On the way to pole position:

The effect of tire grip on learning to drive a racecar

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***Abstract*—Racecar drivers could benefit from new training methods for learning to drive fast lap times. Inspired by the learning-from-errors principle, this simulator-based study investigated the effect of the tire-road friction coefficient on the training effectiveness of a car racing task. Three groups of 15 inexperienced racecar drivers (low grip (LG), 66% of normal grip; normal grip (NG); high grip (HG), 150% of normal grip) completed four practice sessions of 10 minutes in a Formula 3 car on an oval track of 800 m. After the practice sessions, two retention sessions followed: a retention session with normal grip in a Formula 3 car and another retention session with a Formula 1 car. The results showed that LG was significantly slower than HG in the first retention session. Furthermore, LG reported a higher confidence and lower frustration than NG and HG after each of the two retention sessions. In conclusion, practicing with low grip, as compared to practicing with normal or high grip, resulted in increased confidence but slower lap times.**

Keywords-learning from errors, simulator-based training, racecar driving, learning, retention, transfer, task difficulty

I. Introduction

The primary goal of a driver during the qualifying session of a car-racing event is to drive the fastest possible lap time. In a typical race format, the fastest lap time of each driver during this session determines the starting order for the ensuing race. Racing drivers, like other athletes, are interested in training methods that prepare them better than their competitors.

Driving simulators are powerful training tools because they provide several advantages over on-road driving, including a) inexpensive training and testing time, b) experimental control of the environment, c) accurate measurements of the vehicle state, and d) a safe environment for the driver. In a simulator, drivers are able to explore the limits of their behavior without risking serious consequences. A simulator thus offers the possibility to learn from errors, something which is much more restricted in reality. There is a growing body of evidence showing that performance in a driving simulator is predictive of performance in real cars and that skills learned in the simulator transfer to new situations [1]-[7]. In this study we adopt a novel approach to simulator-based driver training, by intentionally degrading the handling characteristics of the car with the aim to learn from errors.

Research in motor and verbal learning has shown that deteriorated practice conditions can have a positive effect on posttraining retention performance. A review of Schmidt and Bjork [8] showed that random practice is better than blocked practice, a reduction of the feedback frequency is better than more feedback, and varying task conditions are better than constant task conditions, when the aim is to enhance performance during retention tests. These practice conditions reduced task performance during practice but improved the level of performance in the long term and in altered contexts.

The racing task is considerably more complex than the motor and verbal tasks reported by Schmidt and Bjork. Car racing is a continuous task during which the driver controls the vehicle though different control interfaces: a throttle and a brake pedal for longitudinal control, and a steering wheel for lateral control. The dynamics are of second order, meaning that the inputs influence the vehicle's acceleration. Furthermore, car dynamics are nonlinear when driving near the limit of the tires.

Concerning the training of complex tasks, a study about the training of helicopter flying has shown that pilots training in an agile helicopter performed better when being tested in a sluggish helicopter than vice versa [9]. In previous work, we conducted an experiment in a passenger car driving simulator where the grip of the car was modified to influence task difficulty [10]. The results showed that the four 8-min practice sessions with low grip resulted in a lower speed during two 8-min retention sessions (of which the second one was administered the following day) and a workload reduction from practice to retention. The high-grip group performed the task of keeping the car near the center of the lane better than the normal-grip and low-grip groups and also had a higher confidence during practice. The higher confidence of the high-grip group disappeared in the retention sessions. In summary, previous research has shown that task conditions during practice has an influence on retention performance, and that the level of confidence and workload can quickly change when the task conditions change when transferring from practice to retention.

In the present study, the tire-road friction coefficient was altered. Three groups were compared: low grip (LG) with a maximum tire-road friction coefficient of 1.1, normal grip (NG) with a maximum tire-road friction coefficient of 1.7, and high grip (HG) with a maximum tire-road friction coefficient of 2.6. After the training, all groups drove a retention session in the same Formula 3 (F3) car with normal grip and; after that they drove another retention session with a Formula 1 (F1) car.

Table I and Fig. 1 show data of record laps driven by an experienced racecar driver for the three different grip levels in the F3 car, and for the F1 car. With high grip, no braking was necessary and the driver could be aggressive with the throttle pedal and steering wheel without losing control. With normal grip, braking was necessary before the corners and the throttle and steering wheel had to be controlled with more caution than with high grip. The low-grip condition resulted in the lowest cornering speeds; the driver had to actively control the steering, brakes, and throttle for a larger proportion of the lap resulting in the most difficult and error-prone practice conditions.

