

Regarding ACR 6

RC 024

10/16/15

To all Board of Fish members,

The Alitak District sockeye escapement has numerous problems that need to be discussed before we start fishing next summer. The two I would like to focus on are escapements to Upper Station and the recurring large numbers of jacks to Frazer.

The 19% jack escapement into Frazer this last summer (2015) is almost double the target amount suggested by Fish & Game. I am going to show why jacks are a problem and why 4% is a more desirable percentage.

I have provided the Board with a recent study on jack characteristics that influence returning salmon. *Sneaker "jack" males outcompete dominant "hooknose" males under sperm competition in Chinook salmon –2013*

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Their studies clearly show:

- "Overall, an embryo had a probability of 0.576 of being sired by a jack male....In other words, jack sperm were 1.36x as competitive as hooknose sperm..."
- "Jack sperm swim faster than hooknose sperm and sperm velocity is a primary determinant of fertilization success in sperm competition in numerous fish species..."
- "If inbreeding avoidance mechanisms exist in Chinook salmon, they are likely to favor jack male sperm."
- "Our finding that jack males make competitively superior sperm, calls into question a common viewpoint that jack males are less fit than dominant males and are making the best of a bad situation."
- "Reichard et al. (2007) reviewed theoretical and empirical examples where females might actually benefit from allowing sneaker males (jacks) to fertilize their eggs, including increased genetic diversity in their offspring. Interestingly, female bluegill spawn more eggs when sneaker males are present, and sneaker males in that system also fertilize a disproportionate share of eggs (Fu et al. 2001). This could be an example whereby female choice favors fertilization by sneaker males. In fact, precocious sexual

maturity might be a general indication that sneaker males are more genetically robust to environmental stresses, a very different viewpoint that one that assumes they are poor quality individuals. “

- “We demonstrated that sneaker jack males outcompete dominant hooknose males via a loaded raffle (higher quality sperm).”
- “In addition, female egg donors affected sperm competition outcomes.... (favoring the jacks).”
- “Jacking is also affected by environmental influences, one of the biggest of these beside food intake is temperature. Temperature accelerates metabolism and the fastest growing salmon are the ones that preferentially jack. “

There are some benefits that jacks bring to the genetic pool, however. They help the overall fitness of a run since they have much higher MHC diversity (disease recognition and immunity), so when they breed they infuse the population with beneficial genetics. However, a balance must be achieved between too many and not enough. A 4% escapement goal would be more in line with local Kodiak sockeye runs and mirrors the neighboring Ayakulik which has the closest proximity to the Alitak District. And interestingly, most of the sockeye of Frazer Lake are the descendants of the brood stock from the Ayakulik system. Frazer Lake had a 19% jack escapement for this last summer (2015) which is almost 5 times the norm in nearby systems (It has been as high as 70%).

In regards to culling anything over 4%, I suggest it should take place at the Frazer fish pass or weir rather than the Dog Salmon weir. This will eliminate the difficulties encountered at Dog Salmon when large numbers of pinks are returning at the same time.

Another environmental factor that may start becoming an issue (at least in regards to jacks) is the inclination for jacks to form in warmer temperatures. The warmer water accelerates metabolism and the fastest growing salmon are the ones that preferentially jack. This would be a **most** unwelcome development and is worthy of annual monitoring by the department. We had water temps that hit 60 degrees this summer, much higher than in the past.

Another area of concern in the Alitak District is the Upper Station run. The late run barely reached minimum escapement even though no one was fishing for at least 6 weeks prior to shutting down the weir. When the numbers are crunched for the 2015 summer, the escapements indeed fall within the ranges set forth by F&G, but where are the harvestable

fish? There isn't much left for the fishermen. The department has "imposed severe commercial salmon fishery restrictions" for many of the past summers.

This summer, Fish and Game continued the management plan of years past and it is inadequate when dealing with the conflicts of managing a weak system that is in close proximity of a strong one. We were allowed to fish at Dog Salmon flats in 2014 rather than everyone fishing at their traditional spots. This option allowed us to fish on a strong returning run (Frazer) with less interception of fish heading to the neighboring weak Upper Station. The Board needs to rework the wording in the management plan so that F&G has the ability to allow the Dog Salmon Flats openings to occur, particularly when Upper Station escapements are just barely above the minimum for that particular date in time. Every setnetter in the Alitak District is on board with a coop type fishery at Dog Salmon Flats, aimed at conserving Upper Station, while preventing overescapement at Frazer Lake.

