Chubs are preferential hosts for *P. laevis* but can also be infected by *P. tereticollis* (Perrot-Minnot *et al.*, 2019). Since no preferential host of *P. tereticollis* (such as *Barbus barbus*; Perrot-Minnot *et al.*, 2019) was collected during this campaign, the *P. tereticollis* used in this experiment were also collected from the sampled chubs.

The eggs (more precisely, acanthor-stage larvae enclosed in a spindle-shaped envelope, cf. Crompton & Nickol, 1985) were extracted from the parasite body by dissection and stored in 2 ml microtubes filled with lab water. Parasite egg suspensions were checked by microscope. We manually selected, under microscope, batches containing a high density (> 50%) of mature eggs (where developed acanthors were clearly visible) to be genotyped. The bodies of the parasites from which the eggs were obtained were preserved in microtubes containing absolute ethanol for genotyping and species determination by restriction fragment length polymorphism (RFLP). Samples that failed molecular identification were not used for experimentation.

### **Exposure procedure**

For each parasite species, a suspension was prepared by mixing 7 clutches diluted in water so as to obtain a concentration of 80 eggs per microliter, counted under an optical microscope (Nikon E600 x20). Mixing the clutches of several acanthocephalan females overcomes the possible bias towards a more or less infective (or virulent) clutch from a particular female (Franceschi *et al.*, 2010a) and is more representative of what may be encountered by gammarids in the natural environment.

Two infestation sessions were carried out one week apart, one using *P. laevis* parasites, the other with *P. tereticollis*. Gammarids were starved during the 72 hours preceding exposure. The exposure procedure described in Franceschi *et al.* (2008) was then followed. The exposed individuals were placed in pairs in a 60 ml crystallizing dish (in pairs, the gammarids ingest the leaves better than when they are isolated, unpublished data), in the presence of a piece of elm leaf of about 1 cm<sup>2</sup> on which a volume of suspension containing an average of 300 parasite eggs were deposited. This dose, higher than those used in our previous experiments, was a compromise between guaranteeing the success of the infection and avoiding a too high rate of multiple infections (Franceschi *et al.*, 2008), especially in experimental infections involving co-evolved partners (Franceschi *et al.*, 2010b; Bauer and Rigaud, 2015). Pieces of leaves without eggs were distributed to the control batches. After 48 hours, all individuals were placed individually in a crystallizing dish (60 ml) containing lab water and a piece of parasite-free elm leaf. In the *P. laevis* exposure session, 1107 amphipods of unknown genotype were used (1012 exposed individuals, 95 negative controls). All gammarids were genotyped at the end of the experiment. After the removal of *G. pulex* and uncharacterized individuals, the analysis of *P. laevis* infection included 1054 *G. fossarum* (965 exposed and 89 unexposed controls; see Table 1 and Supplementary table 1). Similarly, 1079 individuals were used for

the *P. tereticollis* exposure and 1001 *G. fossarum* were included in the analysis of *P. tereticollis* infection (911 exposed, 90 unexposed controls; Table 1 and Supplementary table 1).

### **Gammarids maintenance and mortality survey**

Throughout the duration of the experiment, the crystallizing dishes were inspected daily, the water topped up and a piece of elm leaf added when the former had been eaten. Dead gammarids were measured (height of the 4th metacoxal pereion plate) and dissected to check their infection status. Dissected tissues were stored in absolute ethanol pending genotyping at the end of the experiment. Daily monitoring made it possible to genotype dead individuals before decay. Every two weeks, one *Chironomus plumosus* larva (Europrix brand frozen fish food cubes) was distributed in each crystallizing dish as a dietary supplement, improving survival in the laboratory (Labaude *et al.*, 2015), and 24 hours later the water was completely replaced.

Based on the *P. laevis* development time observed in our previous experiments (e.g. Franceschi *et al.* (2008); Labaude *et al.*, 2020), the gammarids were inspected under a binocular magnifier from 6 weeks post-exposure (Nikon SMZ 745) to check their parasitic status through the cuticle of their host. Individuals detected as infected were isolated. The growth of the parasites was then inspected twice a week. However, some parasites were visible before these 6 weeks (some of them few days after the beginning of the experiment, a development time much too short to correspond to experimental exposure, see results), corresponding to *P. tereticollis* natural infections (confirmed by genotyping). These animals were analysed separately.

We ended the experiment when no new developing parasites were detected for 15 successive days. The surviving gammarids were euthanized, measured and dissected to confirm their parasitic status. The developmental stage of the parasites was noted for infected individuals. These gammarids, as well as their parasites, were stored individually in absolute ethanol pending genotyping. The parasites at the acanthella stage had to be genotyped to confirm their species (by sequencing, refer to the following paragraph), while the parasites having reached the cystacanth stage were easily recognizable using a binocular magnifier (Perrot-Minnot, 2004).

### **Gammarids & parasites genotyping**

To genotype gammarids still alive at the end of the experiment, between two and four locomotor appendages were detached and placed in a tube filled with ethanol. For individuals who died during the tracking, a larger amount of tissue was used (between one and three body segments) to make up for the

quick degradation of DNA after death. To genotype adult parasites, a piece of about two mm<sup>3</sup> of body tissue was used to extract DNA. For the parasites at the acanthella stage, the whole individual was used.

All DNA extractions were performed using an extraction kit (EZ-10 96 Well Plate Genomic DNA Isolation kit, BioBasic Inc.) following the manufacturer instructions. Elutions were made in 100 µl or 60 µl of elution buffer provided in the kits, for the gammarids and the parasites, respectively.

For both parasites at the acanthella stage and amphipods, the gene encoding the first subunit of cytochrome oxidase (CO1) was amplified using the universal primers LCO1490 and HCO2198 (Folmer *et al.*, 1994). The total reaction volume (20 µL) consisted of 200 nM of each primer, 200 µM of dNTPs, 0.25 U of DNA polymerase (HotStarTaq, Qiagen Inc., Düsseldorf, Germany), 1X of buffer, 5 µL of extracted DNA, and 10,5 µL ultrapure water. The following thermal treatment was applied: activation of the polymerase for 3 min at 95°C, then 39 cycles: denaturation for 20 s at 95°C, hybridization for 45 s at 40°C and synthesis for 1 min at 65°C, then finally 2 min at 65°C (final synthesis). Amplification success was checked by electrophoresis on 2% agarose gel and visualized with ethidium bromide stain. In case of failure of the CO1 amplification for parasites, the ITS region was amplified. The primers BD1f: 5'-GTC GTA ACA AGG TTT CCG TA-3' and ACITS1r: 5'-TTG CGA GCC AAG TGA TTC AC-3' were used (Franceschi *et al.*, 2008). The reaction mixture was subjected to an initial denaturation at 95°C for 3 min, then 39 cycles at 95°C (20 s), 50°C (45 s) and 65°C (45 s). Final elongation was performed for 5 minutes at 65°C.

Adult parasite species were identified by using a RFLP procedure. We first produced our own gene sequences by Sanger sequencing by Genewiz (Leipzig, Germany). The sequences were aligned using Mega software (V10; [www.megasoftware.net](http://www.megasoftware.net)) and compared to reference sequences (see Supplementary table 2). We then used the Sequence Manipulation Suite (SMS) software ([http://www.bioinformatics.org/sms2/rest\\_map.html](http://www.bioinformatics.org/sms2/rest_map.html)) to establish that the restriction enzyme VspI (Thermo Scientific™) enables distinguishing between *P. laevis* (two restriction fragments of 60 and 620 bp) and *P. tereticollis* (two fragments of 450 and 240 bp). 10 U of enzyme were added to 1 µL of associated buffer and 5 µL of PCR product and adjusted with ultrapure water to a reaction volume of 15 µL. The mixture was then placed at 37°C for 16 hours and then at 65°C for 20 minutes to inactivate the enzyme. The migration of 15 µL of RFLP product on a 2% agarose gel (for 20 min at 100 V), then visualization with ethidium bromide made it possible to determine the species of the selected samples. For all parasite acanthellae obtained during the survey, PCR products were sequenced and compared to reference sequences (Supplementary table 2).

CO1 amplicons of most gammarid hosts were sequenced and compared to reference sequences (Supplementary table 1), using pairwise distances corrected by the Kimura two-parameters (K2P) model (see Lagrue *et al.* (2014) and Wattier *et al.* (2020) for details).

For logistic reasons, 108 gammarids were also typed by using a RFLP procedure developed from the analysis of these sequences using Mega and SMS softwares. A first reaction was carried out to distinguish between the *G. fossarum* and *G. pulex* groups: the VspI enzyme (Thermo Scientific™) cuts the DNA of *G. pulex* into two strands of approximately 200 and 450 base pairs. The *G. fossarum* amplicons were then



subjected to a second RFLP with the *DraI* enzyme (Thermo Scientific™), to discriminate between the two groups *Gf* 1-2-3 and *Gf* 6-7 (species groups identified by Lagrue *et al.*, 2014). The PCR products of *Gf* 6 and *Gf* 7 are cut into two strands of approximately 450 and 200 base pairs, while the enzyme does not cut the PCR products of *Gf* 1-2-3. The restriction protocol was the same as detailed before.

All gammarid sequences were submitted to BOLD, in the 'GAMEI' project ([https://v4.boldsystems.org/index.php/MAS\\_Management\\_DataConsole?codes=GAMEI](https://v4.boldsystems.org/index.php/MAS_Management_DataConsole?codes=GAMEI)).

## Statistical analyses

We ran two independent logistic regressions (GLM for binomial distribution with logit transition function) for each infection type (natural and experimental) for the analysis of prevalence according to parasite species (*P. laevis* vs. *P. tereticollis*), host MOTU and their interaction. We did not run a single model with infection type as a factor because experimental infections were made with a subsample of the dataset used to estimate natural infections. Infection intensities were compared between MOTUs by Fisher's exact tests. Parasite surinfections (probability of developing an experimental infection when naturally infected) were compared by using logistic regressions with Firth correction in cases of rare events (Firth, 1993) with the *logistf* package (v1.26.0; Heinze and Schemper, 2002). We considered as 'infected' all the hosts where at least one parasite was detected, regardless of its developmental stage. Parasite development duration to the cystacanth stage was analysed using a GLM (Poisson distribution, Log transition function), with the parasite species, host MOTU, and parasites number as explaining factors, and their interactions.