Errors provide potential for learning, and errors during training may benefit retention performance [5]. Errors may teach drivers what the limit of grip is and how to approach that limit. When the low-grip group receives more grip during the first retention session the driving task becomes less difficult for them. We expected this change in task difficulty to increase the self-confidence of LG, and accordingly we expected LG to explore the limits of the car further, which should result in faster lap times. The following hypothesis was therefore tested: Participants practicing with low grip drive faster lap times in nominal-condition retention sessions than participants practicing with normal or high grip.

II. METHOD

A. Apparatus

The racecar simulator consisted of the chassis of a Formula racing car (Fig. 2). The steering wheel, throttle system and brake pedal of the original car were used. The visual system consisted of a 52-inch LCD screen (Sony KDL52Z5500) positioned 1.3 m in front of the driver's face, resulting in a horizontal and vertical field of view of 27 and 46 degrees, respectively. The active force-feedback system normally used on the simulator was disengaged in order to avoid learning effects caused by haptic guidance [11], as well as to prevent driver fatigue. The virtual world and vehicle dynamics were simulated with the rFactor simulation program (v1.255).

TABLE I. CHARACTERISTICS OF RECORD LAPS DRIVEN BY AN EXPERIENCED RACECAR DRIVER IN A DRIVING SIMULATOR. NOTE THAT THESE LAPS WERE DRIVEN IN IDENTICAL TASK CONDITIONS AS THE EXPERIMENT REPORTED LATER IN THIS PAPER.

	LG	NG	HG	F1
Lap time (s)	22.37	18.23	15.27	13.83
Max. speed (km/h)	181	197	213	266
Min. speed (km/h)	91	118	168	152
Brake pressed (% of time)	24	21	0	14
Full throttle (% of time)	35	69	82	57

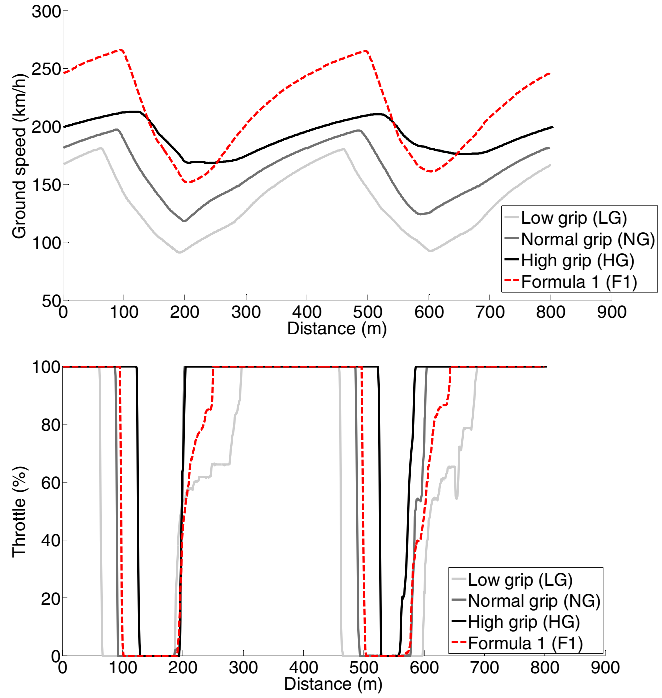

Figure 1. Ground speed (top) and throttle position (bottom) as a function of distance travelled during the lap, for the four laps reported in Table I. Note that these laps were driven in identical task conditions as the experiment reported later in this paper.

Figure 2. The racing simulator during the experiment.

B. Participants

Three groups of 15 male volunteers, all Delft University students, were created through a randomization process. Young males are a typical target group for evaluating a training method for car racing.

At the start of the experiment, each participant was asked to pick a piece of paper without replacement from a basket containing 45 folded pieces of paper; 15 for group 1 (the low-grip group), 15 for group 2 (the normal-grip group), and 15 for group 3 (the high-grip group). An intake questionnaire was administered resulting in the following data concerning the participants: the average age was 23.0 years (SD = 1.4), the average time since licensure was 4.6 years (*SD* = 1.4), the participants played racing games on average 0.6 hours per week (*SD* = 1.7), none of the participants had real-world racing experience, and the average response to the statement “I have good steering skills, for example with cycling, car driving, or computer games” was 7.7 (*SD* = 1.1; anchors: 1 = completely disagree, 10 = completely agree).

