Supplemental Figures

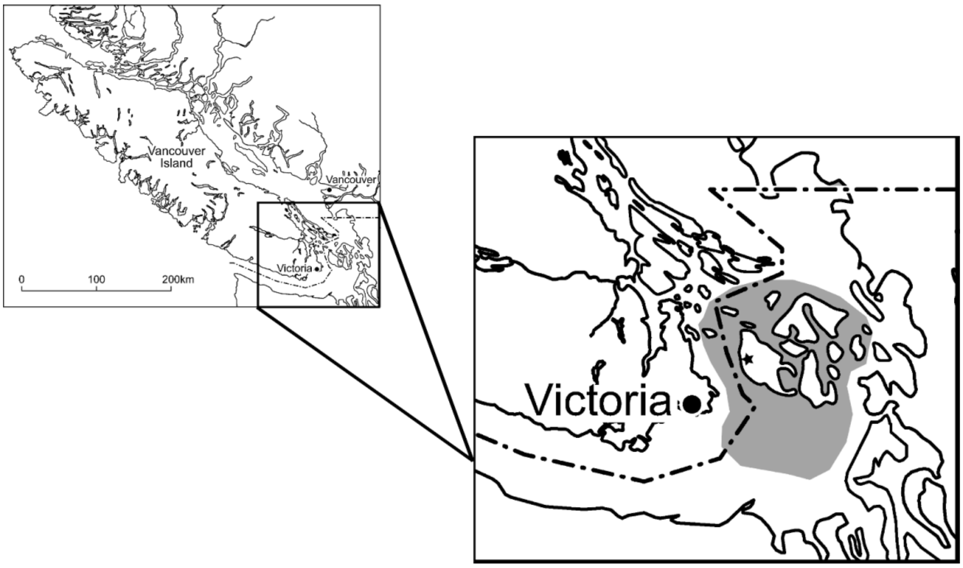

Figure S1. Map of Haro Straight and homerange of Southern resident killer whales Shaded area is approximate location in which data were collected. Star is location of Center for Whale Research. Southern resident killer whales spend the majority of the summer months in this shaded area, which coincides with the presence of Chinook salmon, their primary food source. . Related to Experimental Procedures.

