Operation of Ngenic Tune Improves Thermal Comfort

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Abstract

Ngenic Tune is a sensor-equipped and internet-connected heat pump controller designed to provide a more constant indoor temperature than what the common heat pump default controller is capable of achieving. It has been estimated that Tune can reduce the energy consumption of more than half its users by at least 10%, while either improving or maintaining thermal comfort. To empirically examine the effect of Ngenic Tune on thermal comfort, a field-intervention study was carried out in 106 households in Sweden. Without informing the householders, the Tune service was twice disabled for one week at a time over a 4-week period during the heating season, using a cross-over design in which two randomly selected groups experienced different conditions in any given week. Thermal comfort was assessed by observing the number of times that users made adjustments to their thermostats under the two conditions. These two sets of adjustment frequencies (one with Tune in operation, the other with default heat pump operation) were used in a within-household analysis to determine whether or not their thermal comfort was positively or negatively affected when Tune was in operation, as compared to the heat pump default. While over 75% of households showed no effect, among those that did respond to the imposed changes a Wilcoxon Matched-Pairs Signed-Ranks test indicates that operating Tune had a positive effect on thermal comfort at the $(P < 0.05)$ *level (for a 2-tail test), in that it resulted in significantly fewer thermostat adjustments.*

I. INTRODUCTION

Thermal comfort is defined by the International Organization for Standardization and the American Society of Heating, Refrigerating, and Air-Conditioning Engineers as that condition of mind which expresses satisfaction with the thermal environment [ISO, 2005], [ASHRAE, 2013]. How to achieve and maintain an acceptable level of thermal comfort has been the topic of much research for the past fifty years, see e.g. [Wyon, 2013], [Huizenga, 2006]. Many academic and professional studies have demonstrated the benefits of a constant, optimal indoor temperature, see e.g. [Wyon, 2016], [Wargocki, 2017].

Heat pumps have become a very common method of heating single-family homes. In fact, it is estimated that a heat pump has been installed in at least half of all single-family homes in Sweden [Folksam, 2015]. Since heat pumps use electricity only to transfer heat from one location to another, they are an energy-efficient alternative to traditional furnaces which burn fuel to create heat.

A heat pump regulates indoor temperature by using a "heat curve" (a relationship that determines the amount of energy that should be supplied to the heating system as a function of the current outdoor temperature). The heat curve is usually set at the time of installation and is generally calibrated against default values which are not optimized for the specific house in which it is to be used. Once the heat curve is set, it can sometimes be difficult to recalibrate, and may be impossible to fine-tune.

This results in a common situation where the heat pump of a home is incorrectly calibrated or incapable of fine-tuning. The default heat curve may not be a good match for the home, or renovations may have been made to the house without recalibration of the heat pump. Ngenic can improve this situation by controlling the heat pump with its proprietary control algorithm "Tune", thereby making any recalibration of the heat pump unnecessary as well as providing extra functionality via a smart-phone application.

An incorrectly calibrated heat pump is not only a source of uneven temperature and thus of thermal discomfort, it also wastes energy, because electricity is consumed in causing it to over-shoot the ideal temperature. Optimal heat pump control thus saves energy and increases thermal comfort. Ngenic has found that Tune reduces the heating costs of more than half of its users by 10% and claims that it can provide users with an increased level of thermal comfort during a greater part of the day when compared to their default heat pump installation. The study reported in this paper was an empirical test of the strength of this claim.

In addition to the general energy savings resulting from eliminating uneven temperatures, the Tune smart-phone application also provides the possibility of reducing the power consumption of the heat pump at times when electricity prices are high. The relative benefit of this function for Tune users depends, however, on the price-structure reflected in their electricity bill. That is, whether the hourly market price directly affects the consumer price, and, if so, by how much. Among the participants in this study, only 7% of households used a price-influenced control. Accordingly, this study does not seek to assess the effects of price flexibility on thermal comfort, but focuses rather on the effect of *energy-saving control*.

II. METHODS

i. Field Intervention

A single-blind field intervention study was conducted using a cross-over design that involved 106 Tune-equipped single-family households. Although participants had signed a waiver allowing Ngenic to remotely control their heat pumps occasionally, to prevent any possible influence of expectation they remained unaware that a study of this kind would take place. The pool of test subjects was pseudo-randomly divided into two groups, such that each group was uniformly distributed geographically and with respect to other possible sources of variance (weather, etc.).