C. Instructions

Participants were provided with written instructions on paper. The goal during each driving session was to drive the fastest possible lap. The participants were informed which sessions were practice sessions and which were the retention sessions. They were also informed about the changes in grip level, but no indications were given about the magnitude of the differences in friction coefficient between groups. Also, no indications about the record lap times or the fastest times of other participants were provided. As an extra motivator, participants were invited before the experiment to enter a challenge for the fastest lap time in the second retention session. The prize consisted of a ticket for two kart racing trials. All participants provided written informed consent and agreed not to talk about their lap times to other participants.

D. Track

The racing track was an oval track, had a length of 800 m, and consisted of two 180° corners. A short lap ensures the same lap is driven many times in one driving session, which is beneficial to evaluate the learning process.

E. Procedures

Each participant drove six 10-min sessions: four practice sessions and two retention sessions. Between sessions, a 5-min break was held to give all participants the opportunity to relax and prepare for the next session.

After participants stepped out of the simulator, they were asked to complete the NASA-TLX questionnaire to measure the workload [12] and a confidence questionnaire.

F. Independent variable

The tire-road friction coefficient was the independent variable during this experiment. During the practice sessions all groups drove with a Formula 3 (F3) car (mass = 551 kg, maximum power = 164 kW), with different grip level for the three groups. The maximum friction coefficient (μ) was 1.1, 1.7, and 2.6 for the low-grip, normal-grip, and high-grip groups respectively. During the first retention session all participants drove with a Formula 3 car with normal grip level ($\mu = 1.7$). During the second retention session a Formula 1 (F1) car was used (mass = 607 kg, maximum power = 537 kW, $\mu = 2.4$). This was done to confront all participants with a new challenge, a higher task difficulty with greater time pressure, in order to evaluate the transfer of learning. The tire wear, effects of tire temperature, and fuel consumption were all disabled in order to guarantee constant grip levels within each session.

G. Dependent variables.

1) Lap times

Lap times are the most important performance measure for this car racing task. Just as in a real qualifying session, the primary task goal was to drive the fastest lap within the 10-minute session. We also calculated the average lap time per session. Rejected laps (see next item) were excluded

2) Rejected laps

Laps during which the wall was touched, the asphalt was left with all four wheels, or in which the car drove slower than 30 km/h were classified as rejected. Rejected laps were excluded from all the analysis.

3) FullThrottle

The full-throttle percentage is a measure of how much energy was put into the longitudinal movement of the car. This measure was calculated as the time-percentage that the throttle control input was 100% during all valid (i.e., non-rejected) laps of the session. FullThrottle can also be seen as a measure of task difficulty; the higher FullThrottle, the easier the driving task. When the throttle is fully opened, the car is limited by the engine power and the driver can focus on the lateral control of the car with the steering wheel to position for the next curve.

4) Workload

The NASA-TLX questionnaire was employed to measure the workload. The NASA-TLX comprises six statements to which participants have to respond on a 21-tick bar.

5) Confidence

In the confidence questionnaire, participants had to respond to the following three statements (anchors: strongly disagree, strongly agree on a 21-tick bar): 1) I had a feeling of risk during driving, 2) I feel confident to drive in similar conditions in the real world, and 3) I think I had a faster lap time than the average participant in my group.

H. Statistical analyses

The dependent variables were compared per session for LG vs. NG, LG vs. HG, and NG vs. HG using the independent samples Student’s *t* test.

III. Results

1) Lap times

Tables II and III present the fastest lap times and the average lap times per session, respectively. The fastest and average lap times were significantly different between all groups during the practice sessions with the different grip levels. During Retention 1, with equal grip for all groups, the fastest and average lap times of LG and HG differed significantly from each other. No group differences were found for Retention 2.

