**Supplementary Methods, Tables, and Figures for:**

**Mutual assessment during ritualized fighting in mantis shrimp (Stomatopoda)**

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# METHODS

## Animal Collection and Maintenance

*Neogonodactylus bredini* is widely distributed in seagrass bed habitats across the Caribbean. We collected *N. bredini* individuals from burrows in coral rubble in *Thalassia spp.* seagrass habitats on the Atlantic coast of Panama. All individuals were collected near the Galeta Marine Laboratory (GML) of the Smithsonian Tropical Research Institute (STRI, 09° 24.279’ N, 079° 52.245’ W) between January and April 2014 (body length-matched contests; ANAM Collection Permit #SE/A-115-13) and in October 2015 (randomly-matched contests; ANAM Collection Permit #SE/A-92-15).

Individuals were maintained in a flow-through seawater system at GML in small, perforated plastic bottles. Some individuals were later transported to the STRI Naos Island Laboratory (body length-matched contests) or to Duke University (Durham, NC, USA; 37 body length-matched individuals, ANAM Export Permit #SEX/A-23-14; 57 randomly-matched individuals, ANAM Export Permit SEX/A-106-15). All individuals housed at Naos Island or Duke were maintained in plastic cups filled with natural seawater (Naos Island) or artificial seawater (Duke, mean water temperature 27.2 deg C, 12h/12h light/dark schedule), or in dedicated tanks filled with circulating artificial seawater (Duke, mean water temperature 27.2 deg C, 12h/12h light/dark schedule). All cups and tanks contained sandy substrate and a piece of PVC or vinyl tubing as an artificial burrow. Individuals were fed frozen krill or frozen seafood twice weekly and had at least 10% of their water changed daily.

## Morphological Measurements

We measured each individual’s body length – defined as the distance from the tip of the rostrum to the left medial apex of the telson [1] – within one week of collection using digital callipers (Mitutoyo Digimatic Caliper, range: 0-150mm, resolution: 0.01mm, Mitutoyo Corp., Kawasaki, Japan).

We measured body mass either on the morning of each individual’s use in a contest (body length-matched contests; Mettler AE163 balance; range: 0-31g, readability: 0.00001g, Mettler-Toledo, LLC, OH, USA. Denver Instruments APX-3202 balance; range: 0-3100g, readability: 0.01g, Sartorius AG, Goettingen, Germany) or in the evening after each individual’s use in a contest (randomly-matched contests; Denver Instruments APX-3202). For both body length and body mass, we used the mean of three replicate measurements in all analyses.

## Contest Protocol

All contests were conducted in clear plastic arenas (32.5cm length x 20cm width x 11.5cm depth) with 3 cm of sandy substrate on the bottom and a laminated piece of centimetre graph paper on one of the broad sides.

### Randomly-matched Contest Protocol

In randomly-matched contests, the night before a contest we randomly selected one individual [using the sample function in R version 3.0.1; 2] as a “resident”. We gave this individual 8-18 hours to establish residency in a single-entrance artificial burrow made of clear vinyl tubing. Except for a clear area at the top (to facilitate observations inside the burrow), the burrow was wrapped in black vinyl tape. Burrow volume was matched for resident body length according to *N. bredini*-specific equations established by [3]. The burrow was placed approximately 5cm from one of the short ends of the arena. If the resident did not establish residency in the burrow before the contest began, it was removed from the arena and was used as an intruder in another, randomly-selected contest. We then randomly selected another individual and allowed it to establish residency in the burrow over the following night.

Once a resident had established itself in a burrow, we placed a grey laminated barrier approximately 9cm from the burrow entrance and introduced a second randomly-selected individual (the “intruder”) behind the barrier. We allowed the intruder to acclimate for 10 minutes, then raised the barrier and began videotaping contest behaviours.

Contests were videotaped for 20 minutes using two video cameras (Hero 3+ Silver Edition, GoPro, Inc., USA, 60fps, 1920 x 1080px resolution) placed orthogonal to each other; one facing down over the arena and one facing the broad side of the arena. If competitors did not interact with each other for 20 minutes, we removed both to be randomly selected for use in subsequent days’ contests. If one individual interacted, but the other did not, we discarded the contest data and did not use either individual in subsequent contests. We discarded a total of 10 randomly-matched contests (~20% of initiated trials) and 7 body length-matched contests (~17% of initiated trials) due to a lack of interactions or the presence of one-sided interactions.

## Body length-matched contest protocol

Our dataset from body length-matched contests is a more detailed analysis of contests previously studied in [4]. In [4], we matched competitors for body length, because we had not yet established a metric of RHP. In [4], we also analysed the first contest behaviour, the number of strikes delivered during contests, each individual’s body and appendage morphology, and each individual’s strike performance [performance sensu 5, 6; maximum peak strike force]. In the present study, we used body length and body mass data from the same individuals, but expanded our behavioural analysis beyond the first contest behaviour and the total number of strikes to include contest duration and all contest behaviours.

### Differences between randomly-matched and body length-matched contest protocols

The protocol for body length-matched contests is similar to that of randomly-matched contests [details in 4]. However, there are differences between the protocols and data of randomly-matched and body length-matched contests. For example, body length-matched residents were given 3-6 hours to establish residency, whereas randomly-matched residents were given 8-18 hours. Additionally, randomly-matched and body length-matched contests differed in the average body mass of competitors (randomly-matched mean ± SD: 1.03 ± 0.49; body length-matched mean ± SD: 1.65 ± 0.54).

Despite the differences in protocol, we found no evidence that these differences significantly affected our results. Our previous work [4] found no effect of resident acclimation time between 3-6 hours on the likelihood of a resident winning a body length-matched contest. Therefore, it is unlikely that differences in acclimation time significantly affect our conclusions.

In a post-hoc analysis, we found six data points from randomly-matched competitors that were paired within a similar degree of body length as our body length-matched competitors. We plotted these points within the RHP-cost plots of our body length-matched dataset, and found that the randomly-matched points fit well within the range of our body length-matched points (Supplemental Figure 2). While there is insufficient power to test for statistical differences between the groups, we believe this evidence shows that our conclusions should not be affected by differences in protocol.

## Contest Data

We divided contests into “bouts”: a bout began when individuals first made eye contact (a “track” behaviour) or when one individual approached the other (an “approach” behaviour). A bout ended when one individual made a clear, directed movement away from its competitor and toward the edge of the contest arena (i.e., after a “retreat” behaviour). The winner was the individual that resided in the burrow after its competitor’s retreat. We only analysed data from the first contest bout.