Host survival was analysed with R using the *survival* package (Therneau and Grambsch, 2000). Data were censored if animal was still alive at the end of the experiments (118 days for the individuals exposed to *P. laevis*, and 138 for those exposed to *P. tereticollis*). Cox models were constructed for comparisons. A preliminary analysis showed that survival data did not respect, over the entire follow-up, the condition of proportionality of hazards (checked with the *cox.zph* function from the *survival* package) necessary for the application of a Cox regression model. Indeed, an acceleration of mortality was visible when the cystacanth stage had been reached (see figures 3 and 4). In addition, during the first weeks of the survey, developing acanthellae were too small to be detected with a binocular magnifier when dissecting dead gammarids, making it impossible to distinguish parasitized individuals from uninfected ones. Because of these two constraints, survival was analysed in two steps. In the first step, we distinguished only two groups: the control individuals vs. those exposed to the infection. This analysis was stopped on the day at which the first experimental acanthella was detected after the dissection of a dead gammarid (44 days for *P. laevis* and 61 days for *P. tereticollis*). In the second step, between the day of the first detection and the end of monitoring, the 'uninfected' and 'parasitized' groups were distinguished among exposed gammarids. For each analysis, the condition of proportionality of risks was successfully controlled. Finally, to compare the

parasites virulence in actually infected gammarids, survival data of infected amphipods were analysed after the first detection date of *P. laevis*. Three factors were included in the Cox models: parasite species, host lineage, and intensity of infection (for which data were categorized as follows: one, two and more than two parasites). All possible models with first order interactions were compared by Akaike information criteria, using the *dredge* function of the *MuMin* R package (v. 1.43.17 ; Bartoń, 2009), and the models minimizing the AICc were presented.

## Results

Apart from *G. roeselii*, which were not taken into account in this experiment (see Bauer and Rigaud, 2015, for their analysis), and too few *G. pulex* to be integrated in the analyses (Supplementary table 2), three *G. fossarum* host lineages have been found in the gammarids of the Albane River. Forty-eight *Gf 7* individuals were detected by sequencing. Since they are genetically very close to the *Gf 6* MOTU and belong to the same breeding group (Lagrue *et al.*, 2014), they were referred as *Gf 6* in the dataset and the following analyses. The genotypes of all hosts were obtained only at the end of the experiments, which explains why it was impossible to restore any imbalances in numbers. The dataset is summarized in Table 1.

**Table 1** - Numbers of *G. fossarum* MOTUs analysed, according to their infection status after experimental exposures. They include individuals with natural infections, indicated in brackets by parasite species (*P. laevis* are in light brown, *P. tereticollis* are in blue, and undetermined in black).

<i>P. laevis</i> exposure						
MOTU	controls		exposed			total
	early death	uninfected	early death	infected	eni	
<i>Gf 2</i>	7 (1+1)	18	33	14 (7)	443 (3+23)	515
<i>Gf 6</i>	12	52	58	9 (1+1)	408	539

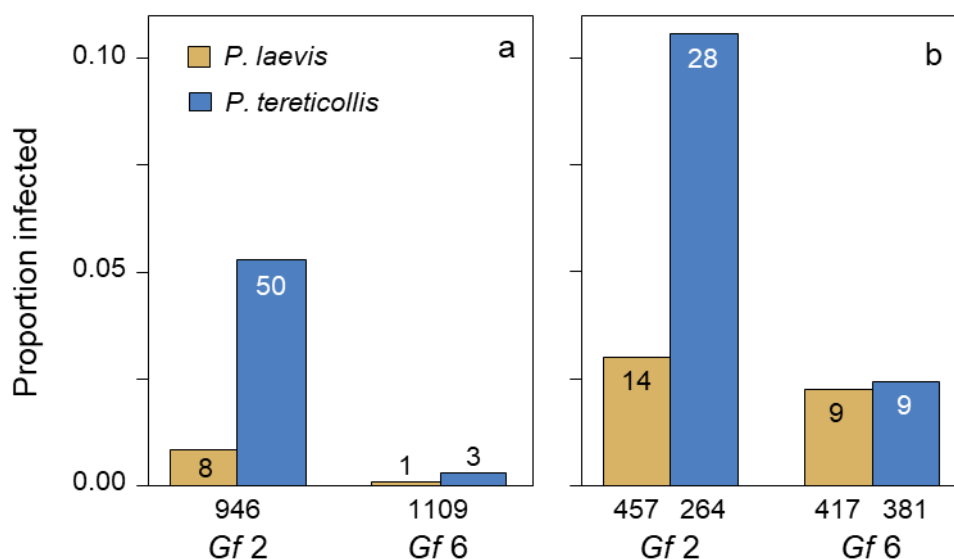
<i>P. tereticollis</i> exposure						
MOTU	controls		exposed			total
	early death	uninfected	early death	infected	eni	
<i>Gf 2</i>	25 (2)	23	119 (1+11+6)	28 (1)	236 (2+6)	431
<i>Gf 6</i>	30 (1)	12	147 (1+2)	9	372	570

*Gf 2* = *G. fossarum* MOTU 2 ; *Gf 6* = *G. fossarum* MOTU 6. *Controls*: gammarids not exposed to parasite eggs. *Exposed*: gammarids experimentally exposed to parasite eggs. *Early death*: gammarids that died before the date of detection of the first acanthella. *Eni (exposed not infected)*: exposed gammarids that did not develop any infection.

## Infection rates

### Natural infections

Some acanthellae were visible 4 days after the exposure date, in both exposed and unexposed animals. Since such a short development time from exposure to acanthella stage is not possible, we inferred that these infections were natural infections for which the quarantine was not long enough for evidencing their development. Most of these infections were *P. tereticollis* parasites (Table 1, Figure 1a). For the two parasite species, the prevalence were higher in *Gf 2* than in *Gf 6*, and the prevalence of *P. tereticollis* was overall higher than the one of *P. laevis* (GLM analysis is in Supplementary table 3).



**Figure 1** - Infections by *P. laevis* and *P. tereticollis* of natural origin (a) and for experimental infections (b) in *G. fossarum* MOTUs from Albane River. Numbers of infected amphipods are indicated at the top of the bars, and total numbers of each MOTU appear below. Early deaths were not considered in (b) since it is not possible to ascertain the success of experimental infection.

### Experimental infections

#### Infection success: prevalence and intensity

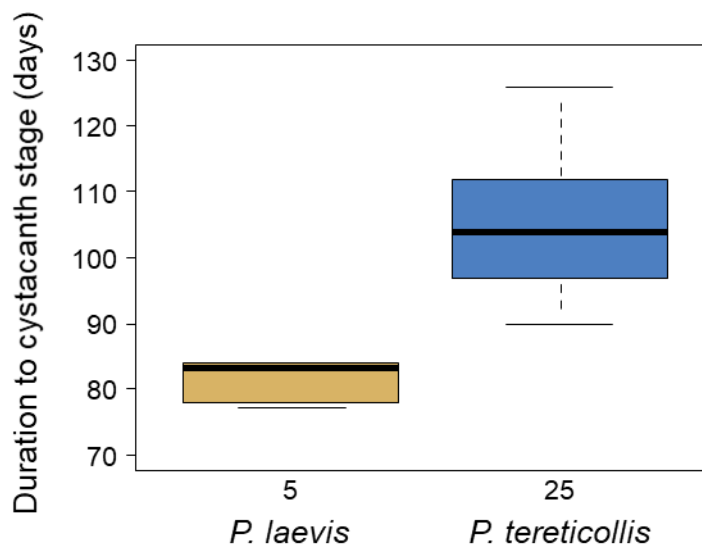
There was no overall significant difference in infection levels between the two gammarid MOTUs, but they were not infected by the two parasites in the same way, as indicated by the significant interaction in the GLM model: *Gf 2* was significantly more sensitive to *P. tereticollis* than *Gf 6*, while the two host MOTUs were equally sensitive to *P. laevis* (GLM analysis in Supplementary table 3).

The average *P. laevis* infection intensity was 2.07 parasites per host in *Gf 2* (half of the individuals were infected by one parasite, and the other half hosted between 2 and 7 parasites). The average infection intensity was 4 parasites per host in *Gf 6* (six were mono-infected, one harbored 3 parasites, but two individuals presented a very high load of 12 and 15 parasites, which skews the distribution). This difference between *Gf 2* and *Gf 6* was not significant (Fisher's exact test,  $p = 0.254$ ). The amphipods were mostly mono-infected by *P. tereticollis* and the maximum load was 3 (the difference in parasite intensity was not significant: Fisher's exact test,  $p = 1$  ; the average intensities being 1.28 for *Gf 2* and 1.22 for *Gf 6*).

### Development duration of parasites

The dissections of gammarids that died during the tracking allowed detecting the first experimental *P. laevis* acanthellae 44 days post-exposure and those of *P. tereticollis* after 61 days. The first *P. laevis* reached the cystacanth stage at 77 days and the first *P. tereticollis* at 90 days.

Interactions between explaining factors were not significant and therefore removed from the model (Supplementary table 4). There was no effect of parasites number on development duration and we neither found a difference between development duration according to host lineage. However, it took significantly less time for *P. laevis* to reach the cystacanth stage (81 days on average) than for *P. tereticollis* (106 days), and the variation between early and late cystacanths differentiation was found to be larger in this latter species (Figure 2).



**Figure 2** - Development duration of parasites in the two species until the cystacanth stage, in days post-exposure. Thick black bars indicate medians, boxes are the upper and lower quartiles, and whiskers represent the upper and lower values. Numbers are sample size. Sample size are lower than in Table 1, because several gammarid hosts died before the cystacanth stage was reached.

## Probability of natural and experimental coinfections

Natural infections by *P. laevis* influenced significantly subsequent experimental infection by *P. laevis* (2.53 % probability of infection when not firstly infected (22/870) and 25.0 % in gammarids already infected (1/4), logistic regression with Firth correction,  $\chi^2 = 4.959$ ,  $p = 0.026$ ) but not those by *P. tereticollis* (5.61 % (36/642) and 2.77 % (1/3) respectively, logistic regression with Firth correction:  $\chi^2 = 3.56$ ,  $p = 0.059$ ), but since numbers were very low for some categories, the relevance of the statistics are questionable.