Our family has had some difficult seasons over the past 14 years. The Alitak area is struggling and the trend is for more of the same. There are numerous actions Fish and Game can take to improve the conservation of the Alitak sockeye runs. This dire situation needs to be addressed. We have some suggestions that we think could be beneficial. This is why we are hoping to continue the discussion with the Board in the near future. The problems affecting our area are clearly a conservation issue at the very least. Thanks for taking the time to consider our request.

The Underwood Family

References

Reichard, M.,S. C. Le Comber, and C. Smith. 2007. Sneaking from a female perspective. *Anim. Behav.* 74:679-688

Young B, Conti DV, Dean MD. 2013. Sneaker "jack" males outcompete dominant "hooknose" males under sperm competition in Chinook salmon (*Oncorhynchus tshawytscha*). *Ecol Evol.* 3:4987-4997

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To Board Members Regarding ACR 6

From: Brad Underwood

Ecology and Evolution

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Sneaker "jack" males outcompete dominant "hooknose" males under sperm competition in Chinook salmon (*Oncorhynchus tshawytscha*)

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Abstract

In a variety of taxa, males deploy alternative reproductive tactics to secure fertilizations. In many species, small "sneaker" males attempt to steal fertilizations while avoiding encounters with larger, more aggressive, dominant males. Sneaker males usually face a number of disadvantages, including reduced access to females and the higher likelihood that upon ejaculation, their sperm face competition from other males. Nevertheless, sneaker males represent an evolutionarily stable strategy under a wide range of conditions. Game theory suggests that sneaker males compensate for these disadvantages by investing disproportionately in spermatogenesis, by producing more sperm per unit body mass (the "fair raffle") and/or by producing higher quality sperm (the "loaded raffle"). Here, we test these models by competing sperm from sneaker "jack" males against sperm from dominant "hooknose" males in Chinook salmon. Using two complementary approaches, we reject the fair raffle in favor of the loaded raffle and estimate that jack males were ~1.35 times as likely as hooknose males to fertilize eggs under controlled competitive conditions. Interestingly, the direction and magnitude of this skew in paternity shifted according to individual female egg donors, suggesting cryptic female choice could moderate the outcomes of sperm competition in this externally fertilizing species.

Introduction

Evolutionary processes have produced a stunning variety of characteristics that appear adaptive for male reproductive success, including morphological weaponry, genitalic, and sperm features, and alternative mating strategies (Andersson 1994). While dominant males fight to secure territory and access to females, many species include "sneaker" males that forego the physiological costs associated with dominance and instead attempt to reproduce surreptitiously. Sneaker males usually encounter numerous obstacles to fertilization, including reduced access to females, and the virtual guarantee that their sperm will be competing with sperm from other males. Nevertheless, sneaking represents an evolutionarily stable strategy under many conditions.

How sneaker males compensate for their apparent reproductive disadvantages is a subject of much interest. Using game theory, Parker (1990b) formalized the "sneak-guard" model to identify conditions where sneaker males represent an evolutionarily stable strategy (Maynard Smith 1982; Gross 1985, 1991, 1996; Parker 1990a,b; Tanaka et al. 2009). Finite resources create a fundamental trade-off between development of precopulatory (i.e., weaponry) versus postcopulatory (i.e., sperm competitive ability) traits (Parker 1990a; Pitcher et al. 2009; Tazzyman et al. 2009; Fitzpatrick et al. 2012). In general, dominant males invest in weaponry that can be used to monopolize access to females, while sneaker males invest in ejaculates to win fertilizations through sperm competition.

Under the sneak-guard model, sneaker males invest in ejaculates via two nonexclusive mechanisms, the "fair

raffle" versus the "loaded raffle". A fair raffle implies that sperm competition outcomes are determined by the relative quantity of competing sperm, and selection favors sneaker males that produce more sperm per unit body mass than dominants. Consistent with this prediction, sneaker males in many different species have larger testes relative to their body mass compared with dominant males (Stockley and Purvis 1993; Gage *et al.* 1995; Stockley *et al.* 1997; Taborsky 1998; Simmons *et al.* 1999; Rasotto and Mazzoldi 2002; Neff *et al.* 2003; Schulte-Hostedde *et al.* 2005; Rudolfsen *et al.* 2006; Montgomerie and Fitzpatrick 2009; Simmons and Fitzpatrick 2012). Under a loaded raffle, selection favors sneaker males that produce higher quality sperm compared with dominant males (Parker 1990a). Sperm quality can include enhanced velocity and/or ATP stores (Taborsky 1998; Uglem *et al.* 2001; Vladić and Järvi 2001; Burness *et al.* 2004; Fitzpatrick *et al.* 2007; Locatello *et al.* 2007; Pitcher *et al.* 2009; Vladić *et al.* 2010; Beausoleil *et al.* 2012; Tourmente *et al.* 2013), increased longevity (Smith and Ryan 2010), and/or morphological features (Stockley *et al.* 1997; Simmons *et al.* 1999; Balshine *et al.* 2001; Burness *et al.* 2004; Snook 2005; Smith and Ryan 2010; Gómez Montoto *et al.* 2011; Tourmente *et al.* 2011). Differences in sperm quality can also arise from a male's behavioral adaptations, such as better-timed sperm release close to eggs.

