

CAN YOU FEEL THE DIFFERENCE? THE JUST NOTICEABLE DIFFERENCE OF LONGITUDINAL ACCELERATION

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In developing the next generation of engines and powertrains in the automotive industry, a deep knowledge of acceleration and its perception by the customer is essential. Because the vehicle's longitudinal acceleration is one of the most dominant factors in perceived driving experience, the desired increase or accepted decrease of this factor should be carefully controlled. The main objective of the present study is to identify the point at which the difference in longitudinal acceleration becomes just noticeable. In particular, this means locating the minimum point at which a vehicle's acceleration can differ from another and still be noticed by the subject. For this purpose, an experimental vehicle was equipped with an application control device, which allowed the vehicle's acceleration performance to change within a few seconds. That on the other hand enabled an experiment to be conducted with 16 subjects and using adapted methods from the field of psychophysical research. The obtained threshold of about 0.1m/s^2 (level of maximum acceleration) and about 1m/s^3 (acceleration gradient, 95% confidence interval) demonstrated a way that this research problem can be taken from the laboratory and applied under real life conditions to obtain application-oriented results.

INTRODUCTION

Motivation

The development of modern powertrains has reached a very advanced level in the automotive industry. It has to fulfill specific requirements depending on where the car falls in the OEM's portfolio. Aside from certain highly specialized vehicle concepts like high efficiency or super sport vehicles, the character of a vehicle's powertrain is caught between the requirements of sportiness, fuel saving and comfort.

One major factor influencing both fuel consumption and the perceived performance of a vehicle is the acceleration performance (Müller, 2012). Depending on the positioning of the vehicle, the objective in development is to reduce fuel consumption or enhance the driving experience. Both cases affect the energy consumption of the vehicle. The eco-vehicle is designed to provide lower energy consumption with minimal noticeable performance degradation. The increasing use of energy for an enhanced acceleration of a sport-vehicle on the other hand, has to be as noticeable as possible for the driver.

For that reason, an in-depth knowledge of the human perception of longitudinal acceleration of the vehicle is essential in developing the next generation of both efficient and effective engines and powertrains.

In summary: the aim of this study is to develop a method to investigate human perceptual performance in the field of longitudinal acceleration and to apply it in an experimental situation.

Prior Research

Basic studies on this topic were conducted mainly in the 1960s by Rockwell and Snider. To come straight to the numerical results: according to Rockwell and Snider the

absolute threshold of linear acceleration in the automotive context lies between 0.01g ($\sim 0.1\text{m/s}^2$) and 0.02g ($\sim 0.2\text{m/s}^2$). This experiment was conducted using methods from the field of classical psychophysical methods: method of adjustment and method of constant stimuli (Rockwell, 1965).

According to that study, the Driver Performance Data Book (Henderson, 1987) is citing a study of Ernst and Rockwell from 1966 in which the dependence of the acceleration threshold on the vehicle's speed was investigated:

Acceleration to 35mph ($\sim 55\text{km/h}$): 0.012g ($\sim 0.12\text{m/s}^2$), acceleration to 50mph ($\sim 90\text{km/h}$): 0.0115g ($\sim 0.11\text{m/s}^2$) (Ernst and Rockwell (1966) cited in Henderson (1987)).

Except Rockwell's experiments, most of the other studies investigated linear acceleration thresholds of 0.06m/s^2 to 0.1m/s^2 under laboratory conditions. Howard (1986) provides an overview in Boff (1986).

Present Research

The present study takes up this topic again and aims for the investigation of the just noticeable difference (instead of the absolute threshold) and furthermore for a more detailed investigation of the human perception performance of longitudinal acceleration. The acceleration process will therefore be divided into several parts in order to analyze them separately.

Also the following hypothesis will be investigated: the direction of approaching the perceptible threshold of the maximum acceleration has an influence on the value of the threshold.

The concept for the technical implementation will also be included in this study. The methodological procedure will be based on modern adaptive methods of psychophysical research, in contrast to classical methods.

Furthermore the research question will be brought out of the laboratory to generate application-oriented results under real life conditions.

To summarize the research question: what is the just noticeable difference for longitudinal acceleration and is it possible to investigate this threshold separately for the acceleration gradient and the maximum acceleration level?