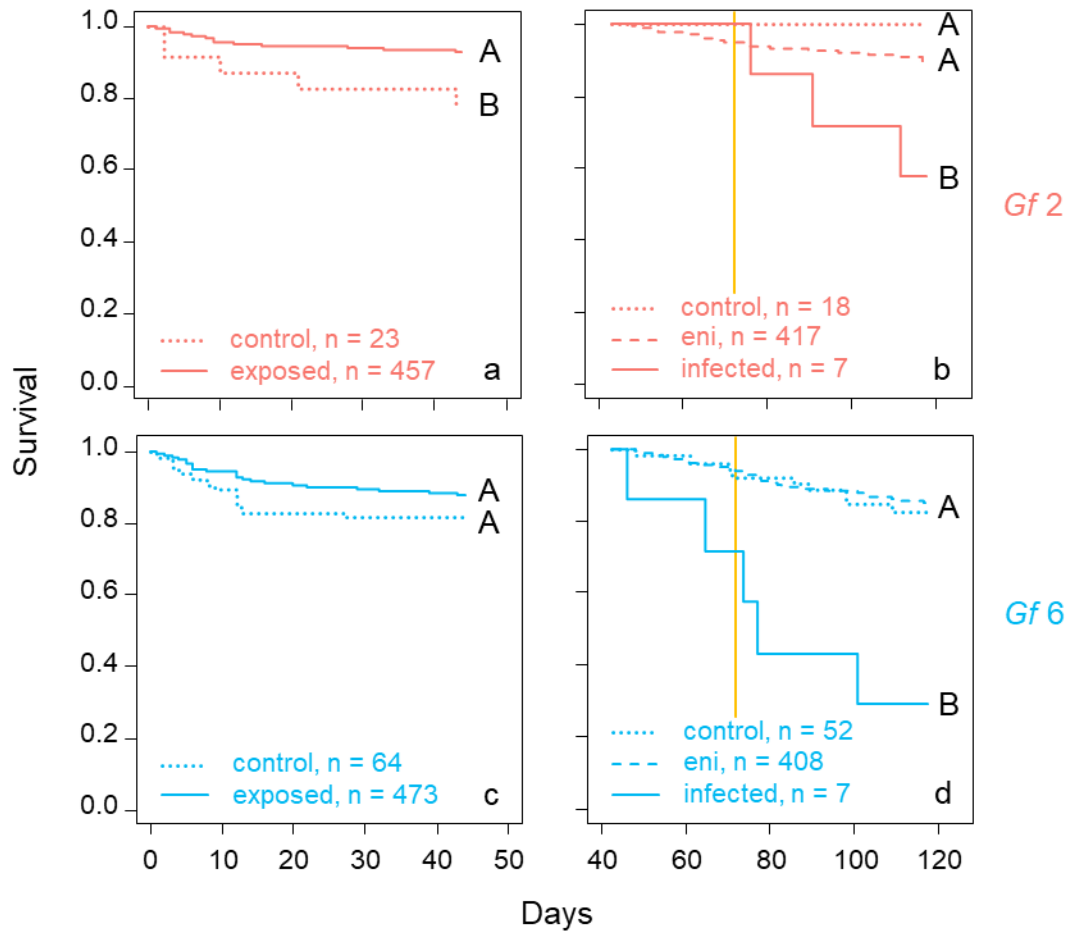
Natural infections by *P. tereticollis* strongly influenced an experimental coinfection by *P. laevis*: while the probability of *P. laevis* lab infection in gammarids not previously infected was 1.78 % (15/843), it reached 25.81 % (8/31) in gammarids already naturally infected by *P. tereticollis* (logistic regression with Firth correction:  $\chi^2 = 28.330$ ,  $p < 0.0001$ ). For lab infections by *P. tereticollis*, the previous effect of *P. tereticollis* natural infection was non-significant (logistic regression with Firth correction:  $\chi^2 = 0.019$ ,  $p = 0.889$ ), the prevalence reaching 5.79% (37/639) in animals uninfected naturally and 0.0 % (0/6) in animals already infected.

## Parasite virulence

### *P. laevis*-exposed individuals

In the first part of the tracking, *Gf 2* gammarids survived slightly better than *Gf 6*, and, overall, exposed individuals survived better than the control gammarids (figure 3a,c; Supplementary table 5). However, when testing only *Gf 6* individuals, the survival of exposed and control individuals was not significantly different ( $\beta = -0.481$ ,  $z = -1.516$ ,  $p = 0.129$ ).

In the second part of the tracking, increased mortality of parasitized individuals appeared as soon as the first acanthellae became detectable by dissection in *Gf 6*, but it occurred later, from the date of differentiation of the first cystacanths, in *Gf 2* (figure 3b,d; Supplementary table 5). The survival of uninfected individuals - 'exposed but not infected (eni)' and 'controls' – was similar. Globally, survival was better in *Gf 2* than in *Gf 6*.

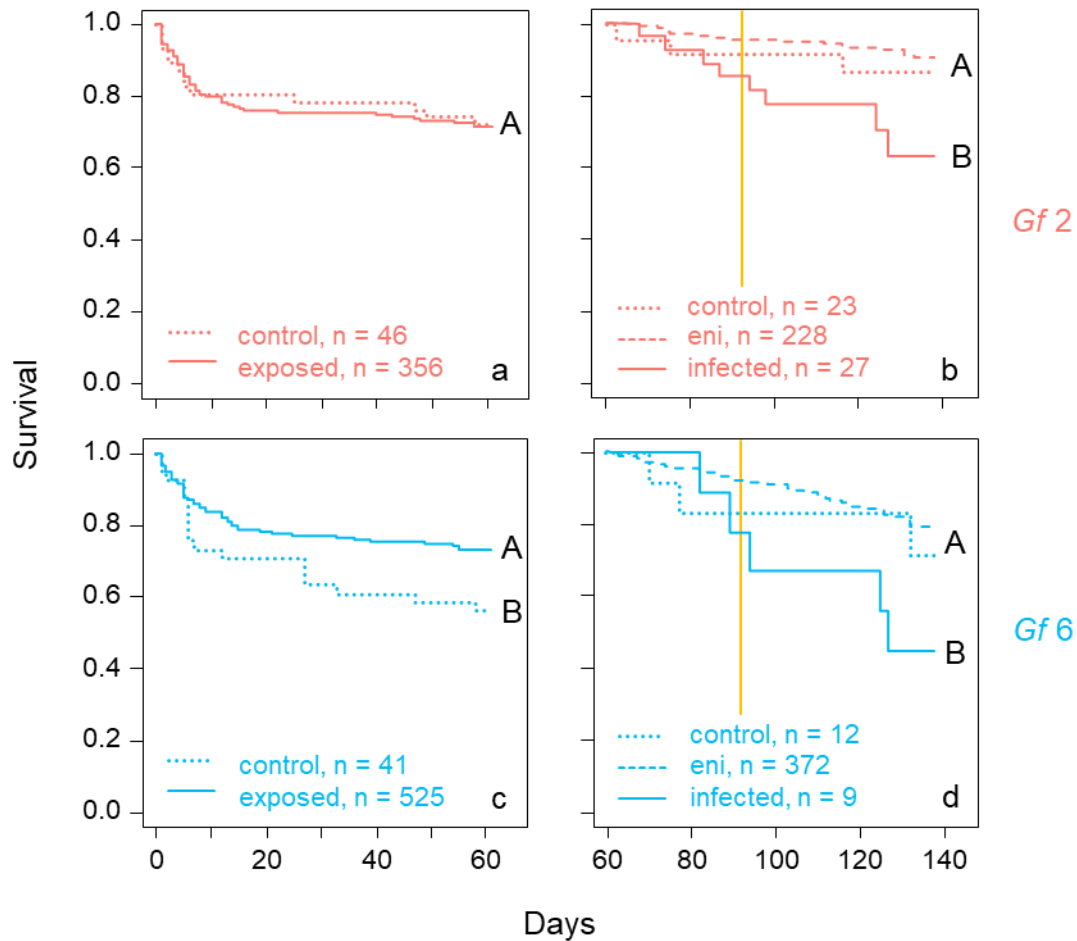


**Figure 3** - Survival of *P. laevis* exposed gammarid MOTUs (plain lines) and controls (dotted lines), before the first acanthella detection date (a,c). Survival of *P. laevis* exposed gammarid MOTUs and controls (dotted lines), after the first acanthella detection date (b,d). Infected individuals (plain lines) can now be distinguished from exposed but not infected ones ('eni', in dashed lines). Letters on the right of the graphs indicate the statistical groups. The vertical orange lines denote the first cystacanth detection date.

#### *P. tereticollis*-exposed individuals

High mortality of gammarids exposed to *P. tereticollis* was observed at the beginning of the survey (compared to *P. laevis* exposed ones), the same trend was observed in both exposed and control gammarids (figure 4a,c; Supplementary table 6). No significant overall difference in survival was observed between *Gf 2* and *Gf 6* MOTUs. However, when testing only *Gf 6* individuals, exposed animals survived better than control ones ( $\beta = -0.575$ ,  $z = -2.296$ ,  $p = 0.022$ ).

In the second part of the follow-up and for both MOTUs, parasitized individuals showed increased mortality compared to uninfected, whether the latter were eni or controls (figure 4b,d; Supplementary table 6).

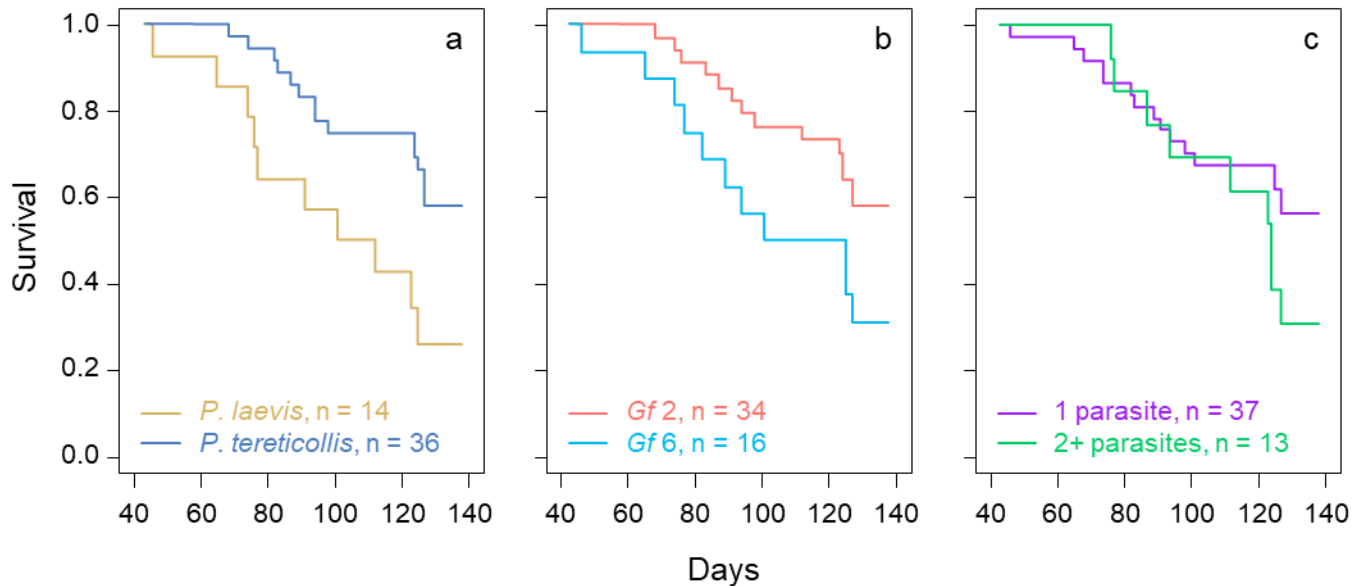


**Figure 4** - Survival of *P. tereticollis* exposed gammarid MOTUs (plain lines) and controls (dotted lines), before the first acanthella detection date (a,b). Survival of *P. tereticollis* exposed gammarid MOTUs and controls (dotted lines), after the first acanthella detection date (c,d). Infected individuals (plain lines) can now be distinguished from exposed but not infected ones ('eni', in dashed lines). Letters on the right of the graphs indicate the statistical groups. The vertical orange lines denote the first cystacanth detection date.