From the first bout, we analysed total bout duration in seconds (also termed “total contest duration”). We also coded all contest behaviours using JWatcher [7], following an ethogram similar to that of Dingle & Caldwell [8]. Our ethogram consisted of 14 mutually exclusive contest behaviours (Supplementary Table 1).

## Analysis Techniques

We conducted separate analyses for the body length-matched and randomly-matched datasets. We removed four total outliers from the datasets – two from the randomly-matched and two from the body length-matched datasets. We statistically identified outliers based on the criterion that they had a contest duration greater than three standard deviations from the mean [uv.outliers function, BIOSTATS package, R Version 3.0.1; 9]. The resulting trends were the same with and without inclusion of the outliers (Supplementary Tables 7 & 8). All data were analysed using R Version 3.0.1 [2].

### RHP Analysis

Body size is the most common metric of RHP across the assessment literature [10]. We compared two measures of body size as potential RHP metrics, body mass (g) and body length (mm), following the method of [10]. We randomly selected one competitor from each contest as a “focal” individual. We then created a metric of focal body length or mass relative to opponent body length or mass:

We tested the effect of relative mass and relative body length, as well as their interaction, on focal contest outcome (win or lose) using a binomial generalized linear model (GLM) with a log link function [11]. The full model was:

Because we were interested in which metric(s) best predicted outcome, not necessarily the significance of the models, we compared the support of all possible models using an Akaike Information Criterion (AIC) score. We looked at which models had the lowest AIC score [within 2 delta AIC; 12] and chose which variable appeared most frequently in those best-supported models as our metric of RHP.

### Effects of RHP and Residency on Contest Outcome

Given that both RHP and resource ownership can affect contest outcome [13], once we established a metric of RHP we tested for the effects of RHP and burrow residency on contest outcome in two ways. First, we ran a binomial GLM with focal outcome (win/lose) as the dependent variable and relative RHP, focal role (resident or intruder), and their interaction as explanatory variables:

Since we were interested in how these combined predictors affected contest outcome and we were not focusing on which variable best predicted outcome, we did not use AIC to compare the support of individual models. Instead, we assessed the relative contributions of RHP, residency, and their interaction to the determination of contest outcome by significance values and effect sizes (z-values) in the full model. As recommended by [14] and [12], to avoid increasing the possibility of Type I error we did not simplify models and test significance.

We also tested for the “effective RHP increase” experienced by residents, which is defined as the benefit, in RHP units, of residency [13, 15]. In this case, we ran a binomial GLM with the (binary, win/lose) probability of an intruder winning the contest as the dependent variable and the intruder minus resident RHP as the independent variable:

We used the slope and intercept estimates of this binomial equation to calculate the RHP value at which the intruder had a 50% chance of winning the contest (the inflection point of the resulting binomial plot). If there were no resident effect, the intruder would have a 50% chance of winning at an intruder minus resident RHP value of 0. If there were a residency effect, we would expect this relationship to be right-shifted; that is, an intruder would have a 50% chance of winning the contest only if its RHP were greater than that of the resident [13].

### Correlational tests of assessment models

We used multiple linear regression to test the effects of RHP and residency on two measures of contest costs: total contest duration (in seconds) and the total number of strikes exchanged during a contest. Both contest duration and number of strikes were log-transformed [log10(duration) and log10(1 + number of strikes)] to meet assumptions of normality.

For randomly-matched contests, we followed methods recommended by [16] and [17] to test correlations between winner and loser RHP and contest costs. We ran two multiple regressions, each with one cost variable (duration or number of strikes) as the dependent variable. Our independent variables included winner RHP, winner role (resident or intruder), loser RHP, loser role, the interaction of winner and loser RHP, and the interaction of winner and loser role. We included these interaction terms because contests are inherently an interaction between two individuals; including interaction terms makes the statistical model more realistic, given the biology of the system [17]. The full model was:

We did not simplify the multiple regression models to avoid statistical issues associated with testing significance on simplified models [14]. Instead, we assessed the direction, strength, and statistical significance of winner and loser effects for the full models [16].

For body length-matched contests, we tested for the presence of correlations across averaged competitor RHP, competitor residency, and contest costs [16, 18]. Our multiple regression approach was similar to analyses performed on the randomly-matched contests; however, our independent variables included the averaged RHP of both competitors and the interaction term between winner and loser role:

As in randomly-matched contests, we did not simplify the multiple regression models for body length-matched contests; instead, we assessed the directionality and statistical strength of each effect for the full model [16].

### Sequential Behavioural Analysis

Sequential analysis is a technique developed by social scientists to analyse trends in inter- and intra-individual behaviour. We used sequential analysis to visualise how competing *N. bredini* individuals progressed through behaviours during contests, and we then assessed whether these trends were congruent with predictions made by competitive assessment models [19-21].

One purpose of a sequential analysis is to test if the observed set of behavioural transitions are different from what one would expect by chance. Additionally, one might ask which transitions contributed to this difference. In these cases, it is useful to simplify the overall dataset to identify individual transitions that occurred more frequently than expected. We used common methods in sequential analysis to simplify our behavioural sequence data.

After coding all contest behaviours from the first contest bout, we combined these behaviours into sequences for all body length-matched competitors and, separately, all randomly-matched competitors.

In these sequential datasets, each behavioural transition is represented in one row of data. For each row, column 1 represents the first behaviour in the transition, and column 2 the second behaviour. In each subsequent row, column 1 shows the second behaviour (i.e., column 2) from the preceding row and column 2 shows the behaviour that follows from it. In [row, column] notation, [r1, c1] is the first behaviour in a sequence, and [r1, c2] is the behaviour that follows from it. In the next row, [r2, c1] = [r1, c2], and [r2, c2] is the behaviour that follows from [r2, c1]. The table below shows a representative sample of coding from the dataset of randomly-matched competitors:

|  |  |  |
| --- | --- | --- |
|  | Preceding behaviour | Subsequent behaviour |
| Transition 1 | x | t |
| Transition 2 | t | a |
| Transition 3 | a | m |
| Transition 4 | m | r |
| Transition 5 | r | b |

This dataset represents the sequence of transitions “x 🡪 t 🡪 a 🡪 m 🡪 r 🡪 b”.

The behavioural transitions are organized into a contingency table [22] or, in the network analysis notation used by the igraph package in R [23], an “adjacency matrix”. The adjacency matrix simply tallies the number of times one behaviour transitioned to another across the total dataset. Each row in the adjacency matrix represents the precending behaviour in a sequence, and each column represents a subsequent behaviour. The table below shows a portion of the adjacency matrix from our full dataset on randomly-matched competitors:

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  |  | Subsequent behaviours | | | |
|  |  | Bout start | Track | Approach | Meral spread |
| Preceding behaviours | Bout start | 0 | 44 | 11 | 1 |
| Track | 0 | 0 | 28 | 8 |
| Approach | 0 | 15 | 0 | 13 |
| Meral spread | 0 | 0 | 2 | 0 |

In this adjacency matrix, “bout start” was followed by “track” 44 times, by “approach” 11 times, and by “meral spread” once. Also, “track” was followed by “approach” 28 times, and by “meral spread” 8 times.