Most direct studies of sperm competition among dominant and sneaker males have been unable to distinguish the fair and loaded raffle models. Fu *et al.* (2001) estimated that sneaker bluegill males fertilized 78% of embryos when in competition with a dominant male, but it is not clear whether this was due to differences in spawning behavior, ejaculate volume, density, and/or sperm quality. Stoltz and Neff (2006) estimated that sneaker male sperm was nearly twice as competitive as dominant male sperm, but sneaker male sperm were released closer to the female's eggs to mimic natural conditions. Vladić *et al.* (2010) competed sperm from sneaker and dominant males in Atlantic salmon, finding that sneaker males fertilized 3.6× as many offspring as dominant males after sperm numbers were controlled. Other sperm competition experiments controlled sperm count and distance to female gametes, but competing males were chosen randomly instead of explicitly testing a dominant versus sneaker male (Evans *et al.* 2003; Gage *et al.* 2004; Hoysak *et al.* 2004; Liljedal *et al.* 2008; Boschetto *et al.* 2011).

Here, we perform controlled *in vitro* sperm competition experiments between dominant "hooknose" and sneaker "jack" males in Chinook salmon (*Oncorhynchus tshawytscha*). Using a combination of maximum likelihood, logistic regression, and independent subsampling,

we reject the fair raffle in favor of the loaded raffle model, demonstrating that sneaker jack males make competitively superior sperm to dominant males. Although jack males outcompeted hooknoses overall, the magnitude and even the direction of their competitive superiority shifted with individual female egg donor, suggesting females influence the outcomes of sperm competition.

Materials and Methods

Study system

Chinook salmon offer an ideal study species for asking whether a sneak-guard system follows the fair or loaded raffle. Young fry leave their natal stream during the smolt and spend the next few years in the open ocean (Healey 1991). As in many salmonids, large dominant "hooknose" males return to their natal streams after 3–7 years, and possess elaborate secondary sexual characteristics such as a kype (the "hooked nose"), a defensive hump, and elongated teeth, which they use to fight for dominance and establish access to nesting females (Gross 1985; Healey 1991; Quinn and Foote 1994; Allen *et al.* 2007). Sneaker males, referred to as "jacks", are roughly half the size of hooknose males and do not develop any of these secondary sexual characteristics (Berejikian *et al.* 2010; Williamson *et al.* 2010). Instead, jacks take on cryptic coloration and occupy the peripheral edges of rivers, where they wait for hooknose males to begin spawning with females, then dart in and around the spawning pair to release their sperm while avoiding aggressive interactions with dominant males (Heath *et al.* 1994; Fleming and Reynolds 2004).

Because dominant males vigorously defend nesting females, they are expected to outcompete jack males for access to ova (Rutter 1903; Ginzburg 1972; Gile and Ferguson 1995; Perchec *et al.* 1998; Hoysak and Liley 2001; Kime *et al.* 2001; Cosson 2010; Sørum *et al.* 2011). Consistent with this expectation, sneaker males only sire about 20% of offspring under natural spawning conditions when competing against dominant males (Hutchings and Myers 1988; Jordan and Youngson 1992; Berejikian *et al.* 2010). However, in spite of their reproductive disadvantages, jacks represent ~10% of the males in the population, across multiple salmonid species (Myers *et al.* 1998; Appleby *et al.* 2003; Carlson *et al.* 2004; Fleming and Reynolds 2004). In combination with the high heritability of jacking (Heath *et al.* 2002; Berejikian *et al.* 2011), these results suggest that sneaking is an evolutionarily stable strategy in this system and that jacks compensate for their disadvantaged mating positions via other mechanisms such as sperm competitive ability.

Fish selection and gamete collection

Our experimental design represents a trade-off between testing numerous fully independent parents versus multiple observations from the same gamete combinations. We increased the number of observations per sperm-egg combination in order to test for sperm-by-egg interactions. We account for the non-independence of this approach using a variety of statistical methods and subsampling as described below.