The two groups were then put on an intervention schedule alternating between "Tune on" and "Tune off" at approximately week-long intervals, with one group experiencing each condition in any given week, so that any exceptional weather conditions would affect thermal comfort in both conditions in the same way. During the interventions with Tune disabled, the heat pump was allowed to operate on its default heat curve setting. The intervention length was chosen so as to minimize any variance resulting from household behaviour that occurred on a weekly cycle. The intervention schedule, shown in Table 1, was chosen so that the households could settle into their new thermal state before considering the intervention to be in effect. The experiment was run for a total of four weeks, so that each household experienced each condition twice in non-contiguous periods.

It is sometimes the case that during the installation of an Ngenic Tune system, the default configuration of the heat pump must be altered. An example of this is the case where customers are instructed to fully open their radiator valves when Tune is installed. If the heat curve happens to be calibrated very steeply, the household becomes very warm very quickly when Tune is disabled. These users would contribute a great deal of variance as they would experience considerable discomfort when Tune was not in operation and they were therefore removed from the study.

Identifying possible sources of such bias was not easy, since Ngenic did not possess prior-knowledge of the system configuration of each customer. A short pre-study was therefore conducted on both groups, in which Tune was disabled for a four-hour period in the middle of the night. Any system that showed an in-

Table 1: *Intervention schedule.*

	11/17 - 11/21	11/24 - 11/29	12/7 - 12/12	12/14 - 12/18
Group 1	Tune On	Tune Off	Tune On	Tune Off
Group 2	Tune Off	Tune On	Tune Off	Tune On

crease or decrease in indoor temperature of 0.45° C or more was considered for removal from the study. Of these systems, the decision on whether to remove them from the study was based on the historical performance of the system: those showing a consistent negative correction by Tune (i.e. when Tune was consistently pushing the system to produce more heat than it normally would) were removed. Additionally, any customers who experienced a level of discomfort that caused them to contact Ngenic to report a problem were removed from the study. These measures were taken in order to prevent any customers from experiencing unreasonable discomfort during the study, even though this was likely to reduce any observed difference in thermal comfort between conditions.

The initial pool of households consisted of 144 Tune-equipped single-family homes. Of these, 28 were removed during the pre-study: 17 because of a warm bias, 11 because of a cold bias. A further 8 were removed during the experimental period because they had contacted Ngenic to report an abnormal level of discomfort when Tune was disengaged. Lastly, 2 households were removed from the study because they engaged the planning feature of Tune, which allows users to reduce their energy consumption by lowering their household temperature while no one is home. After these adjustments to the test pool, a total of 106 households remained in the study, with 55 in one group and 51 in the other.

ii. Thermal Comfort Metric

The smart-phone application which accompanies an Ngenic Tune system allows users to adjust the set-point temperature (their preferred indoor temperature) which their Tune-enhanced heat pump will then attempt to maintain. Even with the Tune algorithm disabled, users were able to continue to adjust their set-point temperature (although this had no effect on the heat pump operation).

In order to assess the thermal comfort of the participants in the study, the assumption was made that users would adjust their set-point temperature up or down if they became sufficiently uncomfortable. Throughout the study, the number of times an adjustment was made was recorded for each household as they experienced the intervention periods with Tune alternatively engaged or disengaged. At the conclusion of the study, these numbers were added together for each household, separately for all four "Tune on" periods and for all four "Tune off" periods. By comparing these two values, a statistical test was made as to whether or not the mean adjustment frequency differed during periods when Tune was disengaged.

iii. Hypothesis Test

The hypothesis tested in this study can be stated as follows:

$$\mathcal{H}_0 : \text{The Ngenic Tune algorithm does not affect thermal comfort (the Null Hypothesis).}$$

This is tested against the alternative hypothesis, stated as follows:

$$\mathcal{H}_1 : \text{The Ngenic Tune algorithm does affect thermal comfort.}$$

The Wilcoxon Signed-Ranks test for matched pairs is ideally suited to test this hypothesis. Developed by Frank Wilcoxon in 1945, the Signed-Ranks test for matched pairs is applicable to two sets of measurements taken from the same individual (in this case, the same household) under the two conditions to be compared (in this case, Tune on and Tune off) [Wilcoxon, 1945]. Let X and Y be random variables with mean values μ_X and μ_Y. The Wilcoxon Signed-Ranks test provides a method for testing the hypothesis that $\mu_X = \mu_Y$.

