Supplementary materials for strength assessment and conflict resolution through mutual motor coordination

December 10, 2017

1 Supplementary materials

1.1 Mathematical analysis of the cumulative assessment model

In the cumulative assessment model, animals accumulate costs as a result of their own activity as well as the activity of their opponent. Therefore the rate of cost accumulation is a function $f(q_1, q_2)$ of both q_1 and q_2 which denote the resource holding potentials of the first and the second animal (assume $q_1 < q_2$). The total damage animal 1 is willing to accept before surrender is a function of only his own RHP and we express it as $g(q_1)$. The fight time is given as $t = \frac{g(q_1)}{f(q_1,q_2)}$. If the variation in qualities is small we can write both f and g as Taylor series, which, if we keep only the linear terms, will yield the equation $t = K\frac{1+\alpha_1 q1}{1+\alpha_2 q_1+\alpha_3 q_2}$, where the normalization constant K is used to normalize the baseline values of f and g.

The correlations observed between t, q_1 and q_2 depend on the value of the coefficients $\alpha_1, \alpha_2, \alpha_3$. For α_1, the only biologically plausible value range would be for $\alpha_1 > 0$, since higher quality should translate to a greater ability to persist despite accumulating damage. However, this does not necessarily mean that increases in the value of q_1 increase the fight times. It may be the case that the value of α_2 exceeds the value of α_1. Then, the ability to accept greater costs with increasing quality is overwhelmed by simultaneous tendency of higher quality individuals to expend more energy when attacking (such a trade-off may be rational if attacks are particularly damaging to the opponent). Thus, depending on the values of α_1, α_2, q_1 may have a positive or negative effect on fight times.

The case of α_3 is easier to analyze. A higher quality opponent should result in more damage elicited with each attack or a greater attack rate. α_3 should therefore be positive and q_2 should be negatively correlated with fights times, which is the case we observe in our data. As one final point, we note that if $\alpha_3 = 0$, then we are left with only the quality/RHP of the looser as the determinant of the fight duration. The specific case is important, because a dependence of fight times on only the RHP of the looser is widely taken to be an indicator of the WOA model. Our analysis thus points to further ambiguities that occur when one tries to determine assessment models solely based on analysis of RHP and fight time covariation. It also further motivates the utility of our new technique in circumventing these ambiguities by testing the underlying assumptions of the different assessment models directly.

1.2 Supplementary methods

1.2.1 Measurement of color changes

The easiest way to estimate color changes is to calculate the average intensity of each fish identified fish whose silhouette has been separated from the background by thresholding the image intensity. However, this approach brings with it certain biases, because the arena is not uniformly illuminated. The area near the walls in particular tends to have a stronger shadow than the central arena. Since fighting fish distribute themselves near the walls during the asymmetric phase and near the center during the symmetric phase, use of the raw intensity risks confounding the effects of location and intrinsic intensity change.

In order to remove the bias, we used linear regression to dissociate the effects of time and space on fish intensity. The rectangular arena was divided into a 6-by-6 grid and each grid rectangle was associated with a regression coefficient. Time likewise was partitioned into 2 minute long segments and each segment associated with a regression coefficient. For each fight and each fish, we carried out a separate linear regression between the fish intensity, the location and time. We used the regression coefficients associated with time as indicators of the reflectance change of each fish.

A linear regression model was used because of the following fact of physics. Reflected illumination is the product of incident light intensity $I(x, y)$ which in the setup depends on position and not on time, and the reflectance of the fish r(t), which evolves over time but not over space. Overall fish intensity C is given as $C = I(x, y)r(t)$. If we assume that the changes in reflectance and incident light intensity are small, then color change at any given time and place is well approximated as $\Delta C(x, y, t) = r_{mean}\Delta I(x, y) + I_{mean}\Delta r(t) + \Delta I(x, y)\Delta r(t) \approx r_{mean}\Delta I(x, y) + I_{mean}\Delta r(t)$, which is linear in both reflectance and illumination.