A total of five females, five jack males, and five dominant hooknose males (Appendix S1) were collected at the Big Creek Hatchery weir (Oregon Department of Fish and Wildlife) in northwestern Oregon during early October of the 2008 spawning season. Jack males were distinguished from hooknose males based on their smaller size, lack of defensive hump, lack of kype, smaller teeth, and cryptic coloration resembling a female. Only sexually mature fish in good physical condition – without injuries, fungus, and fin wear – were selected.

Prior to gamete collection, fish were wiped dry with paper towels to preclude contamination with water and mucus. Sperm were collected in a beaker by gently bending the male and immediately placed at 4°C. Sperm are quiescent at this stage and do not become active until exposure to water (Kime *et al.* 2001; Cosson 2010). Females were euthanized and egg masses dissected. Eggs from each female were divided into five approximately equal batches for subsequent exposure to sperm. Sperm count for each male was measured with three independent spermatocrit reads; the ejaculate was centrifuged and the percent of packed sperm taken as a measurement of sperm count per ejaculate (Bouck and Jacobson 1976; Appendix S2). Jack and hooknose sperm are indistinguishable in their sperm head length or width, or flagellum length (Flannery *et al.* 2013), so spermatocrit measurements are appropriate for comparing sperm counts between males. No formal attempt was made to equalize sperm counts across treatments, but no significant difference was observed between jack and hooknose spermatocrit ($F_{1,20} = 0.98$, $P = 0.33$; Appendix S2). Therefore, paternity skew between male morphs cannot be

ascribed to differences in sperm count. In an attempt to minimize experimental noise associated with similar experiments (Gharrett and Shirley 1985; Withler 1988), each jack:hooknose sperm mixture was mixed once, then applied to five different aliquots of female eggs (five total sperm mixtures rather than 25 total sperm mixtures, Table 1).

Experimental crosses/mating scheme

To include male–female interaction terms, a variant of the North Carolina II breeding design (Comstock and Robinson 1948) was employed, with each of five rows representing eggs from one female, and each of five columns representing a unique mixture of sperm from one hooknose and one jack male (5 mL sperm from one hooknose male, 5 mL from one jack male, 10 males total; Table 1). Sperm combinations were mixed by gently swirling a beaker for 5 min. Approximately 500 eggs from each female were placed on one side of a new beaker and 1 mL of the sperm mixture on the opposite side. Gametes were mixed with the turbulent addition of 1000 mL of natural temperature Big Creek river water and swirled for 10 sec. The egg–sperm mixtures were allowed to stand for 5 min before transfer to Heath tray incubators at the Big Creek Hatchery facilities. Fertilized eggs were reared according to standard hatchery practices, with each individual replicate in a separate tray. Mortalities were removed and collected each week until the eyed stage (approximately 40 days postfertilization), at which time, all eggs were euthanized and preserved for subsequent genetic analysis. Mortality was so low (<5%) that even if one male type sired all the dead eggs in a tray, our conclusions below would not change.

Genetic analysis/parentage assignment

DNA was extracted from muscle tissue taken from the 15 possible parents and from the heads of individual embryos using an Epicentre MPC extraction kit, following the manufacturer's instructions. Three microsatellite loci – OTS213 (Greig *et al.* 2003), OTS107 (Nelson and Bea-

Table 1. Paternity under sperm competition

| | Hooknose 1:Jack 1 | Hooknose 2:Jack 2 | Hooknose 3:Jack 3 | Hooknose 4:Jack 4 | Hooknose 5:Jack 5 | Row sum |
|------------|---------------------|---------------------|---------------------|---------------------|---------------------|---------------------|
| Female 1 | 31:55 (0.36:0.64) | 31:49 (0.39:0.61) | 39:49 (0.44:0.56) | 25:44 (0.36:0.64) | 17:29 (0.37:0.63) | 143:226 (0.39:0.61) |
| Female 2 | 26:35 (0.43:0.57) | 18:28 (0.39:0.61) | 19:27 (0.41:0.59) | 32:45 (0.42:0.58) | 10:36 (0.22:0.78) | 105:171 (0.38:0.62) |
| Female 3 | 47:44 (0.52:0.48) | 37:47 (0.44:0.56) | 14:28 (0.33:0.67) | 27:41 (0.40:0.60) | 39:29 (0.57:0.43) | 164:189 (0.46:0.54) |
| Female 4 | 42:35 (0.55:0.45) | 38:8 (0.83:0.17) | 32:14 (0.70:0.30) | 7:39 (0.15:0.85) | 23:45 (0.34:0.66) | 142:141 (0.50:0.50) |
| Female 5 | 28:17 (0.62:0.38) | 22:47 (0.32:0.68) | 31:14 (0.69:0.31) | 10:59 (0.14:0.86) | 39:50 (0.44:0.56) | 130:187 (0.41:0.59) |
| Column sum | 174:186 (0.48:0.52) | 146:179 (0.45:0.55) | 135:132 (0.51:0.49) | 101:228 (0.31:0.69) | 128:189 (0.40:0.60) | 684:914 (0.43:0.57) |