At this point, the dataset may be simplified such that we can identify which transitions occurred more frequently than would be expected by chance. For example, in our data above, we might ask if the eight transitions from “track” to “meral spread” are more common that we would expect, given the frequencies of each individual behaviour.

Permutation tests can be used to simplify the sequential data to only transitions that occurred more frequently than expected by chance [24]. We developed a permutation procedure for sequential data in R. The code for executing this procedure is available in the Electronic Supplementary Material.

The permutation procedure establishes the 95% quantile of 10,000 randomized datasets holding constant only the number of times each behaviour was observed in the original dataset. This creates a null distribution of expected transitions where any behaviour can transition to any other behaviour, only constrained by the frequency of each behaviour’s occurrence.

The procedure first resamples the second column of the two-column raw behavioural transitions dataset. This technique keeps constant the frequency of individual behaviours, but reshuffles the sequence of these behaviours.

The dataset is resampled 10,000 times. After each resampling, the raw transition data is organized into and saved as an adjacency matrix. Therefore, at the end of the permutation procedure, 10,000 randomized adjacency matrices are saved.

Our goal is to identify which transitions in our observed dataset occurred more frequently than an upper quantile of our expected dataset. From our permuted adjacency matrices, we extracted the 95% quantile for each cell, over the entire adjacency matrix. We would expect transitions that significantly contribute to the structure of our observed dataset to have a higher adjacency matrix value than the 95% quantile. The table below shows the observed transition values and (in parentheses) the 95% quantile values for a subset of our randomly-matched dataset. Cells in bold and italics represent transitions that occurred more frequently than expected:

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  |  | Subsequent behaviours | | | |
|  |  | Bout start | Track | Approach | Meral spread |
| Preceding behaviours | Bout start | 0 (0) | ***44 (17)*** | ***11 (11)*** | 1 (7) |
| Track | 0 (0) | 0 (20) | ***28 (13)*** | 8 (9) |
| Approach | 0 (0) | ***15 (13)*** | 0 (8) | ***13 (6)*** |
| Meral spread | 0 (0) | 0 (9) | 2 (6) | 0 (4) |

From this example, the transitions “bout start 🡪 track”, “bout start 🡪 approach”, “track 🡪 approach”, “approach 🡪 track” and “approach 🡪 meral spread” occurred more frequently than expected. While “track 🡪 meral spread” was observed 8 times, it was not observed more frequently than expected (9 times).

Once the observed dataset has been simplified to those behaviours that occurred more frequently than expected, the transition data can be plotted using the igraph package or any other data visualisation technique.

We converted the matrices of significant transitions into graph objects (igraph package), then plotted these graphs as networks (one network for each of randomly-matched and body length-matched behaviours). Individual behaviours are represented as network vertices (circles), and statistically significant transitions between behaviours are represented as directed network edges (arrows). We grouped the size of the vertices to be proportional to five categories of scaled degree – the percentage of total contest behaviours made up by one behavioural state. Similarly, we grouped the size of the edges to be proportional to five categories of transitional probability – the number of times a transition from one behaviour to another occurred divided by the sum of transitions from that behaviour to all others (higher values are more likely transitions).

## Ethics Note

All methods complied with legal requirements of the Panamanian Minesterio de Ambiente and of Duke University. After the conclusion of all trials in Panama, some animals were released at the same sites where they were collected, while others were transported to Duke University for use in other research (ANAM Export Permits #SEX/A-23-14 and #SEX/A-106-15).

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# SUPPLEMENTARY TABLES AND FIGURES

Supplementary Table 1 – Ethogram of contest behaviours. All behaviours are mutually exclusive. Further definitions are provided in Methods.

|  |  |
| --- | --- |
| Behaviour name | Description |
| Bout start | Start of contest bout, coding begins |
| Still | No movement |
| Out of sight | Individual cannot be seen by human observer |
| Track | Track competitor; often clear eyestalk movement or “eye contact” |
| Approach | Clear, directed movement toward competitor |
| Antennular flick | Antennae/antennules are rapidly moved medially and laterally |
| Meral spread | Raptorial appendages spread laterally |
| Lunge | Rapid movement toward competitor, much faster than approach |
| Strike | Strike competitor by using raptorial appendages |
| Telson coil | Coil telson in front of body |
| Telson push | While in coiled position, rapidly push telson toward competitor |
| Retreat | Clear, directed movement away from competitor, toward edge of arena |
| Chase | Rapidly follow retreating competitor |
| Bout end | End of contest bout, coding stops |

Supplemental Table 2 – In randomly-matched contests, body mass was a better predictor of contest outcome than body length (BL); body length and body mass had similar support in body length-matched contests. For randomly-matched and body length-matched contests, models are ordered by AIC score (lowest score indicates best support). Models with ∆AIC of < 2 from best-supported model are italicized, representing approximately equivalent support. Terms separated by a colon represent an interaction term; e.g., “mass : BL” is the interaction between mass and body length.

|  |  |  |
| --- | --- | --- |
|  | **Model terms** | **AIC** |
| Randomly-matched | *BL+ mass + mass : BL* | *39.4* |
| *Mass + mass : BL* | *39.7* |
| Mass | 44.1 |
| BL + mass : BL | 44.2 |
| BL | 44.8 |
| BL + mass | 46.0 |
| Mass : BL | 47.5 |
| Body length-matched | *BL* | *39.4* |
| *Mass* | *39.8* |
| *BL + mass* | *40.9* |
| *BL + mass : BL* | *40.9* |
| Mass + mass : BL | 41.8 |
| Mass : BL | 42.5 |
| BL+ mass + mass : BL | 42.7 |