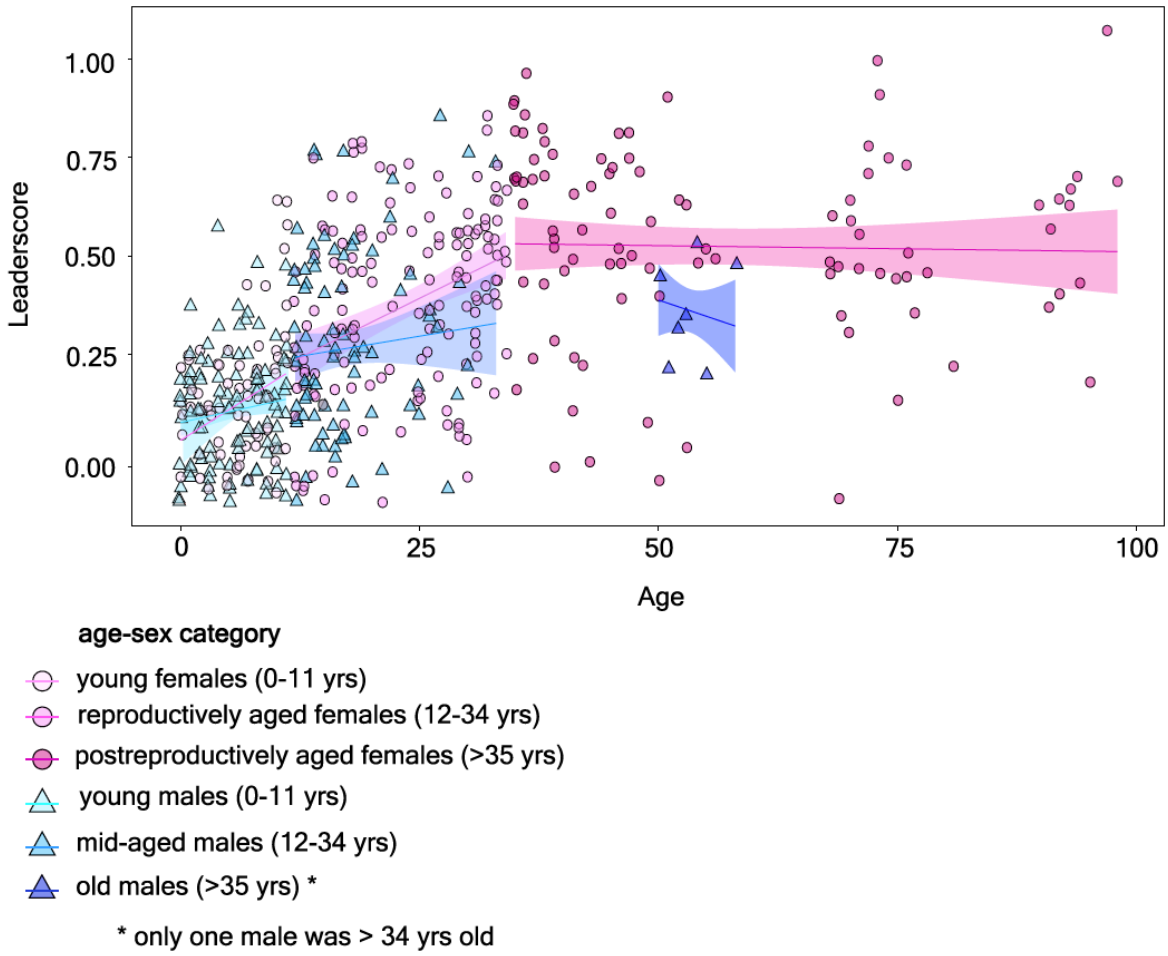

Figure S2. Leaderscore relative to age for Southern resident killer whales. Adult females had significantly higher leaderscores than adult males (*N*=48 females, 24 males, 419 whale years). Statistical models accounted for age as a covariate, to control for the fact that females tend to live longer than males. In a model that contained only adult females, postreproductively aged females had significantly higher leaderscores compared to reproductively aged females (*N*=23 postreproductive females, 32 reproductive females, 307 whale years). Related to Experimental Procedures and see Figure 1.

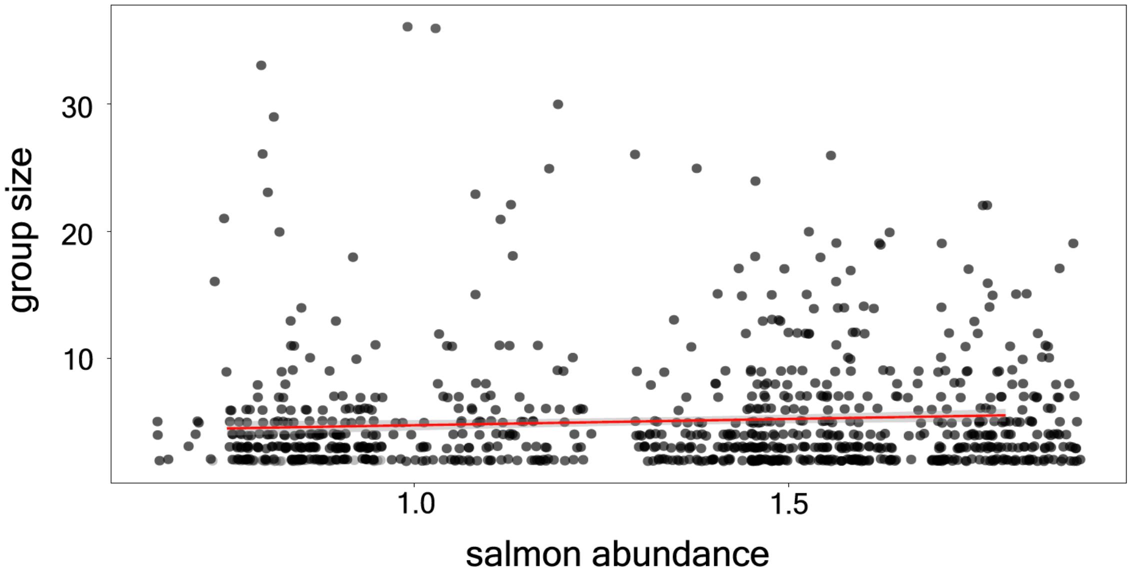

Figure S3. Group size was weakly related to salmon abundance in Southern resident killer whales (*N*=906 observed groups). We accounted for the impact of group size in all of our permutation-based statistical models. Related to Experimental Procedures and see Figure 2.