Number of embryos sired by hooknose:jack (proportions in parentheses).

cham 1999), and RT212 (Spies et al. 2005) – allowed unambiguous paternity assignment in any given cross (Appendix S1). One primer in each pair was dyed with HEX or FAM for downstream scoring. PCR amplifications consisted of 2 min of denaturation at 94°C, followed by 35 cycles of 30 sec denaturation (94°C), 30 sec annealing (each locus-specific temperature), 40 sec elongation (72°C), and a final 5 min extension at 72°C. Genotyping was performed by the University of Arizona Genetics Core on an ABI Prism 3730 DNA Analyzer (Applied Biosystems, Grand Island, NY). A total of 1598 embryos were genotyped, with an average 63.9 embryos genotyped from each of the 25 combinations of sperm and eggs (range = 42–91, standard deviation = 17.1, Table 1).

Statistical analyses

We employed two distinct methods to test for competitive differences between jack male sperm and hooknose male sperm. The first was a maximum-likelihood method that considers each brood as an independent observation, and the second was a logistic regression that considers each embryo as an independent observation. For the maximum-likelihood approach, we also subsampled totally independent datasets from the full dataset. There are 120 different ways to sample the 5 × 5 experimental design where no rows or columns are shared.

Maximum likelihood

Neff and Wahl (2004) developed a maximum-likelihood method to test whether sperm competition outcomes follow fair or loaded raffles. For each of 25 broods (Table 1), paternity outcomes follow:

$$\frac{N_1}{N_1 + N_2} = \frac{S_1}{S_1 + rS_2}$$

where N_1 and N_2 are the numbers of offspring sired by male 1 and male 2 in a brood, respectively; S_1 and S_2 are the numbers of sperm transferred by male 1 and male 2 (taken as the average of the three spermatocrit values taken per male, Appendix S2), respectively; r is the competitive ability of the second male's relative to the first male's sperm; t is a measure of the economy of scale to sperm number. Essentially, t measures whether the returns on transferring additional sperm follow a linear trend. If $t = 0$, then the above equation reduces to $1/(1 + r)$, indicating that sperm competition outcomes are independent of relative sperm number and determined only by r . An individual that makes higher quality sperm gains less per additional sperm transferred if $0 < t < 1$, but gains disproportionately more if $t > 1$. The method optimizes r and t

across the entire set of broods and estimates 95% confidence intervals through permutation (Neff and Wahl 2004). These confidence intervals were used to test the fair raffle model, where $r = 1$ (no differences in sperm competitive ability) and $t = 1$ (sperm competition outcomes related only to S_1 relative to S_2 and r), as well as the sperm-independent model, where $t = 0$. Because spermatocrit numbers did not significantly differ between jack and hooknose males (Appendix S2), our study was probably underpowered to uncover differences due sperm quantity. However, our primary goal was to test the null hypothesis $r = 1$, the prediction under a fair raffle. We applied the maximum-likelihood method to the entire dataset, as well as each of the 120 independent subsamples.

Logistic regression

A second method used logistic regression to model the log odds of the probability that a jack male sired an embryo:

$$\begin{aligned} \text{logit}(\text{Pr}\{Y_i = 1 | F, M\}) \\ = \beta + \sum_{j=2}^5 \beta_{F_j}(F_{ij} - \bar{F}_j) + \sum_{h=2}^5 \beta_{M_h}(M_{ih} - \bar{M}_h) \\ + \sum_{j=2}^5 \sum_{h=2}^5 \beta_{int,jh}(F_{ij} - \bar{F}_j)_i \times (M_{ih} - \bar{M}_h)_i \end{aligned}$$

Y_i is a variable indicating if offspring i was sired by a jack ($Y_i = 1$) or hooknose male ($Y_i = 0$), and F_{ij} and M_{ih} are indicator variables denoting the contributing female j or male sperm mixture h , respectively. It should be emphasized that M refers to a single sperm mixture from two males. These variables were mean-centered to allow the $\text{expit}(\alpha)$ to equal the overall probability of a jack in the sample. Each β represented the log odds ratio and a Wald test used to determine whether a factor significantly affected this ratio.