For the purposes of this study, the adjustment frequencies recorded during the Tune off interventions are interpreted as the outcomes of a random variable X, with those recorded during Tune on as the outcomes of a random variable Y . Thus our hypotheses can be reformulated as follows:

$$\mathcal{H}_0 : \mu_X = \mu_Y.$$
$$\mathcal{H}_1 : \mu_X \neq \mu_Y.$$

Let the outcomes of the random variables X and Y be denoted by the lower-case x and y respectively. Now, given pairs of outcomes (x_i, y_i) where $i = 1, 2, ..., N$, Wilcoxon ranks the N differences $(x_i - y_i)$ by order of size, disregarding the sign, using the mean rank when values are tied. The signed ranks, R_i, are then defined as the rank of the absolute difference $|x_i - y_i|$ with the sign of the corresponding difference, that is:

$$\text{sign}(R_i) = \text{sign}(x_i - y_i).$$

The Signed-Rank statistic, W, is then defined as the sum of positive ranks:

$$W = \sum_{i=1}^{N} R_i \cdot I(R_i > 0),$$

where R_i is the rank of the i-th pair (x_i, y_i) and $I(R_i > 0) = 1$ if $R_i > 0$ and 0 if $R_i \leq 0$. Under $\mathcal{H}_0$, the distribution of the ranks is symmetric around a mean value. In fact, as shown in Wilcoxon's paper from 1947 [Wilcoxon, 1947] and [Mann, 1947], as well as in many textbooks on non-parametric statistics, e.g. [Hollander, 1973], the limiting distribution of W as $N \to \infty$ is $N(\mu, \sigma^2)$ with

$$\mu = N(N+1)/4,$$
$$\sigma^2 = N(2N+1)(N+1)/24.$$

A p-value for W can therefore be calculated with the standardized variable

$$Z = (W - \mu)/\sigma.$$

In the context of the Wilcoxon Signed-Rank test, the hypothesis $\mathcal{H}_0$ can be rejected at a confidence level α if

$$P(Z \leq z) \leq \alpha,$$

where z is an outcome of Z, or

$$2 \cdot P(Z \leq z) \leq \alpha,$$

for a 2-tail test. This represents the probability that the observed value of W could have occurred *by chance* under $\mathcal{H}_0$. If this probability is small, e.g. 0.05 or less, $\mathcal{H}_0$ can be rejected without fear of committing a type I error (falsely rejecting a true hypothesis).

Note that the Wilcoxon Signed-Rank test is non-parametric. That is, no assumptions need be made about the distribution of the data, other than that they can be ranked. In the present experiment, the number of set-point temperature adjustments was recorded on an interval scale, but it is not necessary to assume that thermal comfort was represented by these numbers other than on an ordinal scale, i.e. no linear correlation between number of adjustments and increasing thermal discomfort need be assumed for the analysis to be valid. No information about the distributions of X and Y are needed to test $\mathcal{H}_0$.

III. RESULTS

The per-household total number of adjustments to set-point temperature during the Tune on and the Tune off intervention periods are shown in Table 2. A histogram of the within-household difference between conditions can be seen in Figure 1. The x-axis shows the values taken on by the differences $X - Y$ as the "Diff" column in Table 2. The y-axis shows the number of times each such value occurs. Note that a negative value of $X - Y$ indicates that the customer adjusted their set-point temperature more often when Tune was switched off.

If the hypothesis $\mathcal{H}_0$ is true, that is, if Ngenic customers are equally likely to adjust their set-point temperature regardless of whether or not Tune is in operation, this should result