#### *Survival in infected gammarids*

Survival analysis in infected gammarids began on the day acanthellae became visible. Interactions were not significant and therefore removed from the model (see Supplementary table 7 for the detailed comparison of possible models). We found only a significant effect of parasite species (whole model:  $\chi^2 = 10.69$ , 3 df,  $p = 0.01$ ; Supplementary table 8). Globally, *P. laevis*-infected gammarids died nearly twice

faster than those infected by *P. tereticollis* (Figure 5a). The observed difference in survival between infected *Gf 2* and *Gf 6* (whatever the parasite species, Figure 5b) was not significant, nor the number of hosted parasites (Figure 5c).



**Figure 5** - Comparison of survival of infected gammarids after the first *P. laevis* acanthella detection date: a) effect of parasite species; b) effect of host MOTU; c) effect of the intensity of infection.

## Discussion

### Susceptibility to infections by different parasite species in different host lineages

We investigated by experimental infections two important factors explaining natural patterns of acanthocephalan infections in the wild: infection success and virulence. Behavioural manipulation is a third important factor, because subsequent predation by definitive hosts lowers the overall cystacanth prevalence observed on the field. Unfortunately, we could not investigate this latter aspect of the host-parasite interaction in this study because of the globally low success of infection. It will be necessary to further evaluate differences in manipulation among cryptic hosts to get a more complete picture of the link between host genotype and efficient exploitation by *Pomphorhynchus* spp. acanthocephalans.

To our knowledge, this work presents the first results of an experimental infestation of *Gammarus* spp. with *P. tereticollis*. The experimental infestations with *P. tereticollis* led to a relatively high infection rate in



*Gf 2* and to a lesser extent in *Gf 6*. High prevalence of *P. tereticollis* in *G. fossarum* has been already found in previous field works (Westram *et al.*, 2011; Galipaud *et al.*, 2017; Harris, 2020). Our finding that *Gf 2* is more sensitive to infection than *Gf 6* sharply contrasts with field data from Galipaud *et al.* (2017) in which the prevalence in *P. tereticollis* was found to be similar between these MOTUs.

This study also confirms, under controlled conditions, that all *G. fossarum* MOTUs present in the Albane River can be infected by *P. laevis*. The experimental infection success by *P. laevis* was similar in *Gf 2* and *Gf 6*, and was significantly lower than that by *P. tereticollis* in *Gf 2*. This suggests a lower susceptibility to *P. laevis* of this latter host MOTU. Alternatively, despite our precautions to standardize the infections, we cannot completely rule out another phenomenon. Indeed, even if we controlled the dose of parasite eggs provided to the gammarids, it was not possible to control the number of eggs that were actually consumed.

Our results nevertheless highlight the need for subjecting each of the MOTUs of the *G. pulex / fossarum* complex species to experimental infections to understand their relative sensitivity to the different species of acanthocephalans, as suggested by Poulin and Maure (2015).

Despite low numbers that limited statistical analyses, it is worth noting that experimental infections also suggest that *G. pulex* from Albane River were particularly sensitive to *P. laevis* compared to *Gf 2* and *Gf 6*, but not to *P. tereticollis* (Supplementary table 1 and Supplementary Figure 2). The *G. pulex* of the Suzon population also showed the same pattern (Supplementary figure 1), confirming the field observations of Harris (2020). Because they appear to be contradicting observations by Galipaud *et al.* (2017), who found low *in natura* prevalence of *P. laevis* cystacanths in *G. pulex*, our results need experimental confirmation with a larger number of individuals. However, as showed by Bauer & Rigaud (2015), a low prevalence of cystacanths found after direct collection in nature could simply mean that either parasite virulence is high, or that the parasite increased so much the predation rate of its host that parasitized individuals disappear rapidly from populations. Here, our measures of prevalence were made after quarantine or after experimental infection, i.e. in conditions where predation was absent or the survival controlled, highlighting the usefulness of experimental infections in deciphering host-parasite relationships (Poulin and Maure, 2015). This is particularly true for acanthocephalans, where the prevalence *in natura* reflects a combination of several processes due to the long intra-host development time (Bauer and Rigaud, 2015). One of these processes is parasite virulence that we will discuss thereafter.

### **Natural and experimental coinfections**

Natural infection by *P. tereticollis* favours a further interspecific experimental infection by *P. laevis*. Contrastingly, natural infection by *P. tereticollis* did not influence intraspecific experimental superinfections by *P. tereticollis*, and natural infection by *P. laevis* did not influence either a secondary infection by another acanthocephalan. However, sample size were sometimes so low that the statistical

power of these latter analyses are questionable. Cornet *et al.* (2009) showed that the level of immune defences of *G. pulex* is strongly depressed by the acanthocephalans *P. laevis* and *P. tereticollis*, and that acanthocephalan infection favors superinfection by *Escherichia coli* bacteria. However, Dianne *et al.* (2010), using successive experimental infections by *P. laevis*, did not observe any increase of acanthocephalan intraspecific superinfection. It is therefore possible that the immune depression only favours interspecific parasite/pathogens superinfections but not intraspecific ones, suggesting that this immune depression is a costly by-product of the acanthocephalan infections. Since multiple infections are the rule in nature, further experimental investigations are welcome, particularly for the study of the evolution of virulence (Alizon *et al.*, 2013).

### **Development duration of parasites**

Acanthocephalans development time in their intermediate hosts is strongly influenced by the environment (Awachie, 1966; Lackie, 1972; Tokeson and Holmes, 1982; Bratney, 1986; Labaude *et al.*, 2020), highlighting the necessity of studying this life-history trait under controlled conditions. The development duration of *Polymorphus minutus* and *P. laevis* under laboratory conditions have already been studied (Hynes and Nicholas, 1957; Butterworth, 1969; Franceschi *et al.*, 2008; Labaude *et al.*, 2015, 2020), but *P. tereticollis* development was not documented before this study. The development time in *P. laevis* observed here was similar to the one found by Labaude *et al.* (2020) at a similar temperature. The development of *P. tereticollis* took 23 % longer than *P. laevis* under the same conditions. The among-host variation in maturation time (time between the appearance of the first and the last cystacanths) was also larger and more variable than that of *P. laevis*. This longer development time explains *a posteriori* why we observed so many natural *P. tereticollis* infections after the quarantine we imposed to gammarids, since the quarantine time was estimated from our previous experience on *P. laevis* development.

### **Virulence**

We first observed higher mortality in the *P. tereticollis* exposure experiment, at the beginning of the survey, compared to the *P. laevis* exposure. Since this pattern was found both in exposed and control unexposed gammarids, the higher mortality was not linked to parasite eggs exposure. It is therefore likely that conditions of the *P. tereticollis* experiment were more stressful than those of the *P. laevis* experiment, even if it was made in the very same room only a few days later.

Ingestion of parasites (both *P. laevis* and *P. tereticollis*) and the early beginning of larval development did not negatively affect the host survival. Therefore, the wounds inflicted when the acanthors pierce the digestive tract of the arthropod to pass into the general cavity, and/or a possible early resistance to

infection (cellular response, humoral and immune encapsulation (Crompton and Nickol, 1985) were not costly enough to increase mortality. The literature is contradictory about the host survival in early stages of infection by acanthocephalans. Increased mortality shortly after acanthocephalan experimental exposure was observed by Crompton & Nickol (1985) and Hynes & Nicholas (1957), but these studies were most likely carried out with massive doses of eggs. Although the dose used in these works is not mentioned, the high prevalence reported and the known dose-dependant prevalence relation (Franceschi *et al.*, 2008), the high dose exposure hypothesis is reasonable to consider. In such cases, the damages inflicted by many acanthors crossing the digestive tract wall may have been deleterious. On the other hand, Uznanski & Nickol (1980) did not find any increased mortality in the first 24 hours post-exposure in *Hyaella azteca* exposed to *Leptorhynchoides thecatus*. Yet, here again, the high infection success suggested the usage of high doses of eggs. Even more intriguing, experimental infections of *Asellus* by *Acanthocephalus lucii* studied by Bratley (1986) and Benesh & Valtonen (2007) induced early increased mortalities, whereas Hasu *et al.* (2006) found a better survival of infected individuals on the same biological models. This latter and somewhat intriguing result is what we observed in the present study: gammarids exposed to parasite eggs showed improved survival in the early days post-exposure, i.e. before the infection can be detected. Only speculative discussions on these observations can be proposed because it was not possible to ensure whether individuals dying early in the survey had been infected or not. At least, we can exclude a selective mortality due to exposure. One of the possible explanations is that the observed improved survival of exposed gammarids could be part of 'parasite manipulation', where the parasite would protect its host from predation, before becoming infective to the next host (Parker *et al.*, 2009). Such a 'protection' was described for *P. laevis* in the late acanthella stage (Dianne *et al.*, 2011; Rigaud *et al.*, 2023), but this was a protection against mortality due to predation, which is not the case here. A mechanistic explanation of such a phenomenon could be that the early stages of the parasite divert some of the host energy in such a way as to improve the host survival. Castrating parasites are known to divert energy normally allocated to host reproduction to their own purpose, in particular for the survival of the host they infect (Benesh and Valtonen, 2007). Gammarid acanthocephalans are known to castrate their hosts, partially (Bollache *et al.*, 2002) or totally (Bollache *et al.*, 2002; Bailly *et al.*, 2018). It is not known precisely at what stage of parasite growth castration occurs in *Pomphorhynchus*, but it happens early during *Polymorphus* ontogeny, at least before the acanthellae are visible in their host (Bailly *et al.*, 2018). Alternatively, egg parasites eaten by gammarids, but unable to develop, can themselves become a form of diet supplementation for the hosts that 'prey' on them (Goedknegt *et al.*, 2012), improving host survival. Finally, perhaps the presence of eggs in the water triggers protective mechanisms (e.g., heat shock proteins, mechanisms against oxidative stress) that help the host sustain stress in the lab.