We tested the fit of the data to different models to understand the effects of male and female variables on the probability an offspring was sired by a jack male. Model 1 was a null model that simply calculated the overall mean Y_i , without any variables. Model 2, Model 3, and Model 4 added M_{ih} , F_{ij} , or both, respectively, to test whether the identity of the female egg donor and/or male sperm mixture influenced Y_i . Model 5 added an interaction between the sexes. Models were compared using a likelihood ratio test (LRT). All tests were performed with customized Python (www.python.org) and R (www.r-project.com) scripts.

Skewed paternity, sex ratio, and growth rates

Strong paternity skew could be correlated with sex ratio if sex-linked meiotic drive reduced the ability of one male

to compete. We tested for sex skew by amplifying X- and Y-specific regions (Devlin *et al.* 1994) from a subset of embryos from two gamete combinations that revealed highly skewed paternity (Hooknose 2:Jack 2+ Female 4 and Hooknose 4:Jack 4+ Female 4, Table 1).

Strong paternity skew could also be correlated with differences in embryonic developmental rate if cryptic female choice yielded offspring genotypes that grew fast. In salmonids, there are paternal and maternal contributions to egg size and egg metabolic rate (Pakkasmaa *et al.* 2001, 2006). Although not a primary objective, we tested for differential growth rate, we weighed embryo + yolk from a subset of embryos from four gamete combinations with skewed paternity (Hooknose 2:Jack 2+ Female 4, Hooknose 2:Jack 2+ Female 5, Hooknose 4:Jack 4+ Female 3, and Hooknose 4:Jack 4+ Female 5). All tests were performed with customized Python (www.python.org) and R (www.r-project.com) scripts.

Results

Jack males outcompeted hooknose males

Because we genotyped loci known to discriminate competing males (Appendix S1), all 1598 embryos that were genotyped were scored unambiguously for paternity.

Maximum likelihood

The methods of Neff and Wahl (2004) rejected the fair raffle model ($r = 1$ and $t = 1$). Specifically, jack sperm were estimated to be $r = 1.34\times$ as competitive as hooknose sperm, significantly different than $r = 1$ ($P < 0.0001$) and very consistent with the $1.36\times$ estimated from logistic regression analyses presented below. t was estimated to be $< 10^{-12}$, which was not significantly different from either $t = 0$ or $t = 1$ ($P = 0.99$, $P = 0.50$, respectively).

From the 5×5 Table 1, there are 120 possible ways to sample five cells with no rows or columns in common. Of these, 82 rejected the null hypothesis $r = 1$ ($P < 0.05$), in favor of the alternative that jack males were superior under controlled sperm competition. The average \pm standard deviation r in these cases was 1.52 ± 0.25 . In contrast, only one independent subsample favored the alternative that hooknose males were competitively superior.

Logistic regression

Overall, an embryo had a probability of 0.576 of being sired by a jack male, significantly different from the null expectation of 0.50 ($P = 3.97 \times 10^{-8}$, Table 2). In other words, jack sperm were $0.576/(1 - 0.576) = 1.36\times$ as competitive as hooknose sperm, a number that is very

similar to the maximum-likelihood estimates presented above. Female 4 deviated significantly from background, with a preference for hooknose sperm ($P = 0.007$, Table 2). Two sperm mixtures were significantly more jack-skewed than background. Jack 4 sired 0.711 of the embryos when in competition with Hooknose 4, and Jack 5 sired 0.601 of the offspring when in competition with Hooknose 5; both were significantly higher than background ($P = 2.05 \times 10^{-7}$, $P = 0.014$, respectively, Table 2).

A model including sperm aliquot as a fixed effect explained the data significantly better than a model ignoring it (Model 2 vs. Model 1, $\chi^2 = 32.70$, $df = 4$, $P = 10^{-6}$, Table 3), as did a model including female donor (Model 3 vs. Model 1, $\chi^2 = 13.63$, $df = 4$, $P = 0.01$), showing that the general superiority of jack male sperm was not uniform across sperm aliquot or egg donor. A model including both male and female fit the data significantly better than models with only male (Model 4 vs. Model 2, $\chi^2 = 13.29$, $df = 4$, $P = 0.01$) or only female (Model 4 vs. Model 3, $\chi^2 = 32.37$, $df = 4$, $P = 10^{-6}$, Table 3). Taken together, these results suggest that both sperm mixture and egg donor influence the outcomes of sperm competition.