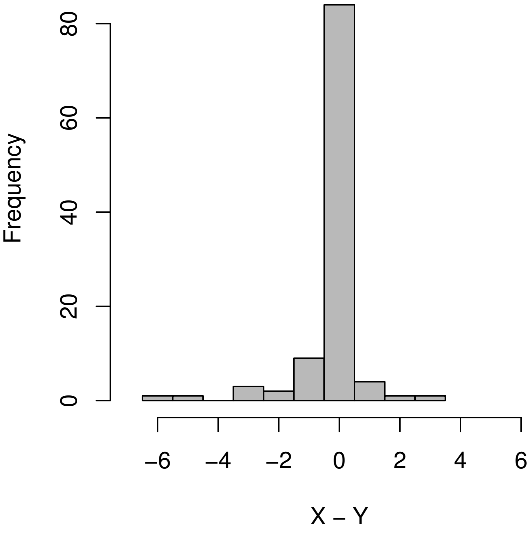

Figure 1: *Histogram of differences in the number of set-point temperature adjustments between conditions for each household, where X were made in the Tune on condition and Y in Tune off. Under $\mathcal{H}_0$, they should be symmetrically distributed around zero.*

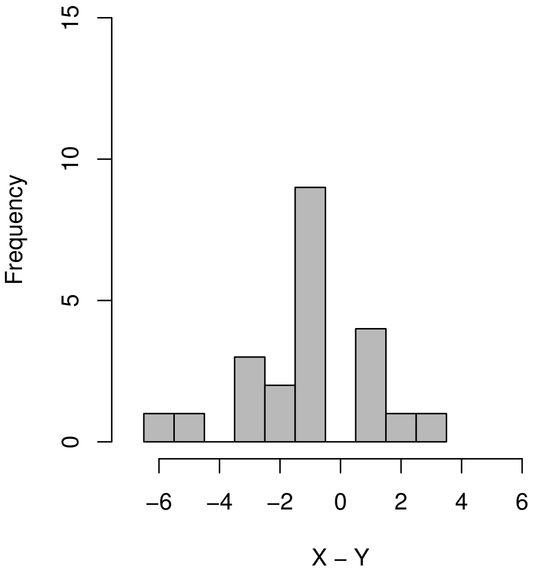

Figure 2: *Histogram of non-zero differences in the number of set-point temperature adjustments between conditions for each household. The distribution is clearly skewed toward more adjustments when Tune was disabled.*

in a histogram with a symmetric distribution around zero. As Figure 2 shows, the distribution skews to the negative, indicating the data support rejecting this hypothesis. To verify this, a Wilcoxon Signed-Ranks test for matched-pairs was performed.

As described in Section II, the differences $X - Y$ which are not equal to the median were ranked according to size, disregarding sign. The positive ranks were then summed, yielding the Wilcoxon Signed-Ranks statistic

$$W = 61.5.$$

Having a sample size of $N = 22$ (the number of non-zero differences), the statistic is standardized using

$$\begin{aligned} z &= \frac{W - N(N+1)/4}{\sqrt{N(2N+1)(N+1)/24}} \\ &= -2.110267. \end{aligned}$$

With $z \in N(0,1)$, a two-sided p-value for $\mathcal{H}_0$ can be computed:

$$p = 2 \cdot P(Z \leq -2.110267) = 0.03483534.$$

As some of the values of the difference between conditions in the number of adjustments were the same for several households, it might be considered appropriate to apply the correction for ties proposed by [Hollander, 1973]:

$$\sigma^2 = \frac{N(2N+1)(N+1)}{24} - \frac{(\sum_{k=1}^{n_{ties}} T_k^3 - T_k)}{48},$$

where n_{ties} is the number of ties which occured and T_k is the k-th tie. The corrected value of z then becomes -2.148211 for a p-value of 0.03169703.

With a p-value < 0.05 under $\mathcal{H}_0$, it may be concluded that the results of this study support the rejection of $\mathcal{H}_0$. As evidenced by the predominantly negative values of the signed ranks, and as can be seen in Figures 1 and 2, users made fewer thermostat adjustments when Tune was engaged. The study therefore supports the claim that Ngenic Tune has a significant and positive effect on thermal comfort, as improving heat pump operation by operating Ngenic Tune resulted in fewer thermostat adjustments when compared to default heat pump operation.

IV. Discussion

There are many reasons why a person would adjust their set-point temperature that may not be related to thermal comfort. One of the main motivations among Ngenic customers is, for example, the ability to reduce temperature (and thereby energy consumption) during the day when no one is at home. The within-subject design of the field experiment, in which the hypothesis is tested within households, eliminates the influence of any such additional factors on the data. The technique of alternating conditions on a weekly schedule ensures that any often-repeated behaviour sums to zero before the rank statistic is calculated, while the simultaneous establishment of both conditions at all times, one for each group, eliminates any bias due to unusual external or weather conditions.