Parasite virulence was expressed in our study when the acanthellae enter their exponential phase of growth. It is interesting to note that *Gf 6* was more sensitive to *Pomphorhynchus* infections than *Gf 2*, whatever the parasite species. In *Hyaella azteca* infected by *Corynosoma constrictum*, a higher mortality

was observed at the time of rapid development of the parasite larvae, only in heavily infected hosts (Duclos *et al.*, 2006). This increased mortality associated with acanthocephalan infections is interpreted as being due to displacement of the host's organs (Bentley and Hurd, 1993; Dezfuli *et al.*, 2008), or effects on metabolism (Rumpus and Kennedy, 1974). In our study, the energy requirements of the two parasites are probably different, since *P. tereticollis* larvae are larger than *P. laevis* (Perrot-Minnot, 2004). However, the virulence of *P. laevis* was higher than that of *P. tereticollis*. An effect on metabolism would therefore only be possible if one considers that *P. laevis* grows faster than *P. tereticollis*, which could exhaust the host's metabolism at higher intensity. If so, this would be in line with the 'boom-bust' and 'slow and steady' strategies proposed by Le Clec'h *et al.* (2019) for schistosome infections. Studies looking at metabolism of infected gammarids have only been carried out with parasites at cystacanth stages (Plaistow *et al.*, 2001; Gismondi *et al.*, 2012; Korkofigas *et al.*, 2016). All these studies showed that parasitized amphipods are deprived of lipid and protein reserves, while they have higher glycogen rates. This shows high demand for immediate energy (glycogen) in infected amphipods, which are forced to draw on their reserves (lipids), probably at the benefit of the parasite metabolism. Such a strategy is common in parasites. In schistosomes, such effects on the host fitness and energy diversion occur both early and in the late development of the parasite (De Jong-Brink *et al.*, 2001). In *Plasmodium*, the intra-host competition in cases of multiple infections is leading to increased energetic demand due to host overexploitation by the faster-developing parasites (De Roode *et al.*, 2005). Differences in survival between *Gf 2* and *Gf 6* hosts may be due to differences in metabolism, a hypothesis that necessitate further investigations. Another possible explanation for a differential in survival between host lineages could be differences in the ability of acanthocephalans to reduce the intensity of the immune responses of their hosts (Cornet *et al.*, 2009a). On the one hand, this partial immunosuppression might be advantageous for the host, owing the cost of mounting an immune response, either in terms of physiology (Moret and Schmid-Hempel, 2000) or because of immune cytotoxicity of enzymes used for the invertebrate immune responses (Sadd and Siva-Jothy, 2006). On the other hand, as discussed before, this immunosuppression can make hosts more susceptible to other infections, such as bacterial infections (Cornet *et al.*, 2009a; Cornet and Sorci, 2010). This immune modification is not observed in all gammarids: infections of various populations of *G. roeselii* by *P. laevis* do not show immunosuppression, with some populations even showing an immune response to the infection (Moret *et al.*, 2007). In addition, the level of immune defenses are variable among gammarid populations (Cornet *et al.*, 2009b). Therefore, *Gf 2* and *Gf 6* could be immunosuppressed differently, a hypothesis that remains to be tested.

Whatever the underlying mechanism, the greater sensitivity of *Gf 6* to acanthocephalans could explain, at least in part, why the prevalences were lower in nature in this MOTU than in *Gf 2*, compared to experimental infections.

## General conclusion

Our results complement those of a previous study on Acanthocephala, carried out *in natura* by counting infections by cystacanths (Galipaud et al., 2017). Different host genotypes within the *G. fossarum* species complex, experimentally exposed to parasites, are significantly different in their susceptibility to *P. tereticollis*, but not to *P. laevis*. These results explain the overall differences in prevalence in the field. Our data therefore indicate that we can no longer ignore cryptic hosts' genetic information to determine the level of specialization of the parasites. In addition to differences in susceptibility to infection, we also showed that a strong virulence is expressed when *P. laevis* or *P. tereticollis* reached the cystacanth stage, but that the different genotypes of *G. fossarum* were not affected with the same intensity, bringing refinement to explain the pattern of prevalence observed in the field.

## Appendices

### Supplementary table 1 – numbers of all gammarid MOTUs and not genotyped individuals sampled

Numbers of gammarids sampled in the Albane River, according to their infection status, including individuals with natural infections in brackets (by parasite species: *P. laevis* in light brown, *P. tereticollis* in blue, and undetermined in black ; & for a mixed *P. laevis* and *P. tereticollis* infection). Undetermined gammarids could not be genotyped.

<i>P. laevis</i> exposure						
MOTU	controls		exposed			total
	early death	uninfected	early death	infected	eni	
<i>Gf</i> 2	7 (1+1)	18	33	14 (7)	443 (3+23)	515
<i>Gf</i> 6	12	52	58	9 (1+1)	408	539
<i>Gp</i> D	1	0	1	2	6	10
undetermined	1	4	4	0	34	43

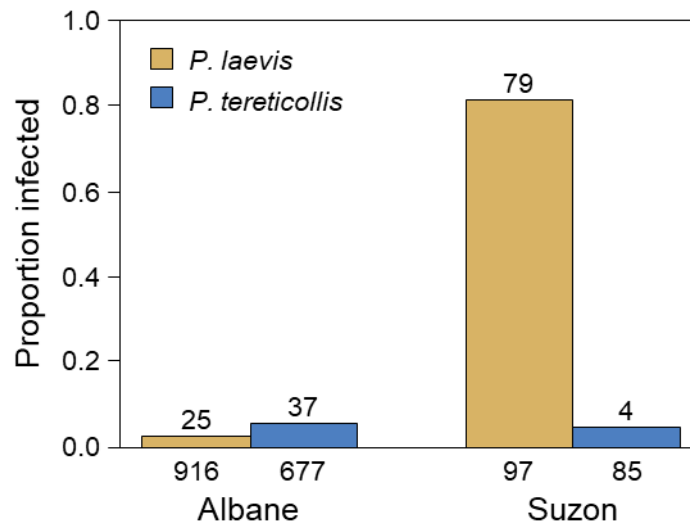
<i>P. tereticollis</i> exposure						
MOTU	controls		exposed			total
	early death	uninfected	early death	infected	eni	
<i>Gf</i> 2	25 (2)	23	119 (1+11+6)	28 (1)	236 (2+6)	431
<i>Gf</i> 6	30 (1)	12	147 (1+2)	9	372	570
<i>Gp</i> D	0	0	19	0	10	29
undetermined	3	2 (1)	22 (1&1+1)	0	22 (1)	49

### Supplementary table 2

Accession numbers of the reference sequences used to assign the gammarid MOTUs and the parasite species

Gammarids		Parasites	
MOTU	GenBank	species	GenBank
<i>G. fossarum</i> 1	MT411346.1	<i>P. minutus</i> CO1	EF467865.1
<i>G. fossarum</i> 2	MT978910.1	<i>P. minutus</i> ITS	JF803287.1
<i>G. fossarum</i> 3	MT411291.1	<i>P. minutus</i> ITS	AY532067.1
<i>G. fossarum</i> 4	MT411024.1	<i>P. laevis</i> CO1	EF051071.1
<i>G. fossarum</i> 5	MT411035.1	<i>P. laevis</i> ITS	AY135417.1
<i>G. fossarum</i> 6	MT980277.1	<i>P. laevis</i> ITS	AY135415.1
<i>G. fossarum</i> 7	MT411467.1	<i>P. tereticollis</i> CO1	AY423351.1
<i>G. pulex</i> A	Wattier, pers. com.	<i>P. tereticollis</i> ITS	KY075817.1
<i>G. pulex</i> B	Wattier, pers. com.	<i>P. tereticollis</i> ITS	LN995058.1
<i>G. pulex</i> C	Wattier, pers. com.		
<i>G. pulex</i> D	Wattier, pers. com.		

### Supplementary figure 1 - Control of the infectivity of parasites using gammarids from Val Suzon



Success of laboratory infections by *P. laevis* and *P. tereticollis*, in gammarids (all MOTUs together) coming from the two rivers Albane and Suzon. Numbers of infected gammarids are given above the bars, and total sample sizes from each river below the bars.

Even if the success of infection by *P. laevis* was low for gammarids from Albane (all MOTUs combined), the high prevalence found in gammarids from the Suzon River showed that the parasites had actually potential for infection. In Suzon gammarids, a high *P. laevis* load was also observed, with an average load of 4.5 parasites per infected hosts (up to 15 parasites in a single individual).

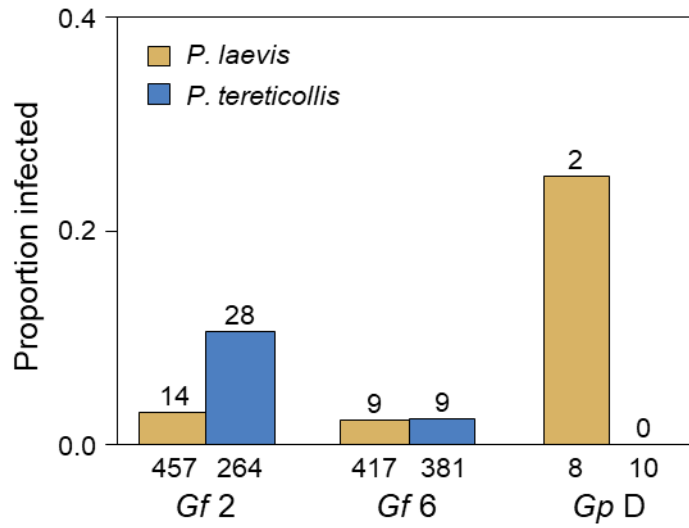
Only 4 individuals from Suzon developed a *P. tereticollis* infection (two with a single parasite and the other with three). The prevalence of *P. tereticollis* was similar among gammarids from the two rivers ( $\chi^2 = 0.001$ , 1 df,  $p = 0.970$ ).

### Supplementary table 3 - Analysis of parasite prevalence

Results of the GLM analysing the prevalence of natural prevalence and the infection success of parasites after experimental exposure, as a function of gammarid MOTUs, parasite species and their interactions.

	Source	estimate	± s.e.	z	df	p
Natural prevalence	MOTU: <i>Gf 2</i> vs. <i>Gf 6</i>	-2.251	1.061	-2.120	1	0.034
	Parasite species: <i>P. laevis</i> vs <i>P. tereticollis</i>	1.879	0.384	4.897	1	<0.001
	Interaction MOTU × parasite species	-0.778	1.217	-0.639	1	0.523
Infection success	MOTU: <i>Gf 2</i> vs. <i>Gf 6</i>	-0.36	0.433	-0.831	1	0.406
	Parasite species: <i>P. laevis</i> vs <i>P. tereticollis</i>	1.323	0.337	3.924	1	<0.001
	Interaction MOTU × parasite species	-1.230	0.584	-2.107	1	0.035

**Supplementary figure 2 - Success of experimental infections in *Gp* D**



Success of experimental infections by the two parasite species according to the host lineages present in the Albane River. Numbers of infected gammarids are given above the bars, and total sample sizes for each MOTU are below the bars.

Despite the low sample size, *Gp* D was found significantly more susceptible than both *G. fossarum* lineages to infection by *P. laevis* (Fisher's exact test between *Gf* 2 and *Gp* D:  $p = 0.028$ ; *Gf* 6 and *Gp* D:  $p = 0.016$ ), whereas no experimental infection by *P. tereticollis* was detected.

**Supplementary table 4 – Parasite development duration to the cystacanth stage**

Results of the GLM analysing the development duration of parasites as a function of parasite species, gammarid MOTUs and number of hosted parasites. The interaction between factors were not significant and removed from the model.