Females may influence the outcomes of sperm competition

In the logistic regression framework, a model including an interaction term between sperm mixture and egg donor fit the data significantly better than a model with only additive male and female effects (Model 5 vs. Model 4, $\chi^2 = 93.82$, $df = 16$, $P = 10^{-13}$, Table 3). This effect is best illustrated by the Hooknose 2:Jack 2 sperm mixture. Jack 2 sired $0.798/(1 - 0.798) = 3.95\times$ more offspring than Hooknose 2 when combined with Female 5 ($P = 0.008$, Table 2) but $0.221/(1 - 0.221) = 0.28\times$ as many offspring as Hooknose 2 when combined with Female 4 ($P = 0.023$, Table 2). Thus, the outcomes of sperm competition between two particular males depended upon female genotype.

An alternative explanation to explain the sperm-by-egg interaction term is that random effects were very high. However, we emphasize that the same exact sperm aliquot was delivered across the eggs from five females. Therefore, random effects are unlikely to explain the sperm-by-egg interaction term.

Paternity skew was not correlated with sex ratio or growth rates

There was no evidence that paternity skew was related to meiotic drive of the sex chromosomes. For the Hooknose

Table 2. Coefficients estimated from full model (Model 5)

| Coefficients (Model parameter) | Estimate | SE | P (sired by Jack) | z-value | Pr (> z) | Significance (P) |
|---|----------|-------|-------------------|---------|-----------|------------------|
| Intercept | 0.306 | 0.056 | 0.576 | 5.492 | 3.97E-08 | ≤0.001 |
| Female 2 (F ₂) | 0.057 | 0.171 | 0.514 | 0.333 | 0.739 | |
| Female 3 (F ₃) | -0.306 | 0.157 | 0.424 | -1.953 | 0.051 | |
| Female 4 (F ₄) | -0.492 | 0.184 | 0.379 | -2.674 | 0.007 | ≤0.01 |
| Female 5 (F ₅) | -0.159 | 0.172 | 0.460 | -0.924 | 0.355 | |
| Hooknose 2:Jack 2 (M ₂) | 0.072 | 0.166 | 0.518 | 0.432 | 0.666 | |
| Hooknose 3:Jack 3 (M ₃) | -0.075 | 0.173 | 0.481 | -0.437 | 0.662 | |
| Hooknose 4:Jack 4 (M ₄) | 0.900 | 0.173 | 0.711 | 5.195 | 2.05E-07 | ≤0.001 |
| Hooknose 5:Jack 5 (M ₅) | 0.409 | 0.167 | 0.601 | 2.456 | 0.014 | ≤0.05 |
| Female 2 * Hooknose 2:Jack 2 (F ₂ * M ₂) | 0.260 | 0.511 | 0.565 | 0.509 | 0.611 | |
| Female 3 * Hooknose 2:Jack 2 (F ₃ * M ₂) | 0.421 | 0.442 | 0.604 | 0.952 | 0.341 | |
| Female 4 * Hooknose 2:Jack 2 (F ₄ * M ₂) | -1.260 | 0.554 | 0.221 | -2.275 | 0.023 | ≤0.05 |
| Female 5 * Hooknose 2:Jack 2 (F ₅ * M ₂) | 1.374 | 0.514 | 0.798 | 2.671 | 0.008 | ≤0.01 |
| Female 2 * Hooknose 3:Jack 3 (F ₂ * M ₃) | 0.399 | 0.503 | 0.599 | 0.793 | 0.428 | |
| Female 3 * Hooknose 3:Jack 3 (F ₃ * M ₃) | 1.104 | 0.498 | 0.751 | 2.219 | 0.026 | ≤0.05 |
| Female 4 * Hooknose 3:Jack 3 (F ₄ * M ₃) | -0.299 | 0.502 | 0.426 | -0.597 | 0.551 | |
| Female 5 * Hooknose 3:Jack 3 (F ₅ * M ₃) | 0.049 | 0.543 | 0.512 | 0.091 | 0.928 | |
| Female 2 * Hooknose 4:Jack 4 (F ₂ * M ₄) | 0.052 | 0.483 | 0.513 | 0.107 | 0.915 | |
| Female 3 * Hooknose 4:Jack 4 (F ₃ * M ₄) | 0.492 | 0.468 | 0.621 | 1.052 | 0.293 | |
| Female 4 * Hooknose 4:Jack 4 (F ₄ * M ₄) | 1.908 | 0.578 | 0.871 | 3.301 | 0.001 | ≤0.001 |
| Female 5 * Hooknose 4:Jack 4 (F ₅ * M ₄) | 2.282 | 0.570 | 0.907 | 4.005 | 0.000 | ≤0.001 |
| Female 2 * Hooknose 5:Jack 5 (F ₂ * M ₅) | 1.023 | 0.582 | 0.736 | 1.758 | 0.079 | |
| Female 3 * Hooknose 5:Jack 5 (F ₃ * M ₅) | -0.191 | 0.498 | 0.452 | -0.384 | 0.701 | |
| Female 4 * Hooknose 5:Jack 5 (F ₄ * M ₅) | 0.893 | 0.512 | 0.709 | 1.745 | 0.081 | |
| Female 5 * Hooknose 5:Jack 5 (F ₅ * M ₅) | 0.787 | 0.533 | 0.687 | 1.476 | 0.140 | |

Significance indicates factors that differed from an overall null model.