Supplemental Table 3 – Pure self-assessment was ruled out in randomly-matched contests because contest duration and the total number of contest strikes correlated negatively with winner mass. Using multiple regressions, winner mass, loser mass, winner residency and loser residency were predictor variables, while log-corrected contest duration and log-corrected total number of strikes exchanged were cost (dependent) variables. Significant terms are italicized.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Cost variable** | **Predictor** | **Estimate** | **Std. Error** | **t-value** | **p-value** |
| Log10(contest duration) | *Intercept* | *1.23* | *0.44* | *2.78* | *0.01* |
| *Winner mass* | *-0.60* | *0.28* | *-2.10* | *0.04* |
| Winner residency | -0.24 | 0.46 | -0.05 | 0.96 |
| Loser mass | -0.81 | 0.47 | -0.17 | 0.87 |
| Loser residency | NA\* | NA | NA | NA |
| Winner mass : winner residency | 0.51 | 0.27 | 1.84 | 0.08 |
| *Loser mass : loser residency* | *1.01* | *0.41* | *2.49* | *0.02* |
| Winner mass : loser mass | 0.08 | 0.32 | 0.25 | 0.80 |
| Winner residency : loser residency | NA | NA | NA | NA |
| Log10(1 + total number of contest strikes) | Intercept | 0.35 | 0.31 | 1.12 | 0.27 |
| *Winner mass* | *-0.48* | *0.18* | *-2.74* | *0.01* |
| Winner residency | NA | NA | NA | NA |
| Loser mass | -0.12 | 0.29 | -0.42 | 0.68 |
| Loser residency | 0.30 | 0.29 | 1.06 | 0.30 |
| Winner mass : winner residency | 0.23 | 0.17 | 1.34 | 0.19 |
| Loser mass : loser residency | 0.32 | 0.25 | 1.27 | 0.21 |
| Winner mass : loser mass | 0.21 | 0.20 | 1.09 | 0.29 |
| Winner residency : loser residency | NA | NA | NA | NA |

\*NA results reflect factors with repetitive and exactly opposite effects; e.g., winner role and loser role are repetitive and exactly opposite. NA results do not affect the directionality or strength of any other relationships, even when factors are re-ordered in the full model equation.

Supplemental Table 4 – Cumulative assessment was ruled out according to the criteria of [18], but not [25], in body length-matched contests because averaged competitor body mass did not correlate with contest duration or the total number of contest strikes. Using multiple regressions, average competitor mass, winner residency and loser residency are predictor variables, while log-corrected contest duration and log-corrected total number of strikes exchanged during contests are cost (dependent) variables. Significant terms are italicized.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Cost variable** | **Predictor variable** | **Estimate** | **Std. Error** | **t-value** | **p-value** |
| Log10(contest duration) | *Intercept* | *1.61* | *0.32* | *4.95* | *<0.01* |
| Average mass | 0.07 | 0.17 | 0.38 | 0.71 |
| Winner intruder : loser intruder | NA\* | NA | NA | NA |
| *Winner resident : loser intruder* | *-0.40* | *0.20* | *-2.02* | *0.05* |
| Winner intruder : loser resident | NA | NA | NA | NA |
| Winner resident : loser resident | NA | NA | NA | NA |
| Log10(1 + total number of contest strikes) | *Intercept* | *0.97* | *0.18* | *5.22* | *<0.01* |
| Average mass | -0.01 | 0.10 | -0.08 | 0.93 |
| Winner intruder : loser intruder | NA | NA | NA | NA |
| *Winner resident : loser intruder* | *-0.39* | *0.11* | *-3.48* | *<0.02* |
| Winner intruder : loser resident | NA | NA | NA | NA |
| Winner resident : loser resident | NA | NA | NA | NA |

\*NA results reflect factors with repetitive and exactly opposite effects; e.g., winner role and loser role are repetitive and exactly opposite. NA results do not affect the directionality or strength of any other relationships, even when factors are moved in the full model equation.

Supplementary Table 5 – In randomly-matched contests, correlations of contest costs as a function of body length and residency were similar to correlations of costs as a function of body mass and residency (Supplementary Table 3). Using multiple regressions, winner body length, loser body length, winner residency, and loser residency are predictor variables, while log-corrected contest duration and log-corrected total number of strikes exchanged are cost (dependent) variables. Significant terms are italicized.

Duration model: F6,28=2.86, R2 = 0.25, p=0.03

Number of strikes model: F6,28=3.06, R2=0.27, p=0.02

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Cost variable** | **Predictor** | **Estimate** | **Std. Error** | **t-value** | **p-value** |
| Log10(contest duration) | Intercept | 4.60 | 3.46 | 1.33 | 0.19 |
| Winner body length (BL) | -0.15 | 0.09 | -1.71 | 0.10 |
| Winner residency | 1.49 | 1.49 | 1.00 | 0.33 |
| Loser BL | -0.13 | 0.11 | -1.14 | 0.26 |
| Loser residency | NA | NA | NA | NA |
| Winner BL : winner residency | 0.02 | 0.04 | 0.59 | 0.56 |
| *Loser BL : loser residency* | *0.07* | *0.03* | *2.69* | *0.01* |
| Winner BL : loser BL | 0.00 | 0.00 | 1.16 | 0.26 |
| Winner residency : loser residency | NA | NA | NA | NA |
| Log10(1 + total number of contest strikes) | Intercept | 3.33 | 2.30 | 1.45 | 0.16 |
| Winner BL | -0.11 | 0.06 | -1.81 | 0.08 |
| Winner residency | 0.63 | 0.99 | 0.63 | 0.53 |
| Loser BL | -0.10 | 0.08 | -1.29 | 0.21 |
| Loser residency | NA | NA | NA | NA |
| Winner BL : winner residency | 0.00 | 0.23 | 0.13 | 0.89 |
| Loser BL : loser residency | 0.30 | 0.02 | 1.65 | 0.11 |
| Winner BL : loser BL | 0.00 | 0.00 | 1.36 | 0.18 |
| Winner residency : loser residency | NA | NA | NA | NA |

Supplementary Table 6 – In body length-matched contests, correlations of contest costs as a function of body length and residency were similar to correlations of costs as a function of body mass and residency (Supplementary Table 4). Using multiple regressions, average competitor body length, winner residency, and loser residency are predictor variables, while contest duration and the total number of strikes exchanged are cost (dependent) variables. Significant terms are italicized.