Theoretical Background

The acceleration of a vehicle can be considered as an objective physical stimulus. This stimulation is mediated primarily by visual (visual flow, speedometer), acoustic (engine, wind, road noise) and kinesthetic information. The way these signals are processed forms the subjective perception of vehicle acceleration.

The field of research dealing with the relation between objective physical stimulus and the resulting subjective perception is called psychophysics. Basic research in this field dates back to the German physicist and philosopher G. Fechner, who in 1860 developed scientific methods for measuring human sensitivity to specific sensory stimuli. A typical question in psychophysical research is: "given a stimulus value equal to a , what is the smallest increment $\Delta(a)$ such that $a + \Delta(a)$ "just noticeably" exceeds a ?" (Boff, 1986, p.1.23) The $\Delta(a)$ is called the just noticeable difference (JND).

Psychophysical research is primarily divided into inner and outer psychophysics. Further classification of outer psychophysics leads to a separation between classical and adaptive methods. Classical psychophysical methods such as the method of limits, method of constant stimuli, or method of adjustment aim at the development of the complete psychometric function (Gescheider, 1997).

The adaptive methods, on the other hand, focus on identifying specific thresholds. Since there is a need to collect much more data (and thus a lot more data besides the threshold we are interested in) to describe the psychometric function, the present experiment was conducted using an appropriate adaptive method.

In summary, the challenge taken up in this experiment was to analyze methods taken from the field of psychophysics and to extend one of them beyond the laboratory for adaptation to field studies with an actual car.

An important factor in psychophysical studies is to focus on a stimulus while precisely suppressing interference and cross-influences through unintended and nonsystematic variation of other stimuli. The main challenges in this study were:

1. Choosing the most appropriate method for an efficient and effective achievement of the given objectives.
2. Analyzing and sectioning the acceleration process.
3. Focusing on one specific part of the acceleration process while keeping the remaining parameters constant.
4. Technical implementation in an experimental vehicle.
5. Carrying out the experiment.

METHOD

Participants

The study was conducted with 16 participants. 3 of them were female and 13 male. The average age of the subject group was 27.0 (SD = 2.45), ranging from 23 to 31.

Technical implementation

Experimental vehicle. The vehicle was a modern 3.0 liter 6 Cylinder Sedan with automatic transmission and four-wheel drive. The test engineer responsible for the manipulation of engine characteristics and the experimenter were on the back seats. The experimenter guided the subject through the experiment and gave instructions to the test engineer regarding the next parameter variation depending on the subjects' previous answer.

Independent parameter variation. The main technical challenge was to precisely vary the acceleration process so that the acceleration gradient remained constant, while the maximum acceleration level can be changed systematically and in defined increments (and vice versa). Figure 1 contains a diagram of the stepwise variation of the maximum acceleration level at a constant gradient.

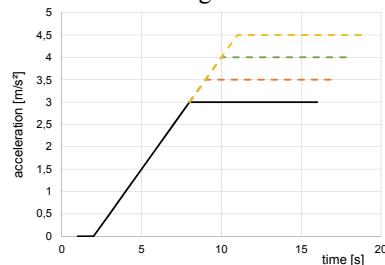


Figure 1. Stepwise variation of maximum acceleration level (dotted)

Numerous preliminary experiments were necessary because of the technical implementation as well as the definition of appropriate step sizes. With the help of the vehicle's application control device it was possible to manipulate the torque curve over the rpm. As a consistent change in the torque over the entire rpm range affects both the gradient and the maximum acceleration level, they were separately changed systematically. In preliminary experiments with subsequent analysis of the measurement plots, the following procedure has been found to be feasible:

Standard Stimulus: The vehicle has 60% of the maximum torque over the entire rpm range. Advantage: It's possible to decrease and also to increase the torque.

Modified Stimulus 1 (maximum acceleration level): The vehicle has 60% of the maximum torque until 2000rpm, which means to have the constant *standard gradient*. For the range of 2000 to 5000rpm the torque is increased or decreased to get a variable maximum acceleration level.

Modified Stimulus 2 (gradient): The torque is increased or decreased until 2500rpm to get a variable acceleration gradient. For the range of 2500 to 5000rpm the vehicle has 60% of the maximum torque, which means to have the constant *standard maximum acceleration*.