Ngenic claims to improve thermal comfort while reducing energy consumption by smoothing-out unnecessary temperature variation through optimal heat pump control. To support the claim that the changes in set-point temperature observed in this study were driven by an increase in variation of indoor temperature when Tune is disabled, standard deviations for the two conditions (Tune on and Tune off) are presented, per household, in Table 3.

The pooled variance across households is derived as 0.402 with Tune off and 0.300 with Tune on. This constitutes an F-ratio (with Tune on in the numerator) of 0.746 which, given the large number of measurements, significantly differs from 1 at the $p \leq 0.001$ level. It can therefore be confidently stated that the Tune control algorithm significantly reduces indoor temperature variation in the majority of households.

As stated in Table 2 and as is apparent in Figures 1 and 2, the majority of test subjects made no adjustments to their set-point temperature under either condition. Certainly, for many of these users, it was the case that the difference in thermal comfort between conditions was too small to motivate a change in set-point temperature. However, the assumption that set-point temperature adjustment maps to thermal comfort is predicated on the willingness and ability of Tune users to interact with the smart-phone application. If customers are not used to using the smart-phone application day-to-day, or if the set-point temperature is regarded as a setting that should not lightly be changed, the level of thermal discomfort may have to be quite high before any adjustment is made. Such customers may be more prone to opening a window when the heat pump overshoots a comfortable temperature.

To provide a context for the set-point temperature adjustments made during the study, adjustments were tabulated during the two-week period preceeding the first intervention. With no intervention in place (i. e. with Tune in normal operation), 16.04% of households adjusted their set-point temperature at some time. The corresponding figures during the study were 14.15% in the Tune on condition and 17.92% in the Tune off condition. The mean number of adjustments made by the households that did alter the set temperature was 1.8, 1.3 and 2.3, respectively, in these 2-week periods.

As stated in Section II, 28 households were removed from the study on suspicion that their default heat pump configuration was altered during Tune installation. This constitutes 19% of the initial subject pool. It is believed by Ngenic that the true number of altered-default systems is fewer than 28 and that included in this number were households whose system was so poorly configured as to resemble the altered-default behaviour (which is exactly the problem Ngenic is able to solve). Regardless of whether or not this was the case, Ngenic was unwilling to subject their customers to unreasonable discomfort.

With these factors in mind, the result obtained by this study, that Tune operation has a significant and positive impact on thermal comfort, must be regarded as conservative.

V. Conclusions

Covert operation of Tune resulted in a statistically significant decrease in the number of thermostat adjustments and a statistically significant decrease in the variance of the indoor temperature. Taken together, this indicates that Tune is able to reduce thermal discomfort as well as save energy.

VI. Acknowledgments

The field-intervention approach reported in this White Paper was suggested by Professor David P. Wyon, International Centre for Indoor Environment and Energy, Department of Civil Engineering, Technical University of Denmark (DTU) as a cost-effective and more valid alternative to conventional measurements, followed by calculation of thermal comfort indices, or questionnaire investigations.

An edited version of this White Paper was produced by David P. Wyon and Jonathan E. Ridenour and published in the peer-reviewed journal *Indoor Air*. Interested readers are referred to the version of record, cited as follows:

D. Wyon and J. Ridenour *A covert field-intervention experiment to determine how heating controls that conserve energy affect thermal comfort*. Indoor Air. 28:763-767 2018 August.

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Table 2: *Sum of adjustments to set-point temperature, per household, during Tune on (X) and Tune off (Y) interventions, with differences.*