Duration model: F2,26=2.12, R2 =0.07, p=0.14

Strikes model: F2,26=6.05, R2 =0.27, p<0.01.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Cost variable** | **Predictor variable** | **Estimate** | **Std. Error** | **t-value** | **p-value** |
| Log10(contest duration) | Intercept | 1.42 | 0.79 | 1.80 | 0.08 |
| Average BL | 0.00 | 0.02 | 0.37 | 0.71 |
| Winner intruder : loser intruder | NA | NA | NA | NA |
| Winner resident : loser intruder | -0.39 | 0.20 | -2.01 | 0.06 |
| Winner intruder : loser resident | NA | NA | NA | NA |
| Winner resident : loser resident | NA | NA | NA | NA |
| Log10(1+ total number of contest strikes) | Intercept | 0.90 | 0.45 | 2.00 | 0.06 |
| Average BL | 0.00 | 0.01 | 0.12 | 0.91 |
| Winner intruder : loser intruder | NA | NA | NA | NA |
| *Winner resident : loser intruder* | *-0.39* | *0.11* | *-3.47* | *<0.01* |
| Winner intruder : loser resident | NA | NA | NA | NA |
| Winner resident : loser resident | NA | NA | NA | NA |

Supplementary Table 7 – Previously-removed outliers were added to the dataset and the effects of RHP and residency on randomly-matched contest costs were re-analyzed here. The overall trends ruling out cumulative and mutual assessment remain consistent across analyses. Compare this table to Supplementary Table 3. NA\* codes are explained in Supplementary Table 3.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Cost variable** | **Predictor** | **Estimate** | **Std. Error** | **t-value** | **p-value** |
| Contest duration | *Intercept* | *1.68* | *0.58* | *2.9* | *0.01* |
| Winner mass | -0.65 | 0.38 | -1.72 | 0.10 |
| Winner residency | -0.40 | 0.61 | -0.67 | 0.51 |
| Loser mass | -0.15 | 0.64 | -0.24 | 0.82 |
| Loser residency | NA\* | NA | NA | NA |
| Winner mass : winner residency | 0.50 | 0.36 | 1.38 | 0.18 |
| Loser mass : loser residency | 0.78 | 0.56 | 1.40 | 0.17 |
| Winner mass : loser mass | 0.13 | 0.44 | 0.31 | 0.76 |
| Winner residency : loser residency | NA | NA | NA | NA |
| Total number of contest strikes | Intercept | *0.87* | *0.33* | *2.63* | *0.01* |
| *Winner mass* | *-0.49* | *0.22* | *-2.23* | *0.03* |
| Winner residency | -0.48 | 0.35 | -1.38 | 0.18 |
| Loser mass | -0.16 | 0.37 | -0.43 | 0.67 |
| Loser residency | NA | NA | NA | NA |
| Winner mass : winner residency | 0.21 | 0.21 | 1.01 | 0.32 |
| Loser mass : loser residency | 0.20 | 0.32 | 0.62 | 0.54 |
| Winner mass : loser mass | 0.24 | 0.25 | 0.98 | 0.34 |
| Winner residency : loser residency | NA | NA | NA | NA |

Supplementary Table 8 – Previously-removed outliers were added to the dataset and the effects of RHP and residency on body length-matched contest costs were re-analyzed. The overall trends ruling out cumulative assessment according to [18] remain consistent across analyses. Compare this table to Supplementary Table 4. NA\* codes are explained in Supplementary Table 4.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Cost variable** | **Predictor variable** | **Estimate** | **Std. Error** | **t-value** | **p-value** |
| Contest duration | *Intercept* | *1.63* | *0.35* | *4.68* | *<0.01* |
| Average mass | 0.16 | 0.18 | 0.89 | 0.38 |
| Winner intruder : loser intruder | NA\* | NA | NA | NA |
| *Winner resident : loser intruder* | *-0.57* | *0.20* | *-2.85* | *0.01* |
| Winner intruder : loser resident | NA | NA | NA | NA |
| Winner resident : loser resident | NA | NA | NA | NA |
| Total number of contest strikes | *Intercept* | *0.98* | *0.19* | *5.17* | *<0.01* |
| Average mass | 0.03 | 0.10 | 0.31 | 0.76 |
| Winner intruder : loser intruder | NA | NA | NA | NA |
| *Winner resident : loser intruder* | *-0.47* | *0.11* | *-4.3* | *<0.01* |
| Winner intruder : loser resident | NA | NA | NA | NA |
| Winner resident : loser resident | NA | NA | NA | NA |

Supplementary Table 9 – Summary statistics of body length, body mass, the difference in body length and body mass, contest duration, total number of strikes exchanged, and total number of contest behaviours between competitors in randomly-matched and body length-matched contests. Each cell shows the mean ± standard deviation and (in parentheses) the minimum and maximum values. Body length difference and body mass differences are in absolute value.

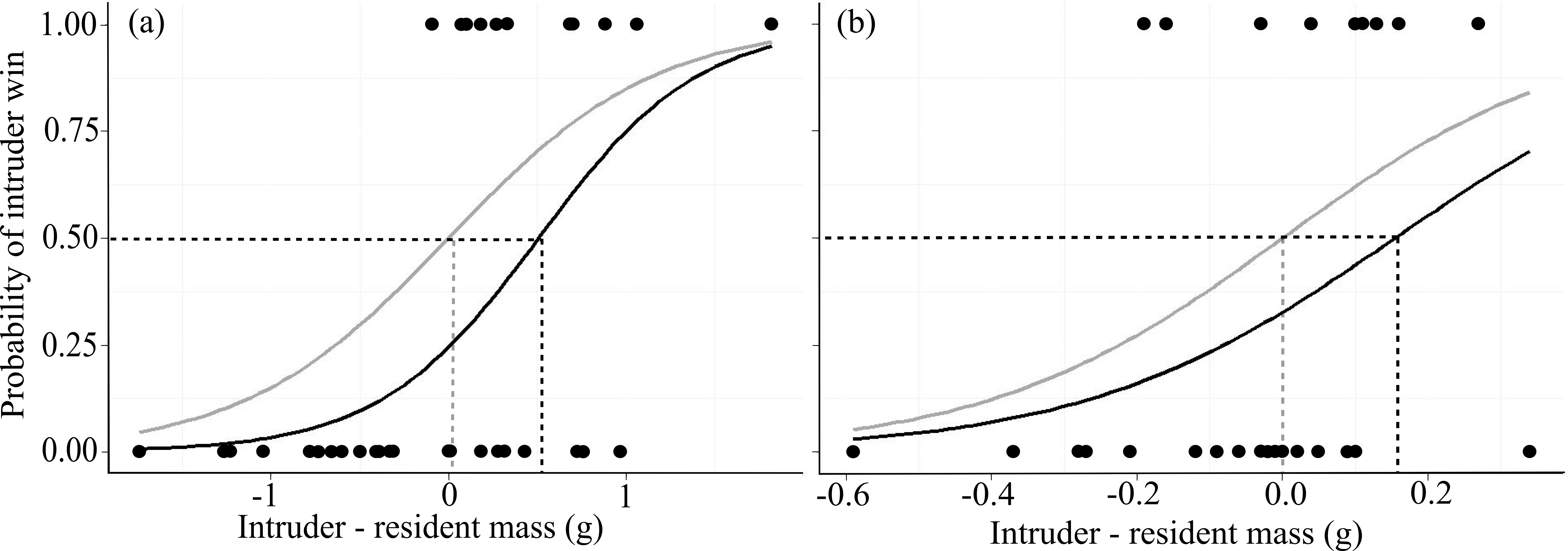
|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | **Body length (mm)** | **Body mass (g)** | **Absolute value of body length difference (mm)** | **Absolute value of body mass difference (g)** | **Total contest duration (s)** | **Total number of strikes exchanged** | **Total number of contest behaviours** |  |
| **Randomly-matched contests (n=35)** | 35.68 ± 5.63  (25.35, 50.62) | 1.03 ± 0.49  (0.40, 2.61) | 6.46 ± 4.55  (0.25, 18.72) | 0.59 ± 0.45  (0.00, 1.82) | 20 ± 19  (2, 78) | 1 ± 1  (0, 5) | 14 ± 8  (6, 36) |  |
| **Body length-matched contests (n=29)** | 43.69 ± 5.12  (34.23, 52.30) | 1.65 ± 0.54  (0.72, 2.56) | 0.80 ± 0.47  (0.01, 1.83) | 0.15 ± 0.13  (0.00, 0.59) | 51 ± 58  (4, 188) | 5 ± 5  (0, 20) | 30 ± 21  (9, 89) |  |