Supplemental Tables

Table S1: Summary of regression models. See also Experimental Procedures.

Question	Model	Response variable	Subjects	Explanatory variables
Who leads?	1.1	# times seen leading relative to # times seen following	All whale as leaders	Age of leader Sex of leader Age of leader * Sex of leader
	1.2	# times seen leading relative to # times seen following	Adult leaders	Age of leader Sex of leader Age of leader * Sex of leader
	1.3	# times seen leading relative to # times seen following	Adult female leaders	Reproductive state of leader (Categorical: reproductively aged, postreproductively aged)
	1.4	# times seen leading relative to # times seen following	Adult female leaders	Salmon abundance Reproductive state of leader Reproductive state of leader * Salmon abundance
Who follows?	2.1	#times whale A followed whale B relative to # times A did not follow B when A and B were together	All whales can be A or B	Sex A Sex B Age A Difference in age between A and B Sex A * Sex B
	2.2	#times whale A followed whale B relative to # times A and B were together	All whales can be A. Adult females can be B	Sex A Age A Is B the mom of A? (Y / N) Reproductive state of B (reproductive / postreproductive) Sex A * Is B the mom of A? (Y / N) Sex A * Reproductive state of B Reproductive state of B * Is B the mom of A? (Y / N)
Does following change in relation to salmon abundance?	3.1	#times whale A followed whale B relative to # times A and B were together	All whales can be A. Adult females can be B	Salmon abundance Is B the mom of A? (Y / N) * Salmon abundance Reproductive state of B * Salmon abundance Is B the mom of A? (Y / N) * Salmon abundance * Sex A Reproductive state of B * Salmon abundance * Sex A Sex A Age A Is B the mom of A? (Y / N) Reproductive state of B (reproductive / postreproductive) Sex A * Is B the mom of A? (Y / N) Sex A * Reproductive state of B Reproductive state of B * Is B the mom of A? (Y / N)

Table S2: Results of regression models. See also Figures 1,2 and 3.

a. Who leads group movement? (all whales as leaders)

Variable	Coefficient	P-value
Age of leader	0.023	<0.001
Sex of leader	-1.11	<0.001
Age of leader* Sex of leader	0.019	<0.001

b. Who leads group movement? (adult whales as leaders)

Variable	Coefficient	P-value
Age of leader	0.010	<0.001
Sex of leader	-0.929	<0.001
Age of leader* Sex of leader	0.009	0.093

c. Who leads group movement? (adult females as leaders)

Variable	Coefficient	P-value
Reproductive state of leader	0.497	<0.001

d. Which adult females lead in relation to salmon abundance?

Variable	Coefficient	P-value
Reproductive state of leader	1.387	0.001
Salmon abundance	0.128	0.015
Reproductive state of leader * Salmon abundance	-0.672	0.048

e. Who do whales follow? (leaders and followers are any age and either sex)

Variable	Coefficient	P-value
Sex of follower	0.191	0.016
Sex of leader	-0.992	<0.001
Age of follower	0.017	<0.001
Difference in age between follower and leader	-0.029	<0.001
Sex of follower * Sex of leader	-0.210	0.512

f. Who do whales follow? (leaders are adult females only)

Variable	Coefficient	P-value
Sex of follower	-0.195	0.001
Age of follower	-0.009	<0.001
Is the leader the mother of the follower? (y/n)	0.865	0.059
Reproductive state of the leader	0.621	0.002
Sex of follower * Is the leader the mother of the follower	0.393	<0.001
Sex of follower * Reproductive state of leader	0.332	0.111
Is the leader the mother of the follower? * Reproductive state of the leader	-0.149	0.172

g. How often do whales follow adult females in relation to salmon abundance?

Variable	Coefficient	P-value
Sex of follower	0.361	0.165
Age of follower	-0.008	0.267
Is the leader the mother of the follower? (y/n)	1.132	0.619
Reproductive state of the leader	1.890	0.163
Sex of follower * Is the leader the mother of the follower?	0.526	0.466
Sex of follower * Reproductive state of the leader	-0.034	0.385
Is the leader the mother of the follower? * Reproductive state of the leader	-0.287	0.577
Salmon abundance	0.445	0.413
Salmon abundance * Is the leader the mother of the follower	-0.158	0.606
Salmon abundance * Reproductive state of the leader	-0.850	0.216
Salmon abundance * Sex of follower	-0.357	0.091
Salmon abundance * Is the leader the mother of the follower * Sex of follower	-0.123	0.536
Salmon abundance * Reproductive state of the leader * Sex of follower	0.199	0.366