Id	Tune on	Tune off	Diff
1	0	0	0
2	0	0	0
3	0	0	0
4	1	0	1
5	1	0	1
6	0	0	0
7	0	0	0
8	0	0	0
9	0	0	0
10	0	0	0
11	0	0	0
12	1	0	1
13	0	0	0
14	2	4	-2
15	0	0	0
16	1	4	-3
17	0	0	0
18	0	0	0
19	0	0	0
20	0	0	0
21	0	0	0
22	0	0	0
23	0	0	0
24	0	0	0
25	0	0	0
26	0	1	-1
27	0	0	0
28	0	0	0
29	0	0	0
30	0	0	0
31	0	5	-5
32	0	0	0
33	0	0	0
34	0	0	0
35	0	0	0
36	0	0	0
37	0	0	0
38	0	0	0
39	0	0	0
40	1	7	-6
41	0	0	0
42	0	0	0
43	0	0	0
44	0	1	-1
45	0	0	0
46	0	0	0
47	0	0	0
48	1	2	-1
49	0	0	0
50	1	3	-2
51	0	0	0
52	0	0	0
53	0	0	0
54	0	0	0
55	0	0	0
56	0	0	0
57	0	0	0
58	0	0	0
59	0	0	0
60	0	0	0
61	0	0	0
62	0	0	0
63	0	1	-1
64	0	1	-1
65	0	0	0
66	1	1	0
67	0	1	-1
68	0	0	0
69	0	3	-3
70	0	0	0
71	0	0	0
72	0	0	0
73	0	0	0
74	2	0	2
75	0	0	0
76	0	0	0
77	0	1	-1
78	0	0	0
79	0	0	0
80	0	0	0
81	0	0	0
82	2	1	1
83	0	0	0
84	1	1	0
85	0	0	0
86	0	0	0
87	0	1	-1
88	1	2	-1
89	1	4	-3
90	0	0	0
91	0	0	0
92	3	0	3
93	0	0	0
94	0	0	0
95	0	0	0
96	0	0	0
97	0	0	0
98	0	0	0
99	0	0	0
100	0	0	0
101	0	0	0
102	0	0	0
103	0	0	0
104	0	0	0
105	0	0	0
106	0	0	0

Table 3: *Standard Deviation (degrees Celsius) of indoor temperatures with Tune On and Tune Off.*

Id	Tune on	Tune off	Id	Tune on	Tune off	Id	Tune on	Tune off	Id	Tune on	Tune off
1	0.596	0.503	28	0.606	0.469	55	0.901	0.801	82	0.804	0.766
2	0.358	0.136	29	0.548	0.356	56	0.927	0.559	83	1.133	1.143
3	0.61	0.416	30	0.262	0.184	57	0.357	0.386	84	0.584	0.653
4	0.493	0.381	31	0.502	0.285	58	0.308	0.37	85	0.316	0.442
5	0.204	0.256	32	0.641	0.367	59	0.453	0.198	86	0.46	0.446
6	0.288	0.329	33	0.405	0.262	60	0.337	0.363	87	2.723	2.366
7	0.168	0.135	34	0.301	0.252	61	0.335	0.256	88	0.549	0.374
8	0.361	0.253	35	0.33	0.273	62	0.348	0.207	89	0.311	0.291
9	0.366	0.335	36	0.378	0.261	63	0.332	0.686	90	0.348	0.384
10	0.683	0.478	37	0.563	0.679	64	0.391	0.349	91	0.756	0.272
11	0.692	0.295	38	0.391	0.326	65	0.636	0.4	92	0.312	0.453
12	0.529	0.617	39	0.371	0.454	66	0.404	0.344	93	0.273	0.235
13	0.558	0.59	40	0.53	0.741	67	0.395	0.476	94	0.632	0.61
14	0.275	0.337	41	0.53	0.523	68	0.258	0.369	95	1.256	0.456
15	0.574	0.302	42	0.993	0.874	69	0.548	0.352	96	0.333	0.365
16	1.47	1.842	43	0.392	0.249	70	0.198	0.155	97	0.334	0.227
17	0.477	0.26	44	0.566	0.194	71	0.341	0.285	98	0.807	0.241
18	0.381	0.325	45	0.355	0.292	72	0.591	0.403	99	0.635	0.278
19	0.476	0.349	46	0.473	0.291	73	0.467	0.265	100	1.105	0.978
20	0.278	0.23	47	0.652	0.377	74	0.346	0.261	101	0.659	0.34
21	0.597	0.541	48	0.652	0.327	75	0.375	0.396	102	0.336	0.24
22	0.783	0.403	49	0.469	0.304	76	0.337	0.232	103	0.162	0.139
23	0.458	0.362	50	0.52	0.251	77	0.55	0.468	104	0.582	0.459
24	0.53	0.305	51	0.354	0.238	78	0.544	0.22	105	0.544	0.276
25	0.887	0.928	52	0.305	0.278	79	0.239	0.21	106	0.41	0.312
26	0.682	0.632	53	0.731	0.463	80	0.275	0.185			
27	0.409	0.198	54	0.397	0.457	81	0.378	0.516			