Supplementary Table 10 – Full transitional data matrix for randomly-matched contests. Each cell indicates the number of transitions from one behaviour (rows) to a subsequent behaviour (columns). Values outside parentheses and brackets represent the observed number of transitions, values in parentheses represent the 95% quantile of the expected number of transitions based on our permutation procedure (see Methods), and values in brackets represent transitional probability. In our sequential behavioural analysis, we simplified the matrix to only those transitions that were more frequent than expected (bolded, italicized cells; see Methods).

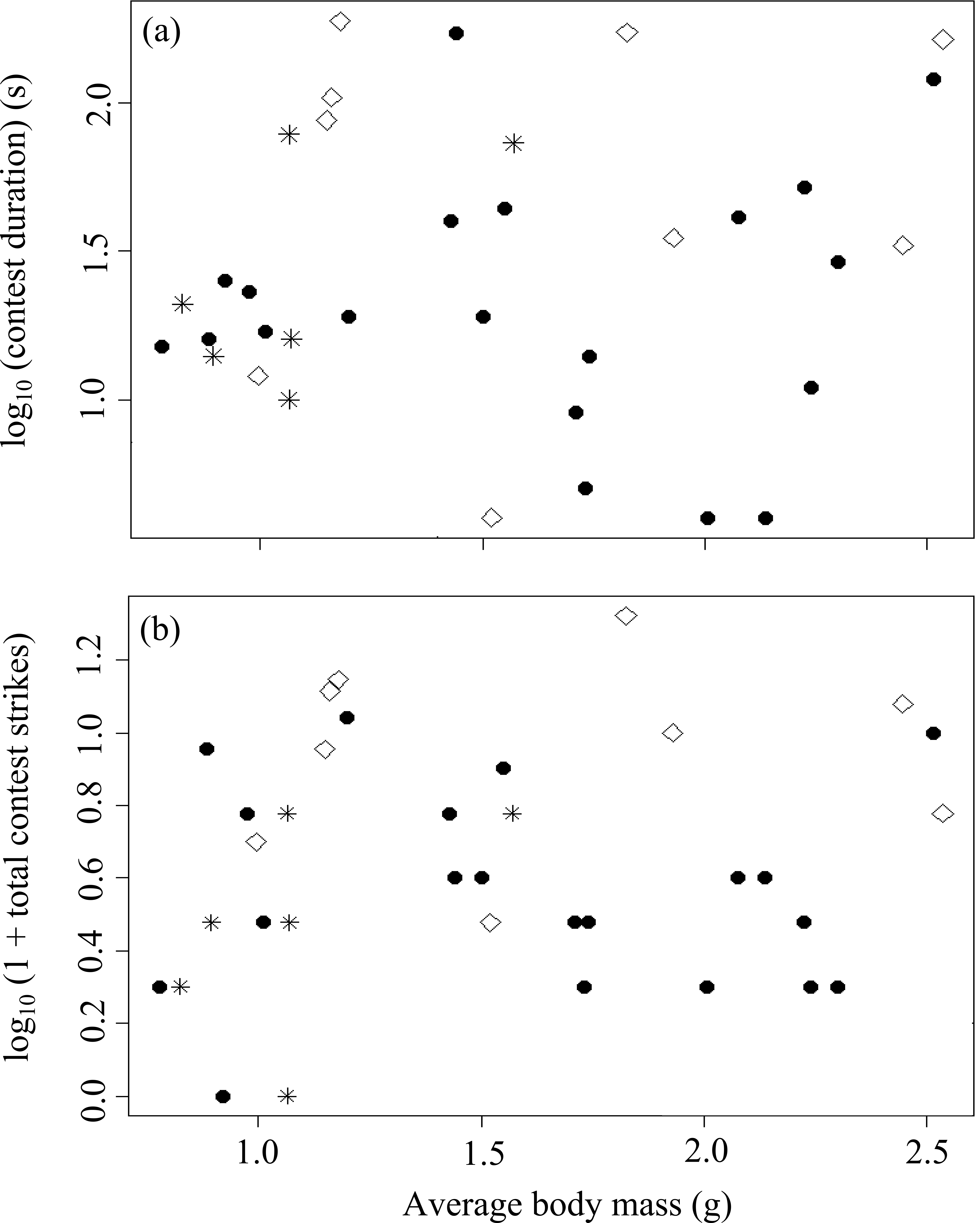
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | Bout start | Still | Out of sight | Track | Approach | Antennular flick | Meral spread | Lunge | Strike | Telson coil | Telson push | Retreat | Chase | Bout end |
| Bout start | 0 (0) [0.00] | 1 (2) [0.01] | ***5 (3) [0.07]*** | ***44 (17) [0.63]*** | ***11 (11) [0.16]*** | 0 (7) [0.00] | 1 (7) [0.01] | 0 (12) [0.00] | 0 (9) [0.00] | 8 (18) [0.11] | 0 (1) [0.00] | 0 (8) [0.00] | 0 (1) [0.00] | 0 (14) [0.00] |
| Still | 0 (0) [0.00] | 0 (1) [0.00] | 0 (1) [0.00] | 2 (3) [0.33] | ***2 (2) [0.33]*** | 0 (1) [0.00] | 0 (2) [0.00] | 0 (2) [0.00] | 0 (2) [0.00] | 1 (3) [0.17] | 0 (0) [0.00] | 0 (2) [0.00] | 0 (0) [0.00] | 1 (2) [0.17] |
| Out of sight | 0 (0) [0.00] | 0 (1) [0.00] | 0 (1) [0.00] | 1 (3) [0.14] | 1 (2) [0.14] | 0 (2) [0.00] | 0 (2) [0.00] | ***3 (2) [0.43]*** | 0 (2) [0.00] | 0 (3) [0.00] | 0 (0) [0.00] | 0 (2) [0.00] | 0 (0) [0.00] | 2 (3) [0.29] |
| Track | 0 (0) [0.00] | 2 (3) 0.02] | 0 (3) [0.00] | 0 (20) [0.00] | ***28 (13) [0.33]*** | ***8 (8) [0.09]*** | 8 (9) [0.09] | 7 (15) [0.08] | 1 (11) [0.01] | 15 (21) [0.18] | 0 (1) [0.00] | ***10 (10) [0.12]*** | 0 (1) [0.00] | 6 (17) [0.07] |
| Approach | 0 (0) [0.00] | 1 (2) [0.02] | 0 (2) [0.00] | ***15 (13) [0.31]*** | 0 (8) [0.00] | ***12 (6) [0.24]*** | ***13 (6) [0.27]*** | 0 (9) [0.00] | 1 (7) [0.02] | 4 (13) [0.08] | 0 (1) [0.00] | 1 (6) [0.02] | 0 (1) [0.00] | 2 (11) [0.04] |
| Antennular flick | 0 (0) [0.00] | ***1 (1) [0.03]*** | 0 (2) [0.00] | 1 (8) [0.03] | 3 (6) [0.10] | 0 (4) [0.00] | 3 (4) [0.10] | ***11 (6) [0.38]*** | 1 (5) [0.03] | 6 (9) [0.21] | 0 (1) [0.00] | 3 (4) [0.10] | 0 (1) [0.00] | 0 (7) [0.00] |