Table 3. Comparison of logistic regression models using likelihood ratio test

| Model number | Variables added | Model architecture | Residual deviance | df | Model comparisons (LRT) |
|--------------|-----------------|---------------------------------|-------------------|------|---|
| 1 | Null | Y ~ 1 | 2182.1 | 1597 | |
| 2 | Male | Y ~ Male | 2149.4 | 1593 | 2 vs. 1: $\chi^2 = 32.70$, df = 4, $P = 10^{-6}$ |
| 3 | Female | Y ~ Female | 2168.4 | 1593 | 3 vs. 1: $\chi^2 = 13.63$, df = 4, $P = 0.01$ |
| 4 | Both | Y ~ Male + Female | 2136.1 | 1589 | 4 vs. 2: $\chi^2 = 13.29$, df = 4, $P = 0.01$ 4 vs. 3: $\chi^2 = 32.37$, df = 4, $P = 10^{-6}$ |
| 5 | Interaction | Y ~ Male + Female + interaction | 2042.3 | 1573 | 5 vs. 4: $\chi^2 = 93.82$, df = 16, $P = 10^{-13}$ |

Significant LRT signifies a better fit to the data in the more complex model. LRT, likelihood ratio test.

2:Jack 2+ Female 4 combination, 11 males and nine females were sired by the hooknose male while two males and one female were sired by the jack male. For the Hooknose 4:Jack 4+ Female 4 combination, three males and two females were sired by the hooknose male while eight males and nine females were sired by the jack male. Pooling these data revealed 19 male and 18 female offspring sired by the winning male, compared with five males and three females sired by the losing male (Fisher's Exact Test, $P = 0.71$).

There was no evidence that growth rate of embryos correlated with winning sires. Pooling across the four gamete

combinations surveyed in this manner, 69 embryos sired by the winning male (median embryo:total egg weight = 0.188 g) were not significantly different from the 23 embryos sired by losing males (median embryo:total egg weight = 0.187 g, Mann-Whitney $P = 0.66$).

Discussion

Sneak-guard mating systems are prevalent among animal species, but the mechanisms by which sneaker males maintain reproductive fitness remain incompletely characterized (Gross 1996; Taborsky 1998). Here, we reject the

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fair raffle model, showing that sperm from sneaker jack males were competitively superior to sperm from dominant hooknose males in controlled *in vitro* fertilization experiments. Thus, sperm competition outcomes in Chinook salmon are best explained as a loaded raffle (Parker 1990a), helping to explain the stability of sneaker males in this system.

Several hypotheses could explain the general superiority of jack sperm over hooknose sperm. First, jack sperm swim faster than hooknose sperm (Flannery *et al.* 2013), and sperm velocity is a primary determinant of fertilization success in sperm competition in numerous fish species (Burness *et al.* 2004; Gage *et al.* 2004; Liljedal *et al.* 2008; Rudolfsen *et al.* 2008; Boschetto *et al.* 2011; Evans *et al.* 2013) and other external fertilizers (Levitan 1993, 1996, 2000; Kupriyanova and Havenhand 2002; Marshall *et al.* 2002). The speed with which sperm can locate an egg is important. In Sockeye salmon, over 80% of eggs are fertilized within 5 sec of gamete activation

river water; Flannery 2011). Mechanisms of inbreeding avoidance, if they exist, may be more complicated than simple predictions based on interactions between sperm and ovarian fluid, however. For example, genetic variation at the major histocompatibility locus has been shown to affect gamete interactions (Skarstein *et al.* 2005; Yeates *et al.* 2009).

Our finding that jack males make competitively superior sperm calls into question a common viewpoint that jack males are less fit than dominant males and are “making the best of a bad situation”. Reichard *et al.* (2007) reviewed theoretical and empirical examples where females might actually benefit from allowing sneaker males to fertilize their eggs, including increased genetic diversity in their offspring. Interestingly, female bluegill spawn more eggs when sneaker males are present, and sneaker males in that system also fertilize a disproportionate share of eggs (Fu *et al.* 2001). This could be an exam-