2) Rejected laps

Table IV shows the rejected laps per session. During all practice sessions, HG had less rejected laps than LG. HG had the least rejected laps, also less than NG, but this difference was only significant in the second and third practice session. In the first lap of Retention 1 (see Fig. 3) this effect was reversed: HG had significantly more rejected laps than LG ($p = .002$) and NG ($p = .028$). As the Retention 1 session progressed, this effect diminished. No differences were found for the complete Retention 1 or Retention 2 session.

3) FullThrottle

The results are shown in Table V and Fig. 4. All groups differed from each other during all practice sessions. LG had the lowest full-throttle percentages, then NG, and HG had the highest percentages. During Retention 1, LG had a significantly lower full-throttle percentage than the other two groups.

4) Workload

Because the differences between the groups were most pronounced with respect to the frustration element of the NASA-TLX questionnaire, we only took this item into account. The results are shown by Table VI. During Retention 1 and Retention 2, the frustration of LG was significantly lower than the frustration of NG and HG.

5) Confidence

The differences between groups were most pronounced for the third item of the confidence questionnaire. This item showed that during Retention 1 and Retention 2, LG was significantly more confident that they were faster than the average participant in their group than NG and HG. These results can be found in Table VII and are illustrated in Fig. 5.

6) Predictors of fast lap times

As a supplementary analysis, we investigated which variables predicted the fastest lap time during Retention 2, which is the session that was driven with the Formula 1 car. Zero-order correlations were calculated after pooling the data of all 45 participants. The fastest lap time correlated significantly with the average lap time ($r = .78$, $p < .001$) and with the fastest lap time during Retention 1, which was driven with the Formula 3 car ($r = .62$, $p < .001$). However, the fastest lap time did not correlate significantly with the number of rejected laps ($r = .06$, $p = .690$) and the full-throttle percentage ($r = -.20$, $p = .188$), nor with the confidence ($r = -.05$, $p = .746$; see also Fig. 6), frustration ($r = -.08$, $p = .599$), age ($r = .13$, $p = .396$), years of having a driving license ($r = -.01$, $p = .936$), number of racing game hours per week ($r = -.18$, $p = .242$), and self-reported steering skills ($r = -.05$, $p = .746$). These results indicate that the best predictor of fast lap times is previous performance and not self-reported behaviors or skills.

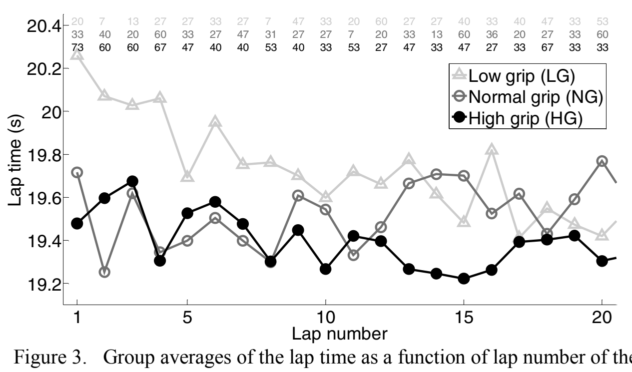

Figure 3. Group averages of the lap time as a function of lap number of the Retention 1 session. Above the graph the percentage of rejected laps are shown per group.

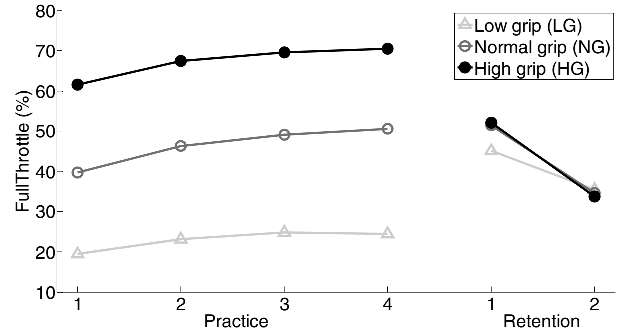

Figure 4. Group averages of the percentage full throttle.

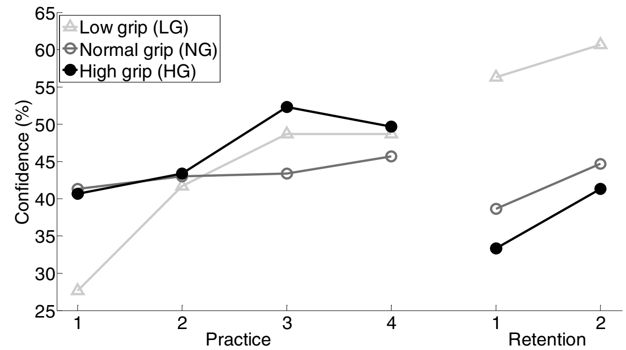

Figure 5. Group averages for Statement 3 of the Confidence questionnaire ("I think I had a faster lap time than the average participant in my group").