Source	estimate	± s.e.	z	df	p
Parasite species: <i>P. laevis</i> vs. <i>P. tereticollis</i>	0.253	0.057	4.462	1	<0.001
MOTU: <i>Gf</i> 2 vs. <i>Gf</i> 6	-0.036	0.046	-0.779	1	0.436
Parasite number: 1 vs. 2	-0.038	0.051	-0.734	1	0.463



### Supplementary table 5 - Statistics of the survival analysis for gammarids exposed to *P. laevis*

Results of the Cox models analysing the survival of gammarids exposed to *P. laevis* as a function of gammarid lineages and parasite treatment, divided according to the parasite development stage (before the first acanthella detection date [1st part] and after this date [2nd part]). The interaction between factors was not significant, and was removed from the model. Global risks proportionality:  $\chi^2 = 0.821$ , 2 df,  $p = 0.66$  for the first part;  $\chi^2 = 1.558$ , 3 df,  $p = 0.67$  for the second part.

Development stage	Comparison	$\beta$	odd ratio	$\pm$ s.e.	z	df	p
1st part	MOTU: <i>Gf</i> 2 vs. <i>Gf</i> 6	0.463	1.589	0.204	2.273	1	0.023
	Treatment: exposed vs. control	-0.655	0.519	0.267	-2.453	1	0.014
2nd part	MOTU: <i>Gf</i> 2 vs. <i>Gf</i> 6	0.528	1.695	0.184	2.869	1	0.004
	Treatment: global						<0.001
	- control vs. 'eni'	0.103	1.108	0.349	0.294	1	0.768
	- control vs. infected	-1.912	0.148	0.489	-3.906	1	<0.001
	- 'eni' vs. infected	-1.809	0.164	0.368	-4.917	1	<0.001

### Supplementary table 6 - Statistics of the survival analysis for gammarids exposed to *P. tereticollis*

Results of the Cox model analysing the survival of gammarids exposed to *P. tereticollis* as a function of gammarid MOTUs and parasite treatment, divided according to the parasite development stage (before the first acanthella detection date [1st part] and after this date [2nd part]). The interaction between factors was not significant, and was removed from the model. Global risks proportionality:  $\chi^2 = 4.47$ , 2 df,  $p = 0.107$  for the first part;  $\chi^2 = 1.717$ , 3 df,  $p = 0.63$  for the second part.

Development stage	Comparison	$\beta$	odd ratio	$\pm$ s.e.	z	df	p
1st part	MOTU: <i>Gf</i> 2 vs. <i>Gf</i> 6	-0.017	0.983	0.123	-0.138	1	0.809
	Treatment: exposed vs. control	-0.297	0.743	0.192	-1.552	1	0.121
2nd part	MOTU: <i>Gf</i> 2 vs. <i>Gf</i> 6	0.777	2.175	0.209	3.712	1	<0.001
	Treatment: global						<0.001
	- control vs. 'eni'	-0.383	0.682	0.424	-0.904	1	0.366
	- control vs. infected	0.982	2.669	0.484	2.029	1	0.042
	- 'eni' vs. infected	-1.365	0.255	0.288	-4.738	1	<0.001

### Supplementary table 7 - Model selection table for the survival analysis of infected gammarids

Model selection table for the survival analysis of infected gammarids (*MuMin* R package). Factors compared : intensity of infection (nb), host MOTU (motu), parasite species (para) and their first order interactions.

Factors						Analysis parameters					
nb	motu	para	nb × motu	nb × para	motu × para	adj R <sup>2</sup>	df	logLik	AICc	delta	weight
+	+	+				0.348	3	-84.9	179.9	0.00	0.163
	+	+				0.267	2	-86.3	177.2	0.31	0.140
		+				0.194	1	-87.5	177.2	0.33	0.139
+		+				0.256	2	-86.5	177.5	0.69	0.116
+	+	+		+		0.367	4	-84.5	179.0	2.13	0.056
+	+					0.212	2	-87.2	179.0	2.15	0.056
	+					0.131	1	-88.4	179.1	2.43	0.049
+	+	+			+	0.359	4	-86.2	179.6	2.71	0.042
	+	+			+	0.273	3	-84.8	179.7	2.80	0.040
+	+	+	+			0.349	4	-84.8	179.7	2.80	0.040
+		+		+		0.265	3	-86.4	179.8	3.00	0.036
						0.000	0	-90.2	180.4	3.54	0.028
+						0.067	1	-89.3	180.8	3.99	0.022
+	+	+		+	+	0.389	5	-84.0	181.2	4.39	0.018
+	+		+			0.212	3	-87.2	181.6	4.74	0.015
+	+	+	+	+		0.368	5	-84.5	181.1	5.23	0.012
+	+	+	+		+	0.362	5	-84.6	182.3	5.48	0.011
+	+	+	+	+	+	0.390	6	-84.0	184.7	7.87	0.003

### Supplementary table 8 - Statistics of the survival analysis for infected gammarids

Results of the Cox model analysing the survival of infected gammarids as a function of parasite species, gammarid MOTUs and intensity of infection, after the first *P. laevis acanthella* detection date. The interaction between factors were not significant and removed from the model. Global risks proportionality:  $\chi^2 = 3.085$ , 3 df,  $p = 0.38$ .

Source	$\beta$	odd ratio	$\pm$ s.e.	z	df	p
Parasite species	-0.958	0.384	0.422	-2.268	1	0.023
MOTU: <i>Gf</i> 2 vs. <i>Gf</i> 6	0.773	2.166	0.416	1.856	1	0.063
Parasite number: 1, $\geq$ 2	0.767	2.125	0.433	1.769	1	0.077

## **Authors contributions**

A.B. and T.R. conceived and planned the experiments. A.B., L.D., S.M., M.T., N.D. and T.R. carried out the experiments. A.B., N.D. and M.T. contributed to sample preparation. A.B. analyzed the data. A.B. and T.R. contributed to the interpretation of the results. A.B. took the lead in writing the manuscript. All authors provided critical feedback and helped shape the research, analysis and manuscript.

## **Acknowledgements**

We thank Jean-Emmanuel Rollin for field sampling and Jean-Sébastien Bolduc for proofreading.

Preprint version 2 of this article has been peer-reviewed and recommended by Peer Community In Infections (<https://doi.org/10.24072/pci.infections.100198>; Grabner, 2024).

## **Data, scripts, code, and supplementary information availability**

The dataset (in French) and data description file explaining the variables are available on the data.InDoRES repository: <https://data.indores.fr/dataset.xhtml?persistentId=doi:10.48579/PRO/X9ZRVB>.

## **Conflict of interest disclosure**

The authors declare that they comply with the PCI rule of having no financial conflicts of interest in relation to the content of the article. TR is recommender for PCI infections.

## **Funding**

This study was funded by the French Agence Nationale de la Recherche (ANR), ANR-13-BSV7-0004-01

## References

- Alizon, S., de Roode, J. C. and Michalakis, Y.** (2013). Multiple infections and the evolution of virulence. *Ecology Letters* **16**, 556–567. doi: 10.1111/ele.12076.
- Awachie, J. B. E.** (1966). The development and life history of *Echinorhynchus truttae* Schrank, 1788 (Acanthocephala). *Journal of Helminthology* **40**, 11–32. doi: 10.1017/S0022149X00034040.
- Bailly, Y., Cézilly, F. and Rigaud, T.** (2018). Stage-dependent behavioural changes but early castration induced by the acanthocephalan parasite *Polymorphus minutus* in its *Gammarus pulex* intermediate host. *Parasitology* **145**, 260–268. doi: 10.1017/S0031182017001457.
- Bärlocher, F. and Kendrick, B.** (1975). Assimilation efficiency of *Gammarus pseudolimnaeus* (Amphipoda) feeding on fungal mycelium or autumn-shed leaves. *Oikos* **26**, 55. doi: 10.2307/3543277.
- Bartoń, K.** (2009). MuMIn: multi-model inference. R package version 1. 0. 0. <http://r-forge.r-project.org/projects/mumin/>.
- Bauer, A. and Rigaud, T.** (2015). Identifying a key host in an acanthocephalan-amphipod system. *Parasitology* **142**, 1588–1594. doi: 10.1017/S0031182015001067.
- Bauer, A., Trouvé, S., Grégoire, A., Bollache, L. and Cézilly, F.** (2000). Differential influence of *Pomphorhynchus laevis* (Acanthocephala) on the behaviour of native and invader gammarid species. *International journal for parasitology* **30**, 1453–1457.
- Benesh, D. P. and Valtonen, E. T.** (2007). Proximate factors affecting the larval life history of *Acanthocephalus lucii* (Acanthocephala). *Journal of Parasitology* **93**, 742–749. doi: 10.1645/GE-1094R.1.
- Bentley, C. R. and Hurd, H.** (1993). *Pomphorhynchus laevis* (Acanthocephala): elevation of haemolymph protein concentrations in the intermediate host, *Gammarus pulex* (Crustacea: Amphipoda). *Parasitology* **107**, 193–198.
- Bollache, L., Rigaud, T. and Cézilly, F.** (2002). Effects of two acanthocephalan parasites on the fecundity and pairing status of female *Gammarus pulex* (Crustacea: Amphipoda). *Journal of Invertebrate Pathology* **79**, 102–110. doi: 10.1016/S0022-2011(02)00027-7.
- Bratley, J.** (1986). Life history and population biology of larval *Acanthocephalus lucii* (Acanthocephala: Echinorhynchidae) in the isopod *Asellus aquaticus*. *The Journal of Parasitology* **72**, 633–645.
- Butterworth, P. E.** (1969). The development of the body wall of *Polymorphus minutus* (Acanthocephala) in its intermediate host *Gammarus pulex*. *Parasitology* **59**, 373–388. doi: 10.1017/S0031182000082342.
- Carrau, T., Martínez-Carrasco, C., Garijo, M. M., Alonso, F., Vizcaíno, L. L., Herrera-Russert, J., Tizzani, P. and Ybáñez, R. R. de** (2021). Epidemiological approach to nematode polyparasitism occurring in a sympatric wild ruminant multi-host scenario. *Journal of Helminthology* **95**, e29. doi: 10.1017/S0022149X21000183.