1.3 Supplementary figures

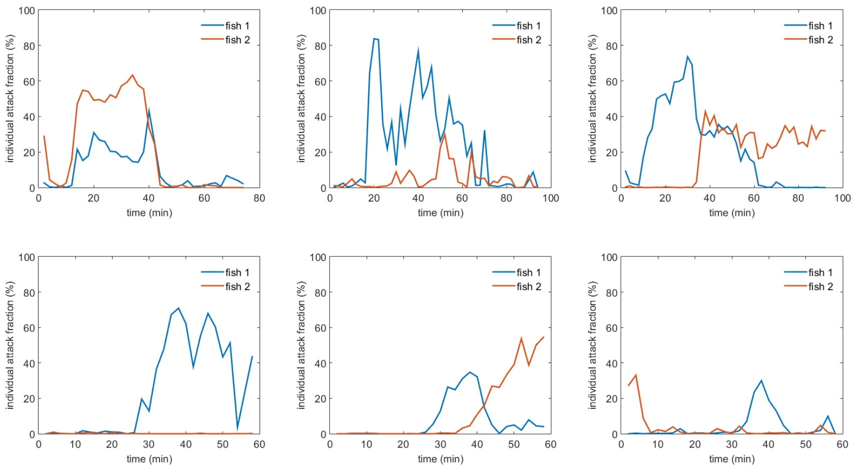

Figure S1: **An illustration of variability in fight dynamics**. A plot of the time series of attack rates for 6 different fights. Top left: a fight with a symmetric phase that ends without an asymmetric phase. Top middle: One animal predominantly attacks but the attack rate is irregular. Note the short duration symmetric phase around the 50 minute mark. Top right: A fight where the symmetric phase is both preceded and followed by an asymmetric phase.The animal who dominates in the beginning is not the eventual winner. Bottom left: a fight with only an asymmetric phase and one animal dominant. Bottom middle: a fight without a symmetric phase where the dominant individual switches in the middle of the fight without a symmetric phase. Bottom right: a fight with irregular and sporadic asymmetric attacks on both sides.

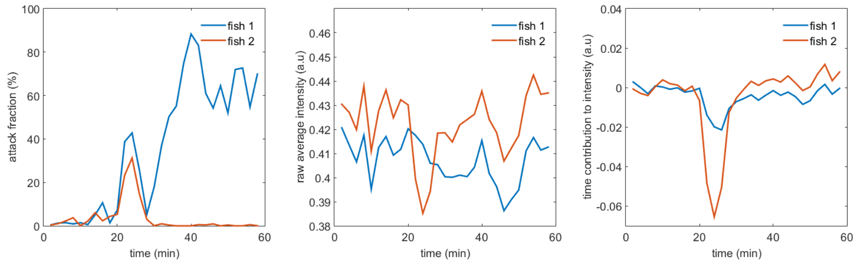

Figure S2: **Measuring changes in color**. Left panel: attack rates for the two animals over the course of the fight. Middle panel: raw average intensity of each animal over the course of the fight, the confounding influence of spatial variation in illumination has not been removed. Right panel: the change of intensity of both animals over time with confounding effects of spatial illumination inhomogeneity removed (see supplementary methods). The plots reveal a transient darkening which occurs in both animals during the fight. Notice the larger change in intensity in the eventual looser.

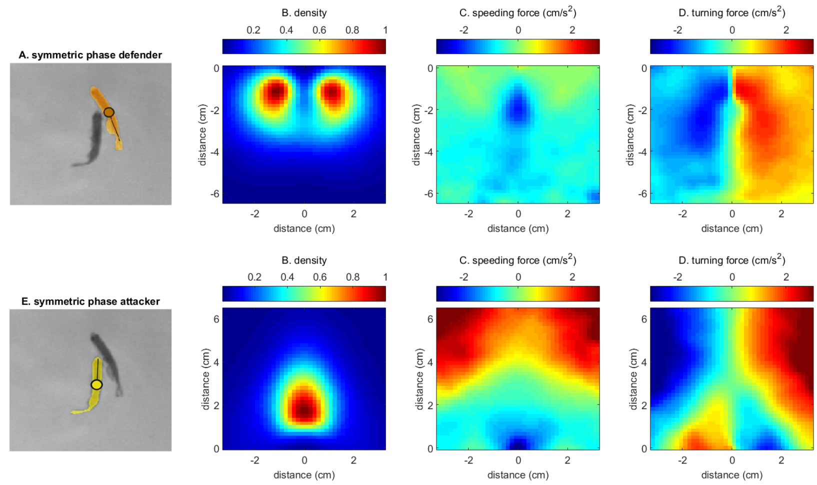

Figure S3: **Forcemaps of the symmetric phase with periods of collision removed**. Same maps as shown in main paper Figure 3 and 4 top row panels. They differ from how the maps in the main paper were calculated by the fact that we have removed the periods where the two animals were physically colliding. Top panels: Maps of the defender during the symmetric phase of the fight. Bottom panels: Maps of the attacker during the symmetric phase of the fight.