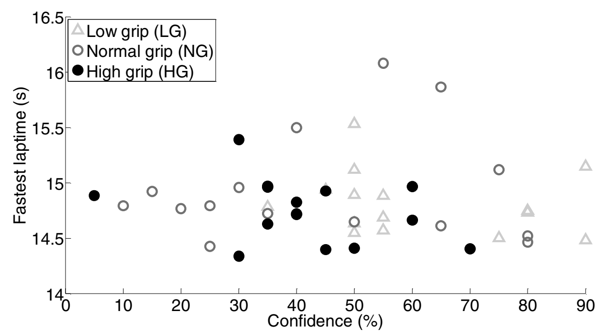

Figure 6. Fastest lap time during Retention session 2 (driven with the Formula 1 car) as a function of the response to Statement 3 of the Confidence questionnaire ("I think I had a faster lap time than the average participant in my group") for all 45 participants.

IV. Discussion

This simulator-based study investigated the effect of the tire-road friction coefficient on the training effectiveness of a car racing task. Three groups of inexperienced racecar drivers practiced with different grip and were tested on their ability to drive the fastest possible lap with normal tire-road friction coefficient. Practicing with low grip level resulted in slower lap times, higher self-confidence, and less frustration. The higher self-confidence of the low-grip group was as expected, but apparently, this higher self-confidence did not lead to faster lap times. Instead, these participants thought they were faster than the average participant in their group, were not as frustrated, and also crashed less in the opening laps. Thus, it appears that the low-grip group was more complacent and drove at a more comfortable speed, further from the grip limit of the normal-grip car.

The effects of the low-grip training were strongest in the opening laps of the first retention session (see Fig. 3). For racecar driver training, it would be relevant to study long-term retention effects as well. Considering that sleep has an important role in consolidation of memory, we expect a skill improvement for all groups on the following day (cf. [13]). Previous research in a driving simulator showed that training effects are retained overnight, although the effect sizes between groups were attenuated as compared to immediate retention [14].

Previous research showed that there is a significant correlation between the lap times driven in the racing simulator and lap times driven in real-world practice sessions [15]. However, care must be taken to extrapolate the results of this simulator-based study to the real world. The risk perception of drivers in the simulator was low (overall average 29% to Statement 1 of the confidence questionnaire), which is without doubt much lower than in reality. One of the advantages of the driving simulator, driver safety, might also cause behavior that is not realistic: many laps were rejected because the car hit the wall or left the tarmac. On the other hand, these errors are part of our new method of training; a method only possible in the safe simulator environment.

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TABLE II. GROUP AVERAGES (*SD*) OF THE FASTEST LAP TIME (S) AND *P*-VALUES FOR GROUP COMPARISONS

Group	Practice 1	Practice 2	Practice 3	Practice 4	Retention 1	Retention 2
LG	24.24 (0.71)	23.90 (0.57)	23.76 (0.50)	23.76 (0.45)	19.18 (0.30)	14.81 (0.28)
NG	19.39 (0.35)	19.19 (0.28)	19.12 (0.30)	19.09 (0.34)	19.03 (0.27)	14.95 (0.48)
HG	16.19 (0.33)	15.90 (0.21)	15.88 (0.20)	15.80 (0.20)	18.97 (0.19)	14.75 (0.28)
LG vs. NG	**.000**	**.000**	**.000**	**.000**	.169	.379
LG vs. HG	**.000**	**.000**	**.000**	**.000**	**.032**	.526
NG vs. HG	**.000**	**.000**	**.000**	**.000**	.483	.190