Supplemental Experimental Procedures

Study population and sampling. We studied the Southern resident killer whale population that is regularly seen around the southern end of Vancouver Island during the summer months that coincide with the migration of Chinook salmon (*Oncorhynchus tshawtscha*) [S1, S2] (Figure S1). This population has been the focus of a long-term monitoring program run by the Center for Whale Research, San Juan Island, WA, U.S.A. since 1976. Individual killer whales were identified by differences in fin shapes, saddle patches and the presence of any nicks or scratches. Sex was determined by distinct pigmentation patterns around the genital slits [S3]. Dates of birth for animals born before the start of the study were determined according to previously described methods [S4]. Briefly, birth dates for juveniles born before the start of the study were estimated by subtracting the mean age of maturity (15 years for both sexes) from the year they matured [S4]. Dates of birth for adult females born before the start of the study were estimated by subtracting 15 years from the estimated year of birth of her oldest offspring, which was assumed to be her first viable calf. Dates of birth of adult males born before the start of the study were estimated by assuming that they attained physically maturity the year they were first observed. We made use of data collected during the summer (May-Sept) of 2001 to 2009 during which time 102 individuals (58 females and 44 males) ranging from 0 to 91 years of age were observed. The survey effort totalled 3806 hours, 42% of which was in the presence of the whales. During this time, trained staff from the Center for Whale Research collected a total of 751hrs of video footage from boats and the shore, which we used to quantify leading and following.

Quantifying leadership. One of the challenges of defining leadership in animal groups is to determine the information status of individuals [S5]. To quantify leadership patterns, we used a standard approach [S6, S7], which infers information status and leadership by identifying which individuals occupy the front (lead) position within groups during directional travel. This approach is supported by work demonstrating that individuals who have a larger influence on patterns of group movement occupy the front positions [S8-S10]. We used video clips of whales travelling in the same direction and at the same speed and in which all individuals could be identified. We defined 'groups' as individuals travelling within ~3 body lengths of any other individual using the chain rule [S4, S11]. We recorded the spatial position of group members during successive surfacings and classified the individual positioned at the front of a group as the leader, and all other individuals as followers (Figure 1a, Movie S1). Within a given day individuals were recorded a maximum of once as a leader and/or follower. We removed one whale that was only observed in one of the nine years of study from analyses.

Salmon Abundance. Yearly Chinook salmon abundance was calculated using data provided by the Pacific Salmon Commission test fisheries (http://www.psc.org/info.htm) as the number of fish caught in three specific areas (the west coast of Vancouver Island, the north coast of British Columbia, and south-eastern Alaska) that are frequented by resident killer whales, divided by the total catch for the reference period from 1979 to 1982 [S12].

Statistical Analyses. We ran a series of binomial regression models to address three general questions: 1) Who leads group movement?, 2) Who do whales follow?, and 3) Does following change in relation to salmon abundance? (Table S1). We divided our data by each of our nine years of observation, which resulted in a total of 647 whale years. We used permutation tests to control for group-size effects, autocorrelations, repeated-measures, and sampling biases [S13]. We generated permuted datasets (10,000 samples, 1000 swaps per sample) by randomizing either the identity of the leader within a group while preserving group composition (questions 1 and 2) or by randomizing the identities of followers between groups within the same year while holding the identity of the leader constant (question 3). We fit our regression models to our permuted data, the results of which we used as null models. We generated P-values by comparing our observed regression coefficients to the distribution of regression coefficients derived from the permuted data [S14]. We ran regression models in the lme4 package in R [S15].

Who leads group movement? We tested whether individuals with specific attributes (i.e. age, sex) were more likely to lead group movement. To do this, we ran four regression models with a binomial distribution and logit link function with the response variable coded as the number of times an individual was observed leading group movement in a given year relative to the number of times that individual was observed as a follower. We removed individuals that were only observed once in a given year, regardless of whether they were leading or following when observed. The general annotation of the models that ask who leads group movement is found in syntax 1.

wholeads <- glm(cbind(number of times observed leading, number of times observed following) ~ explanatory variables $X_{i\text{-}j}$, data = wholeads, family = binomial)