| Meral spread | 0 (0) [0.00] | 0 (2) [0.00] | 0 (2) [0.00] | 0 (9) [0.00] | 2 (6) [0.06] | ***4 (4) [0.13]*** | 0 (4) [0.00] | ***11 (7) [0.35]*** | 0 (5) [0.00] | 7 (9) [0.23] | 0 (1) [0.00] | ***6 (5) [0.19]*** | 0 (1) [0.00] | 1 (7) [0.03] |
| Lunge | 0 (0) [0.00] | 0 (2) [0.00] | 1 (2) [0.02] | 3 (15) [0.05] | 0 (9) [0.00] | 0 (6) [0.00] | 3 (7) [0.05] | 0 (11) [0.00] | ***35 (8) [0.59]*** | 12 (15) [0.20] | 0 (1) [0.00] | 0 (7) [0.00] | 0 (1) [0.00] | 5 (12) [0.08] |
| Strike | 0 (0) [0.00] | 0 (2) [0.00] | 0 (2) [0.00] | 2 (11) [0.05] | 0 (7) [0.00] | 0 (5) [0.00] | 0 (5) [0.00] | 0 (8) [0.00] | 0 (6) [0.00] | ***36 (11) [0.90]*** | 0 (1) [0.00] | 1 (6) [0.02] | 0 (1) [0.00] | 1 (9) [0.02] |
| Telson coil | 0 (0) [0.00] | 1 (3) [0.01] | 1 (3) [0.01] | 16 (21) [0.18] | 2 (13) [0.02] | 5 (9) [0.06] | 3 (9) [0.03] | ***27 (15) [0.30]*** | 2 (11) 0.02] | 0 (22) [0.00] | ***1 (1) [0.01]*** | ***15 (10) [0.17]*** | ***1 (1) [0.01]*** | 16 (17) [0.18] |
| Telson push | 0 (0) [0.00] | 0 (0) [0.00] | 0 (0) [0.00] | 0 (1) [0.00] | 0 (1) [0.00] | 0 (1) [0.00] | 0 (1) [0.00] | 0 (1) [0.00] | 0 (1) [0.00] | ***1 (1) [1.00]*** | 0 (0) [0.00] | 0 (1) [0.00] | 0 (0) [0.00] | 0 (1) [0.00] |
| Retreat | 0 (0) [0.00] | 0 (2) [0.00] | 0 (2) [0.00] | 1 (10) [0.03] | 0 (7) [0.00] | 0 (4) [0.00] | 0 (5) [0.00] | 0 (7) [0.00] | 0 (6) [0.00] | 0 (10) [0.00] | 0 (1) [0.00] | 0 (5) [0.00] | 0 (1) [0.00] | ***35 (8) [0.97]*** |
| Chase | 0 (0) [0.00] | 0 (0) [0.00] | 0 (0) [0.00] | 0 (1) [0.00] | 0 (1) [0.00] | 0 (1) [0.00] | 0 (1) [0.00] | 0 (1) [0.00] | 0 (1) [0.00] | 0 (1) [0.00] | 0 (0) [0.00] | 0 (1) [0.00] | 0 (0) [0.00] | ***1 (1) [1.00]*** |
| Bout end | 0 (0) [0.00] | 0 (0) [0.00] | 0 (0) [0.00] | 0 (0) [0.00] | 0 (0) [0.00] | 0 (0) [0.00] | 0 (0) [0.00] | 0 (0) [0.00] | 0 (0) [0.00] | 0 (0) [0.00] | 0 (0) [0.00] | 0 (0) [0.00] | 0 (0) [0.00] | 0 (0) [0.00] |

Supplementary Table 11 – Full transitional data matrix for body length-matched contests. Each cell indicates the number of transitions from one behaviour (rows) to a subsequent behaviour (columns). Values outside parentheses and brackets represent the observed number of transitions, values in parentheses represent the 95% quantile of the expected number of transitions based on our permutation procedure (see Methods), and values in brackets represent transitional probability. In our sequential behavioural analysis, we simplified the matrix to only those transitions that were more frequent than expected (bolded, italicized cells; see Methods).