TABLE III. GROUP AVERAGES (*SD*) OF THE AVERAGE LAP TIME (S) AND *P*-VALUES FOR GROUP COMPARISONS

Group	Practice 1	Practice 2	Practice 3	Practice 4	Retention 1	Retention 2
LG	25.56 (1.28)	24.60 (0.77)	24.51 (0.65)	24.45 (0.55)	19.76 (0.34)	15.67 (0.45)
NG	20.20 (0.73)	19.83 (0.43)	19.64 (0.36)	19.65 (0.36)	19.54 (0.34)	16.02 (0.70)
HG	16.86 (0.43)	16.32 (0.24)	16.26 (0.29)	16.19 (0.27)	19.42 (0.29)	15.83 (0.59)
LG vs. NG	**.000**	**.000**	**.000**	**.000**	.114	.134
LG vs. HG	**.000**	**.000**	**.000**	**.000**	**.009**	.432
NG vs. HG	**.000**	**.000**	**.000**	**.000**	.300	.456

TABLE IV. GROUP AVERAGES (*SD*) OF THE REJECTED LAPS (% OF TOTAL LAPS) AND *P*-VALUES FOR GROUP COMPARISONS

Group	Practice 1	Practice 2	Practice 3	Practice 4	Retention 1	Retention 2
LG	58 (17)	45 (18)	47 (14)	45 (16)	33 (18)	29 (8)
NG	45 (23)	37 (22)	35 (20)	34 (17)	33 (14)	27 (9)
HG	33 (17)	24 (13)	19 (10)	23 (13)	41 (18)	28 (14)
LG vs. NG	.114	.331	.071	.104	.909	.513
LG vs. HG	**.001**	**.001**	**.000**	**.000**	.214	.696
NG vs. HG	.107	**.049**	**.012**	.054	.201	.928

TABLE V. GROUP AVERAGES (*SD*) OF THE PERCENTAGE FULL THROTTLE PER LAP AND *P*-VALUES FOR GROUP COMPARISONS

Group	Practice 1	Practice 2	Practice 3	Practice 4	Retention 1	Retention 2
LG	19 (7)	23 (7)	25 (5)	24 (5)	45 (5)	35 (5)
NG	40 (9)	46 (5)	49 (5)	51 (5)	51 (5)	35 (6)
HG	62 (8)	67 (8)	70 (8)	70 (6)	52 (4)	34 (5)
LG vs. NG	**.000**	**.000**	**.000**	**.000**	**.004**	.694
LG vs. HG	**.000**	**.000**	**.000**	**.000**	**.001**	.386
NG vs. HG	**.000**	**.000**	**.000**	**.000**	.704	.717

TABLE VI. GROUP AVERAGES (*SD*) OF FRUSTRATION ITEM (HOW INSECURE, DISCOURAGED, IRRITATED, STRESSED, AND ANNOYED WERE YOU?; PERCENTAGE FROM LOW TO HIGH) OF THE NASA-TLX AND *P*-VALUES FOR GROUP COMPARISONS.

Group	Practice 1	Practice 2	Practice 3	Practice 4	Retention 1	Retention 2
LG	48 (31)	31 (13)	44 (21)	41 (23)	16 (11)	24 (21)
NG	50 (18)	52 (20)	52 (24)	52 (21)	52 (23)	47 (24)
HG	54 (23)	52 (21)	45 (23)	53 (22)	57 (21)	55 (21)
LG vs. NG	.832	**.002**	.342	.157	**.000**	**.010**
LG vs. HG	.577	**.002**	.903	.157	**.000**	**.000**
NG vs. HG	.631	.930	.426	.966	.571	.337

TABLE VII. GROUP AVERAGES (*SD*) OF STATEMENT 3 (I THINK I HAD A FASTER LAP TIME THAN THE AVERAGE PARTICIPANT IN MY GROUP; PERCENTAGE FROM STRONGLY DISAGREE TO STRONGLY AGREE) OF THE CONFIDENCE QUESTIONNAIRE AND *P*-VALUES FOR GROUP COMPARISONS.

Group	Practice 1	Practice 2	Practice 3	Practice 4	Retention 1	Retention 2
LG	28 (16)	42 (17)	49 (22)	49 (16)	56 (19)	61 (17)
NG	41 (21)	43 (24)	43 (21)	46 (24)	39 (22)	45 (24)
HG	41 (19)	43 (18)	52 (17)	50 (17)	33 (18)	41 (15)
LG vs. NG	.055	.862	.503	.688	**.027**	**.047**
LG vs. HG	.052	.800	.617	.867	**.002**	**.003**
NG vs. HG	.927	.966	.212	.600	.475	.656