Syntax 1

We used each of the four models to address a specific question. First, we asked who leads group movement among all whales (Table S1). Data from males and females of all ages were included in this analysis. Age and sex were explanatory variables, as was the interaction between them to account for sex differences that are age-specific. We next explored leadership among adult whales only because young animals often follow their mothers [S4]. All juveniles (younger than 12 years, therefore classed as pre-reproductive: [S16]) were removed from this analysis. We next explored the impact of reproductive state on leadership in adult females. Females were categorised as either reproductively aged (12-34 years old) or postreproductively aged (35+ years). We used age categories to indicate reproductive state instead of data on whether or not a female had ceased reproduction due to the potential impact of missed reproductive events, e.g. miscarriages, calves that die before being sighted, in addition to the censored nature of our data, i.e. females that are still alive may give birth in up-coming years. The lower age limit of females in the postreproductive category was based on the mean age at last reproduction (mean = 35.2, SD = 6.6, n = 17) for Southern resident female killer whales that lived past the peak age of mortality (50 years).

Finally, we investigated whether salmon abundance influenced leadership in adult females. We asked whether the tendency to lead among females of different reproductive states (reproductive vs postreproductive) was modulated by the abundance of salmon. That is, we asked whether there were differences in the likelihood of postreproductively aged females acting as leaders when salmon abundance was relatively low, compared to the likelihood that reproductively aged females would act as leaders. We did this by including the interaction term between salmon abundance and reproductive state in the model. Null models to determine significance of observed relationships were generated by permuting the identities of leaders within groups. This allowed us to ask whether the likelihood of a given individual leading was greater than would be expected by chance.

Who do killer whales follow? We next examined which types of individuals followed which types of leaders. For each pair of whales observed in a given year, we recorded the number of times whale A followed whale B. We used these data as our response variable in binomial regression models with a logit link function with the response variable coded as the number of times whale A followed whale B in a given year relative to the number of times whale A was in observed travelling in the same group as whale B but was not following whale B. We excluded pairs of whales that were seen together infrequently to improve confidence in our measurement of dyadic leader-follower relationships. Our results did not differ qualitatively when whales seen together fewer than 3, 4, or 5 times were excluded (beyond this, our sample size begins to erode) and we therefore only present results for pairs of whales seen 4 times or more. Explanatory variables included attributes of individual A and individual B. The general annotation of these models is found in syntax 2.

whofollows <- glm(cbind(number of times A followed B, number of times A did not follow B when A and B were together) ~ explanatory variable $X_{i\text{-}j}$, data = whofollows, family = binomial)

Syntax 2

We ran two models, which are outlined in Table S1. First, we asked who whales follow in general. Individuals A and B were whales of all ages and both sexes. The sex of A and B, and the interaction between the sex of A and B were included as explanatory variables. We also included the age of individual A, as well as the difference in age between whales A and B. We found that all whales were more likely to have an adult female leader (Table S2), and therefore examined following of adult females in more detail by restricting the identity of individual B to adult females only. We used our long-term demographic data to determine whether individual B was the mother of individual A. We also classed individual B as either reproductively aged or postreproductively aged. We included the sex of individual A, the age of individual A, the reproductive state of individual B, and whether or not (Y/N) individual B was the mother of individual A as explanatory variables. We additionally examined the interactions between the sex of individual A, the reproductive state of B, and whether B was the mother of A. Null models to determine significance of observed relationships were generated by permuting the identities of leaders within groups. This allowed us to maintain the observed distribution of leader-follower dyads and to ask whether the likelihood of a given individual acting as a follower was greater than would be expected by chance.

Does following change with changes to salmon abundance? Overall, we found that postreproductively aged females lead group movement and do so especially in years with low salmon abundance (Table S2). We also found that whales were more likely to follow postreproductively aged females compared to reproductively aged females, and that males and females did not differ in their tendency to follow postreproductively aged females (Table S3). In order to determine whether the relationship between the sex of the follower and the reproductive state of the leader differed over time, we asked whether, given the available adult female leaders, were males more likely than females to follow postreproductively aged females in times of low salmon abundance (Table S4)? To address this question, we randomized our data 10,000 times, but in this case we held the identities of the leaders constant, while shuffling followers between groups. This permutation allowed us to ask, given the known identities of leaders across years, is the observed likelihood of a follower of a certain type (e.g. males) following a leader of a certain type (e.g. postreproductively aged females) greater in years of low salmon abundance than would be expected by chance.

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