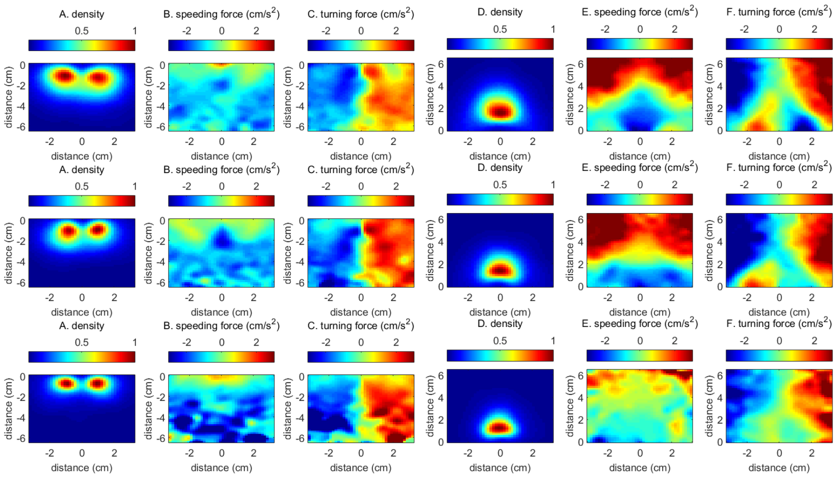

Figure S4: **Example symmetric phase forcemaps calculated based on single fights**. Each row depicts symmetric phase defender (A-C) and attacker (D-E) forcemaps for a different fight. A: defender location map B: defender speeding map C: defender turning map D: attacker location map E: attacker speeding map F: attacker turning map

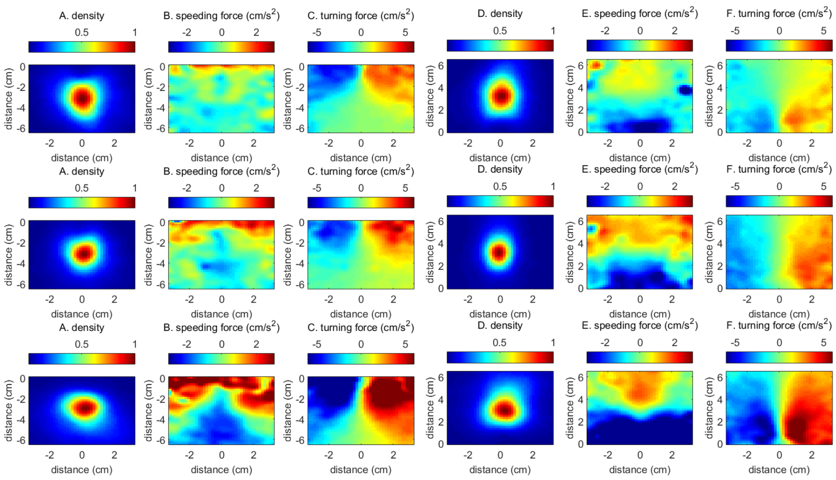

Figure S5: **Example asymmetric phase forcemaps calculated based on single fights**. Each row depicts asymmetric phase defender (A-C) and attacker (D-E) forcemaps for a different fight. A: defender location map B: defender speeding map C: defender turning map D: attacker location map E: attacker speeding map F: attacker turning map

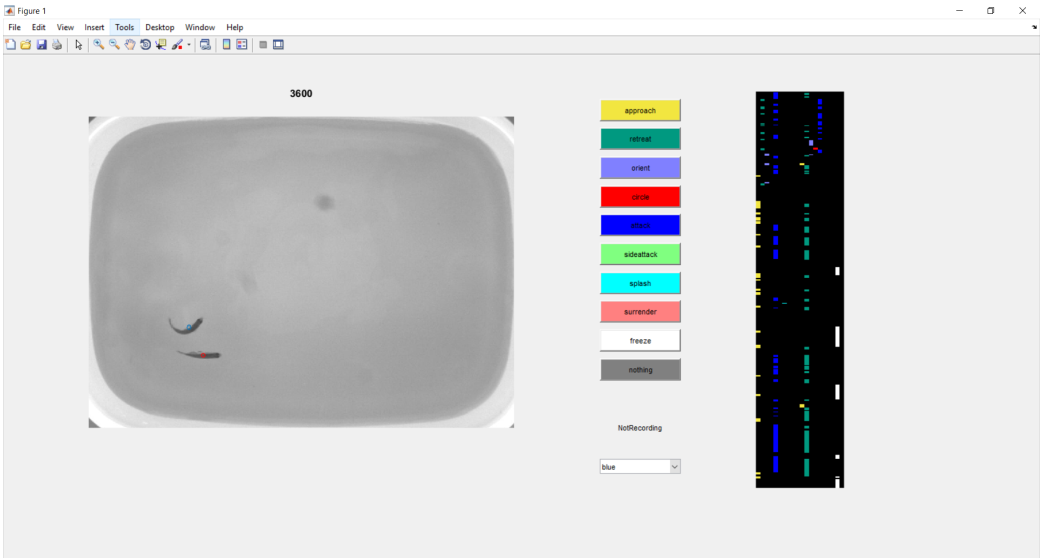

Figure S6: **An example frame of the GUI used to annotate videos**. The left panel shows a scrollable feed of the video which is used to examine the video frame by frame with controllable gain of scrolling. The middle panel displays a set of buttons to annotate behaviors and a menu to choose the focal animal. The right panel shows an ethogram which is dynamically updated as the investigator adds new annotations.