- Chanseau, M., Bosc, S., Galiay, E. and Oules, G.** (2002). L'utilisation de l'huile de clou de girofle comme anesthésique pour les smolts de saumon atlantique (*Salmo salar* L.) et comparaison de ses effets avec ceux du 2-phénoxyéthanol. *Bulletin Français de la Pêche et de la Pisciculture* 579–589. doi: 10.1051/kmae:2002054.
- Copilaș-Ciocianu, D., Borko, Š. and Fišer, C.** (2020). The late blooming amphipods: global change promoted post-Jurassic ecological radiation despite Palaeozoic origin. *Molecular Phylogenetics and Evolution* 143, 106664. doi: 10.1016/j.ympev.2019.106664.
- Cornet, S. and Sorci, G.** (2010). Parasite virulence when the infection reduces the host immune response. *Proceedings of the Royal Society B: Biological Sciences* 277, 1929–1935. doi: 10.1098/rspb.2010.0138.
- Cornet, S., Franceschi, N., Bauer, A., Rigaud, T. and Moret, Y.** (2009a). Immune depression induced by acanthocephalan parasites in their intermediate crustacean host: consequences for the risk of superinfection and links with host behavioural manipulation. *International Journal for Parasitology* 39, 221–229. doi: 10.1016/j.ijpara.2008.06.007.
- Cornet, S., Franceschi, N., Bollache, L., Rigaud, T. and Sorci, G.** (2009b). Variation and covariation in infectivity, virulence and immunodepression in the host–parasite association *Gammarus pulex* – *Pomphorhynchus laevis*. *Proceedings of the Royal Society B: Biological Sciences* 276, 4229–4236. doi: 10.1098/rspb.2009.1299.
- Crompton, D. W. T. and Nickol, B. B.** (1985). *Biology of the Acanthocephala*. Cambridge University Press, New York, USA.
- De Jong-Brink, M., Bergamin-Sassen, M. and Solis-Soto, M.** (2001). Multiple strategies of schistosomes to meet their requirements in the intermediate snail host. *Parasitology* 123, S129–141.
- De Roode, J. C., Helinski, M. E. H., Anwar, M. A. and Read, A. F.** (2005). Dynamics of multiple infection and within-host competition in genetically diverse malaria infections. *The American Naturalist* 166, 531–542. doi: 10.1086/491659.
- Dezfuli, B. S., Simoni, E., Duclos, L. and Rossetti, E.** (2008). Crustacean-acanthocephalan interaction and host cell-mediated immunity: parasite encapsulation and melanization. *Folia Parasitologica* 55, 53–59. doi: 10.14411/fp.2008.007.
- Dianne, L., Perrot-Minnot, M.-J., Bauer, A., Gaillard, M., Léger, E. and Rigaud, T.** (2011). Protection first then facilitation: a manipulative parasite modulates the vulnerability to predation of its intermediate host according to its own developmental stage. *Evolution* 65, 2692–2698. doi: 10.1111/j.1558-5646.2011.01330.x.
- Dianne, L., Bollache, L., Lagrue, C., Franceschi, N. and Rigaud, T.** (2012). Larval size in acanthocephalan parasites: influence of intraspecific competition and effects on intermediate host behavioural changes. *Parasites & Vectors* 5, 166. doi: 10.1186/1756-3305-5-166.
- Dianne, L., Perrot-Minnot, M.-J., Bauer, A., Guvenatam, A. and Rigaud, T.** (2014). Parasite-induced alteration of plastic response to predation threat: increased refuge use but lower food intake in

- Gammarus pulex* infected with the acanthocephalan *Pomphorhynchus laevis*. *International Journal for Parasitology* **44**, 211–216. doi: 10.1016/j.ijpara.2013.11.001.
- Duclos, L. M., Danner, B. J. and Nickol, B. B.** (2006). Virulence of *Corynosoma constrictum* (Acanthocephala: Polymorphidae) in *Hyalella azteca* (Amphipoda) throughout parasite ontogeny. *Journal of Parasitology* **92**, 749–755. doi: 10.1645/GE-770R.1.
- Escalante, G. C., Sweet, A. D., Mccracken, K. G., Gustafsson, D. R., Wilson, R. E. and Johnson, K. P.** (2016). Patterns of cryptic host specificity in duck lice based on molecular data. *Medical and Veterinary Entomology* **30**, 200–208. doi: 10.1111/mve.12157.
- Fayard, M., Dechaume-Moncharmont, F., Wattier, R. and Perrot-Minnot, M.** (2020). Magnitude and direction of parasite-induced phenotypic alterations: a meta-analysis in acanthocephalans. *Biological Reviews* **95**, 1233–1251. doi: 10.1111/brv.12606.
- Fenton, A., Streicker, D. G., Petchey, O. L. and Pedersen, A. B.** (2015). Are all hosts created equal? Partitioning host species contributions to parasite persistence in multihost communities. *The American Naturalist* **186**, 610–622. doi: 10.1086/683173.
- Firth, D.** (1993). Bias reduction of maximum likelihood estimates. *Biometrika* **80**, 27–38. doi: 10.1093/biomet/80.1.27.
- Folmer, O., Black, M., Hoeh, W., Lutz, R. and Vrijenhoek, R.** (1994). DNA primers for amplification of mitochondrial cytochrome c oxidase subunit I from diverse metazoan invertebrates. *Molecular Marine Biology and Biotechnology* **3**, 294–299.
- Franceschi, N., Bauer, A., Bollache, L. and Rigaud, T.** (2008). The effects of parasite age and intensity on variability in acanthocephalan-induced behavioural manipulation. *International Journal for Parasitology* **38**, 1161–1170. doi: 10.1016/j.ijpara.2008.01.003.
- Franceschi, N., Bollache, L., Cornet, S., Bauer, A., Motreuil, S. and Rigaud, T.** (2010a). Co-variation between the intensity of behavioural manipulation and parasite development time in an acanthocephalan–amphipod system. *Journal of Evolutionary Biology* **23**, 2143–2150. doi: 10.1111/j.1420-9101.2010.02076.x.
- Franceschi, N., Cornet, S., Bollache, L., Dechaume-Moncharmont, F.-X., Bauer, A., Motreuil, S. and Rigaud, T.** (2010b). Variation between populations and local adaptation in acanthocephalan-induced parasite manipulation: variation in parasite-induced behavioral manipulation. *Evolution* **2417–2430**. doi: 10.1111/j.1558-5646.2010.01006.x.
- Galipaud, M., Bollache, L. and Lagrue, C.** (2017). Variations in infection levels and parasite-induced mortality among sympatric cryptic lineages of native amphipods and a congeneric invasive species: are native hosts always losing? *International Journal for Parasitology: Parasites and Wildlife* **6**, 439–447. doi: 10.1016/j.ijppaw.2017.04.005.

- Gismondi, E., Cossu-Leguille, C. and Beisel, J.-N.** (2012). Does the acanthocephalan parasite *Polymorphus minutus* modify the energy reserves and antitoxic defences of its intermediate host *Gammarus roeseli*? *Parasitology* **139**, 1054–1061. doi: 10.1017/S0031182012000315.
- Goedknecht, A., Welsh, J. and Thieltges, D. W.** (2012). Parasites as prey. In *Encyclopedia of Life Sciences*, p. John Wiley & Sons, Ltd doi: 10.1002/9780470015902.a0023604.
- Grabowski, M., Mamos, T., Bączela-Spychalska, K., Rewicz, T. and Wattier, R. A.** (2017). Neogene paleogeography provides context for understanding the origin and spatial distribution of cryptic diversity in a widespread Balkan freshwater amphipod. *PeerJ* **5**, e3016. doi: 10.7717/peerj.3016.
- Harris, M.** (2020). *The life cycle of the parasite Pomphorhynchus tereticollis in reference to O+ cyprinids and the intermediate host Gammarus spp in the UK*, Master Thesis. Bournemouth University, Poole, UK.
- Hasu, T., Tellervo Valtonen, E. and Jokela, J.** (2006). Costs of parasite resistance for female survival and parental care in a freshwater isopod. *Oikos* **114**, 322–328. doi: 10.1111/j.2006.0030-1299.14726.x.
- Heinze, G. and Schemper, M.** (2002). A solution to the problem of separation in logistic regression. *Statistics in Medicine* **21**, 2409–2419. doi: 10.1002/sim.1047.
- Hynes, H. B. N. and Nicholas, W. L.** (1957). The development of *Polymorphus minutus* (Goeze, 1782) (Acanthocephala) in the intermediate host. *Annals of Tropical Medicine & Parasitology* **51**, 380–391. doi: 10.1080/00034983.1957.11685828.
- Jacquín, L., Mori, Q., Pause, M., Steffen, M. and Medoc, V.** (2014). Non-specific manipulation of gammarid behaviour by *P. minutus* parasite enhances their predation by definitive bird hosts. *PLoS ONE* **9**, e101684. doi: 10.1371/journal.pone.0101684.
- Janzen, D. H., Hallwachs, W., Blandin, P., Burns, J. M., Cadiou, J.-M., Chacon, I., Dapkey, T., Deans, A. R., Epstein, M. E., Espinoza, B., Franclemont, J. G., Haber, W. A., Hajibabaei, M., Hall, J. P. W., Hebert, P. D. N., Gauld, I. D., Harvey, D. J., Hausmann, A., Kitching, I. J., Lafontaine, D., Landry, J.-F., Lemaire, C., Miller, J. Y., Miller, J. S., Miller, L., Miller, S. E., Montero, J., Munroe, E., Green, S. R., Ratnasingham, S., Rawlins, J. E., Robbins, R. K., Rodriguez, J. J., Rougerie, R., Sharkey, M. J., Smith, M. A., Solis, M. A., Sullivan, J. B., Thiaucourt, P., Wahl, D. B., Weller, S. J., Whitfield, J. B., Willmott, K. R., Wood, D. M., Woodley, N. E. and Wilson, J. J.** (2009). Integration of DNA barcoding into an ongoing inventory of complex tropical biodiversity. *Molecular Ecology Resources* **9**, 1–26. doi: 10.1111/j.1755-0998.2009.02628.x.
- Korkofigas, E., Park, T. and Sparkes, T. C.** (2016). Acanthocephalan-related variation in the pattern of energy storage of a behaviorally and physiologically modified host: field data. *Parasitology Research* **115**, 339–345. doi: 10.1007/s00436-015-4753-z.
- Labaude, S., Cézilly, F., Tercier, X. and Rigaud, T.** (2015). Influence of host nutritional condition on post-infection traits in the association between the manipulative acanthocephalan *Pomphorhynchus laevis* and the amphipod *Gammarus pulex*. *Parasites & Vectors* **8**, 403. doi: 10.1186/s13071-015-1017-9.