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | Bout start | Still | Out of sight | Track | Approach | Antennular flick | Meral spread | Lunge | Strike | Telson coil | Telson push | Retreat | Chase | Bout end |
| Bout start | 0 (0) [0.00] | 2 (3) [0.04] | ***5 (2) [0.09]*** | ***22 (7) [0.39]*** | ***17 (5) [0.30]*** | 0 (5) [0.00] | 0 (5) [0.00] | 1 (16) [0.02] | 0 (14) [0.00] | 9 (21) [0.16] | 0 (3) [0.00] | 0 (4) [0.00] | 0 (1) [0.00] | 0 (7) [0.00] |
| Still | 0 (0) [0.00] | 0 (1) [0.00] | ***2 (1) [0.13]*** | ***3 (3) [0.20]*** | 1 (2) [0.07] | ***2 (2) [0.13]*** | 1 (2) [0.17] | 0 (6) [0.00] | 0 (5) [0.00] | 3 (7) [0.20] | 0 (1) [0.00] | ***2 (2) [0.13]*** | 0 (1) [0.00] | 1 (3) [0.07] |
| Out of sight | 0 (0) [0.00] | 0 (1) [0.00] | 0 (1) [0.00] | ***4 (2) [0.33]*** | 0 (2) [0.00] | 0 (2) [0.00] | 1 (2) [0.08] | 3 (5) [0.25] | 0 (4) [0.00] | 2 (6) [0.17] | 0 (1) [0.00] | 1 (2) [0.08] | 0 (0) [0.00] | 1 (2) [0.08] |
| Track | 0 (0) [0.00] | ***3 (3) [0.06]*** | 0 (2) [0.00] | 0 (6) [0.00] | ***14 (5) [0.26]*** | ***9 (5) [0.17]*** | ***8 (5) [0.15]*** | 8 (15) [0.15] | 0 (13) [0.00] | 9 (20) [0.17] | 0 (3) [0.00] | 1 (4) [0.02] | 0 (1) [0.00] | 1 (7) [0.02] |
| Approach | 0 (0) [0.00] | ***2 (2) [0.05]*** | 0 (2) [0.00] | ***6 (5) [0.15]*** | 0 (4) [0.00] | ***10 (4) [0.25]*** | ***6 (4) [0.15]*** | 6 (12) [0.15] | 0 (11) [0.00] | 10 (16) [0.25] | 0 (3) [0.00] | 0 (3) [0.00] | 0 (1) [0.00] | 0 (5) [0.00] |
| Antennular flick | 0 (0) [0.00] | 1 (2) [0.03] | 0 (2) [0.00] | 0 (5) [0.00] | 1 (4) [0.03] | 0 (4) [0.00] | ***9 (4) [0.25]*** | ***18 (11) [0.50]*** | 1 (10) [0.03] | 4 (14) [0.11] | 0 (2) [0.00] | 1 (3) [0.03] | 0 (1) [0.00] | 1 (5) [0.03] |
| Meral spread | 0 (0) [0.00] | 0 (2) [0.00] | 0 (2) [0.00] | 3 (5) [0.08] | 3 (4) [0.08] | ***9 (4) [0.24]*** | 3 (4) [0.08] | ***13 (11) [0.34]*** | 0 (10) [0.00] | 6 (15) [0.16] | 0 (3) [0.00] | 1 (3) [0.03] | 0 (1) [0.00] | 0 (5) [0.00] |
| Lunge | 0 (0) [0.00] | 0 (6) [0.00] | 0 (5) [0.00] | 1 (15) [0.01] | 0 (12) [0.00] | 0 (11) [0.00] | 3 (11) [0.02] | 2 (39) [0.01] | ***121 (35) [0.74]*** | 35 (54) [0.21] | 0 (7) [0.00] | 1 (9) [0.01] | 0 (1) [0.00] | 0 (16) [0.00] |
| Strike | 0 (0) [0.00] | 1 (5) [0.01] | 1 (4) [0.01] | 0 (14) [0.00] | 0 (11) [0.00] | 0 (10) [0.00] | 0 (10) [0.00] | 0 (34) [0.00] | 2 (31) [0.01] | ***136 (47) [0.96]*** | 0 (6) [0.00] | 0 (8) [0.00] | 0 (1) [0.00] | 1 (14) [0.01] |
| Telson coil | 0 (0) [0.00] | 6 (7) [0.03] | 4 (6) [0.02] | 15 (20) [0.06] | 4 (16) [0.02] | 6 (14) [0.03] | 6 (16) [0.03] | ***111 (53) [0.48]*** | 17 (47) [0.07] | 0 (74) [0.00] | ***18 (9) [0.08]*** | ***21 (12) [0.09]*** | ***2 (2) [0.01]*** | ***21 (21) [0.09]*** |
| Telson push | 0 (0) [0.00] | 0 (1) [0.00] | 0 (1) [0.00] | 0 (3) [0.00] | 0 (3) [0.00] | 0 (2) [0.00] | 0 (2) [0.00] | 0 (7) [0.00] | 0 (6) [0.00] | ***18 (8) [0.95]*** | 1 (2) [0.05] | 0 (2) [0.00] | 0 (0) [0.00] | 0 (3) [0.00] |
| Retreat | 0 (0) [0.00] | 0 (2) [0.00] | 0 (2) [0.00] | 0 (4) [0.00] | 0 (3) [0.00] | 0 (3) [0.00] | 0 (3) [0.00] | 0 (9) [0.00] | 0 (8) [0.00] | 0 (12) [0.00] | 0 (2) [0.00] | 0 (3) [0.00] | 0 (1) [0.00] | ***28 (4) [1.00]*** |
| Chase | 0 (0) [0.00] | 0 (0) [0.00] | 0 (0) [0.00] | 0 (1) [0.00] | 0 (1) [0.00] | 0 (1) [0.00] | 0 (1) [0.00] | 0 (1) [0.00] | 0 (1) [0.00] | 0 (2) [0.00] | 0 (0) [0.00] | 0 (1) [0.00] | 0 (0) [0.00] | ***2 (1) [1.00]*** |
| Bout end | 0 (0) [0.00] | 0 (0) [0.00] | 0 (0) [0.00] | 0 (0) [0.00] | 0 (0) [0.00] | 0 (0) [0.00] | 0 (0) [0.00] | 0 (0) [0.00] | 0 (0) [0.00] | 0 (0) [0.00] | 0 (0) [0.00] | 0 (0) [0.00] | 0 (0) [0.00] | 0 (0) [0.00] |



Supplementary Figure 1 - To have an equal chance of winning a contest, intruders needed (a) 0.51g more mass than residents in randomly-matched contests and (b) 0.16g more mass than residents in body length-matched contests. In (a) and (b), the black solid lines represent the observed GLM fit and the grey solid lines represent a null scenario of no residency effect. In (a) and (b), the black dashed line represents the inflection point of the observed GLM fit, where the probability of an intruder win is 50%; the grey dashed line represents the inflection point of a null scenario of no residency effect. The y-axes are equivalent in (a) and (b).



Supplementary Figure 2 – The distribution of contest costs for randomly-matched competitors within 5% of total body length matches closely to that of body length-matched competitors, suggesting that differences between randomly-matched and body length-matched protocols did not cause substantial differences in contest dynamics. Plots of average competitor body mass against log-corrected (a) contest duration and (b) total contest strikes. Solid circles represent residents in body length-matched contests, open diamonds represent intruders in body length-matched contests. Asterisks represent randomly-matched competitors that were within 5% of total body length, a range like that of our body length-matched competitors.