- Labaude, S., Cézilly, F., De Marco, L. and Rigaud, T.** (2020). Increased temperature has no consequence for behavioral manipulation despite effects on both partners in the interaction between a crustacean host and a manipulative parasite. *Scientific Reports* **10**, 11670. doi: 10.1038/s41598-020-68577-z.
- Lackie, J. M.** (1972). The effect of temperature on the development of *Moniliformis dubius* (Acanthocephala) in the intermediate host, *Periplaneta americana*. *Parasitology* **65**, 371–377. doi: 10.1017/S0031182000043997.
- Lagrange, C., Kaldonski, N., Perrot-Minnot, M. J., Motreuil, S. and Bollache, L.** (2007). Modification of hosts' behavior by a parasite: field evidence for adaptive manipulation. *Ecology* **88**, 2839–2847. doi: 10.1890/06-2105.1.
- Lagrange, C., Wattier, R., Galipaud, M., Gauthey, Z., Rullmann, J.-P., Dubreuil, C., Rigaud, T. and Bollache, L.** (2014). Confrontation of cryptic diversity and mate discrimination within *Gammarus pulex* and *Gammarus fossarum* species complexes. *Freshwater Biology* **59**, 2555–2570. doi: 10.1111/fwb.12453.
- Le Clec'h, W., Diaz, R., Chevalier, F. D., McDew-White, M. and Anderson, T. J. C.** (2019). Striking differences in virulence, transmission and sporocyst growth dynamics between two schistosome populations. *Parasites & Vectors* **12**, 485. doi: 10.1186/s13071-019-3741-z.
- Mamos, T., Wattier, R., Burzyński, A. and Grabowski, M.** (2016). The legacy of a vanished sea: a high level of diversification within a European freshwater amphipod species complex driven by 15 My of Paratethys regression. *Molecular Ecology* **25**, 795–810. doi: 10.1111/mec.13499.
- Manzoli, D. E., Saravia-Pietro Paolo, M. J., Arce, S. I., Percara, A., Antoniazzi, L. R. and Beldomenico, P. M.** (2021). Specialist by preference, generalist by need: availability of quality hosts drives parasite choice in a natural multihost–parasite system. *International Journal for Parasitology*. doi: 10.1016/j.ijpara.2020.12.003.
- Marm Kilpatrick, A., Daszak, P., Jones, M. J., Marra, P. P. and Kramer, L. D.** (2006). Host heterogeneity dominates West Nile virus transmission. *Proceedings of the Royal Society B: Biological Sciences* **273**, 2327–2333. doi: 10.1098/rspb.2006.3575.
- Mlynarek, J. J., Knee, W. and Forbes, M. R.** (2013). Relative geographic range of sibling species of host damselflies does not reliably predict differential parasitism by water mites. *BMC Ecology* **13**, 50. doi: 10.1186/1472-6785-13-50.
- Moore, J.** (1983). Altered behavior in cockroaches (*Periplaneta americana*) infected with an archiacanthocephalan, *Moniliformis moniliformis*. *Journal of Parasitology* **69**, 1174–1176.
- Moore, J. and Gotelli, N. J.** (1996). Evolutionary patterns of altered behavior and susceptibility in parasitized hosts. *Evolution* **50**, 807–819.
- Moret, Y. and Schmid-Hempel, P.** (2000). Survival for immunity: the price of immune system activation for Bumblebee workers. *Science* **290**, 1166–1168. doi: 10.1126/science.290.5494.1166.



- Moret, Y., Bollache, L., Wattier, R. and Rigaud, T.** (2007). Is the host or the parasite the most locally adapted in an amphipod–acanthocephalan relationship? A case study in a biological invasion context. *International Journal for Parasitology* **37**, 637–644. doi: 10.1016/j.ijpara.2006.12.006.
- Müller, J.** (2000). Mitochondrial DNA variation and the evolutionary history of cryptic *Gammarus fossarum* types. *Molecular Phylogenetics and Evolution* **15**, 260–268. doi: 10.1006/mpev.1999.0740.
- Parker, G. A., Ball, M. A., Chubb, J. C., Hammerschmidt, K. and Milinski, M.** (2009). When should a trophically transmitted parasite manipulate its host? *Evolution* **63**, 448–458. doi: 10.1111/j.1558-5646.2008.00565.x.
- Pérez-Ponce de León, G. and Nadler, S. A.** (2010). What we don't recognize can hurt us: a plea for awareness about cryptic species. *Journal of Parasitology* **96**, 453–464. doi: 10.1645/GE-2260.1.
- Pérez-Ponce de León, G. and Poulin, R.** (2018). An updated look at the uneven distribution of cryptic diversity among parasitic helminths. *Journal of Helminthology* **92**, 197–202. doi: 10.1017/S0022149X17000189.
- Perrot-Minnot, M.-J.** (2004). Larval morphology, genetic divergence, and contrasting levels of host manipulation between forms of *Pomphorhynchus laevis* (Acanthocephala). *International Journal for Parasitology* **34**, 45–54. doi: 10.1016/j.ijpara.2003.10.005.
- Perrot-Minnot, M.-J., Guyonnet, E., Bollache, L. and Lagrue, C.** (2019). Differential patterns of definitive host use by two fish acanthocephalans occurring in sympatry: *Pomphorhynchus laevis* and *Pomphorhynchus tereticollis*. *International Journal for Parasitology: Parasites and Wildlife* **8**, 135–144. doi: 10.1016/j.ijppaw.2019.01.007.
- Pinacho-Pinacho, C. D., García-Varela, M., Sereno-Uribe, A. L. and Pérez-Ponce de León, G.** (2018). A hyper-diverse genus of acanthocephalans revealed by tree-based and non-tree-based species delimitation methods: ten cryptic species of *Neoechinorhynchus* in Middle American freshwater fishes. *Molecular Phylogenetics and Evolution* **127**, 30–45. doi: 10.1016/j.ympev.2018.05.023.
- Plaistow, S. J., Troussard, J.-P. and Cézilly, F.** (2001). The effect of the acanthocephalan parasite *Pomphorhynchus laevis* on the lipid and glycogen content of its intermediate host *Gammarus pulex*. *International Journal for Parasitology* **31**, 346–351.
- Poulin, R. and Keeney, D. B.** (2008). Host specificity under molecular and experimental scrutiny. *Trends in Parasitology* **24**, 24–28. doi: 10.1016/j.pt.2007.10.002.
- Poulin, R. and Maure, F.** (2015). Host manipulation by parasites: a look back before moving forward. *Trends in Parasitology* **31**, 563–570. doi: 10.1016/j.pt.2015.07.002.
- Quiles, A., Bacela-Spychalska, K., Teixeira, M., Lambin, N., Grabowski, M., Rigaud, T. and Wattier, R. A.** (2019). Microsporidian infections in the species complex *Gammarus roeselii* (Amphipoda) over its geographical range: evidence for both host–parasite co-diversification and recent host shifts. *Parasites & Vectors* **12**, 327. doi: 10.1186/s13071-019-3571-z.

- Quiles, A., Wattier, R. A., Bacela-Spychalska, K., Grabowski, M. and Rigaud, T. (2020).** *Dictyocoela* microsporidia diversity and co-diversification with their host, a gammarid species complex (Crustacea, Amphipoda) with an old history of divergence and high endemic diversity. *BMC Evolutionary Biology* **20**, 149. doi: 10.1186/s12862-020-01719-z.
- Quiles, A., Rigaud, T., Wattier, R. A., Grabowski, M. and Bacela Spychalska, K. (2021).** Wide geographic distribution of overlooked parasites: rare Microsporidia in *Gammarus balcanicus*, a species complex with a high rate of endemism. *International Journal for Parasitology: Parasites and Wildlife* **14**, 121–129. doi: 10.1016/j.ijppaw.2021.01.004.
- Rigaud, T., Perrot-Minnot, M.-J. and Brown, M. J. F. (2010).** Parasite and host assemblages: embracing the reality will improve our knowledge of parasite transmission and virulence. *Proceedings of the Royal Society B: Biological Sciences* **277**, 3693–3702. doi: 10.1098/rspb.2010.1163.
- Rigaud, T., Balourdet, A. and Bauer, A. (2023).** Time-course of antipredator behavioral changes induced by the helminth *Pomphorhynchus laevis* in its intermediate host *Gammarus pulex*: the switch in manipulation according to parasite developmental stage differs between behaviors. *Peer Community Journal* **3**, e109. doi: 10.24072/pcjournal.346.
- Rousset, F., Thomas, F., De Meeûs, T. and Renaud, F. (1996).** Inference of parasite-induced host mortality from distributions of parasite loads. *Ecology* **77**, 2203–2211. doi: 10.2307/2265713.
- Rumpus, A. E. and Kennedy, C. R. (1974).** The effect of the acanthocephalan *Pomphorhynchus laevis* upon the respiration of its intermediate host, *Gammarus pulex*. *Parasitology* **68**, 271–284.
- Sadd, B. M. and Siva-Jothy, M. T. (2006).** Self-harm caused by an insect's innate immunity. *Proceedings of the Royal Society B: Biological Sciences* **273**, 2571–2574. doi: 10.1098/rspb.2006.3574.
- Streicker, D. G., Fenton, A. and Pedersen, A. B. (2013).** Differential sources of host species heterogeneity influence the transmission and control of multihost parasites. *Ecology Letters* **16**, 975–984. doi: 10.1111/ele.12122.
- Therneau, T. M. and Grambsch, P. M. (2000).** *Modeling survival data: extending the Cox model*. Springer New York, New York, NY doi: 10.1007/978-1-4757-3294-8.
- Tokeson, J. P. and Holmes, J. C. (1982).** The effects of temperature and oxygen on the development of *Polymorphus marilis* (Acanthocephala) in *Gammarus lacustris* (Amphipoda). *Journal of Parasitology* **68**, 112–119.
- Uznanski, R. L. and Nickol, B. B. (1980).** Parasite population regulation: lethal and sublethal effects of *Leptorhynchoides thecatus* (Acanthocephala: Rhadinorhynchidae) on *Hyalella azteca* (Amphipoda). *Journal of Parasitology* **66**, 121–126.
- Wang, T. P., Shrivastava, J., Johansen, M. V., Zhang, S. Q., Wang, F. F. and Webster, J. P. (2006).** Does multiple hosts mean multiple parasites? Population genetic structure of *Schistosoma japonicum* between definitive host species. *International Journal for Parasitology* **36**, 1317–1325. doi: 10.1016/j.ijpara.2006.06.011.

- Wattier, R., Mamos, T., Copilaş-Ciocianu, D., Jelić, M., Ollivier, A., Chaumot, A., Danger, M., Felten, V., Piscart, C., Žganec, K., Rewicz, T., Wysocka, A., Rigaud, T. and Grabowski, M.** (2020). Continental-scale patterns of hyper-cryptic diversity within the freshwater model taxon *Gammarus fossarum* (Crustacea, Amphipoda). *Scientific Reports* **10**, 16536. doi: 10.1038/s41598-020-73739-0.
- Westram, A. M., Baumgartner, C., Keller, I. and Jokela, J.** (2011). Are cryptic host species also cryptic to parasites? Host specificity and geographical distribution of acanthocephalan parasites infecting freshwater *Gammarus*. *Infection, Genetics and Evolution* **11**, 1083–1090. doi: 10.1016/j.meegid.2011.03.024.
- Zittel, M., Grabner, D., Wlecklik, A., Sures, B., Leese, F., Taraschewski, H. and Weigand, A. M.** (2018). Cryptic species and their utilization of indigenous and non-indigenous intermediate hosts in the acanthocephalan *Polymorphus minutus sensu lato* (Polymorphidae). *Parasitology* **145**, 1421–1429. doi: 10.1017/S0031182018000173.