This kind of variation was possible online in several seconds from the backseat of the car. One of the main requirements of psychophysical experiments was thus fulfilled: the two different stimuli are presented to the subject in a very short sequence.

Procedure

At the beginning of the experiment, the subject were given the opportunity to familiarize themselves with the experimental vehicle by driving the 6km distance from the starting point to the test track. The test engineer in the back of the car took into account the fact that the subject was driving with the standard experiment configuration (only 60% of maximum torque) from the very beginning of the experiment. After explaining the goal of the experiment and the test procedure, the subject had the chance to practice the driving maneuver by doing some test runs.

Each subject started by either investigating the JND of maximum acceleration or the gradient. The sequence was permuted. The experimenter guided the subject through the double staircase procedure (as explained in the next subchapter) and gave instructions to the test engineer based on the previous answer of the subject: right answer → decreasing intensity of the next modified stimulus; wrong answer → increasing intensity of the next modified stimulus

For both kinds of stimulus, the driving maneuver was the same:

1. Second gear, manual shifting, constant driving (20km/h) for several seconds
2. The experimenter gave the “go” signal for the standard stimulus
3. Full-throttle acceleration by the subject up to 5000rpm (no kick-down, no gear-shifting)
4. Decelerating to 20km/h while the experimenter was preparing the car for the modified stimulus
5. Constant driving again
6. “Go” signal from the experimenter for the modified stimulus
7. Full-throttle acceleration by the subject up to 5000rpm (no kick-down, no gear-shifting)
8. Asking the subject for his decision, e.g. “was the maximum acceleration level of the modified stimulus higher or lower than the standard stimulus?”

Between the first presentation of the stimulus (1) to the decision-task (8) approximately 20 seconds elapsed.

Design, Stimuli and Tasks

As explained above, we are interested in investigating the perceptible $\Delta(a)$ of longitudinal acceleration. That's why an adaptive method based on the staircase procedure was used. Additional methodological adaptations were necessary for the study: the integration of a constant comparison stimulus (which is an element from the method of constant stimuli) became apparent as helpful for the subjects' task.

The following part of the study contains an explanation of the method used, which consists of a staircase respectively

double staircase procedure and a constant comparison stimulus (= standard stimulus).

The main element of investigating the JND following this method is to present a pair of two stimuli to the subject. The first of these is the standard stimulus and the second is the modified stimulus. Both stimuli are presented to the subject with the shortest time distance possible. The subject is now required to determine whether there is a perceptible difference between the standard and the modified stimulus (Gescheider, 1997). Using the staircase procedure, the first modified stimulus has a much greater intensity than the standard stimulus, so the difference is easy to detect. Figure 2 displays an excerpt of a simple staircase procedure. If the subject gives the right answer (difference existed and difference detected), the difference of intensity decreases by a defined increment until the subject makes an error. At this reversal point the intensity increases until the subject again provides the right answer. Check marks in Figure 2 represent correct answers, crosses wrong answers and check marks respectively crosses with a black frame are reversals.

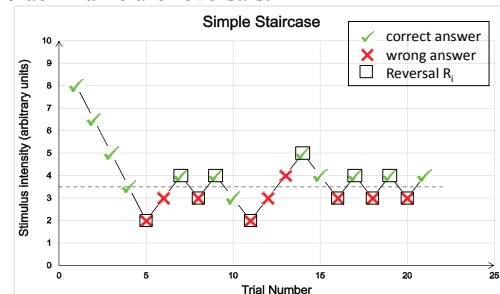


Figure 2. Excerpt of a Simple Staircase procedure

The mean of all reversals is equivalent to the just noticeable difference for this subject. Wetherill und Levitt (1965) cited in Levitt (1971), recommend testing until at least 6 to 8 reversals are obtained.

Experiments following this procedure are subjected to negative effects on the quality of results because of two main-effects: errors of habituation and anticipation (Levine, 1994).

Over the course of the experiment the subject can quickly catch on to this procedure, thus resulting in the negative effects mentioned above. By methodological changes we want to eliminate these negative effects or at least counteract them. The adjusted procedure is a double staircase method. The procedure itself is similar to the simple staircase except the fact that there is now a second staircase run, which can differ in the intensity of the first pair of stimuli, the direction of converging to the threshold or the step size. An exemplary procedure is shown in Figure 3.

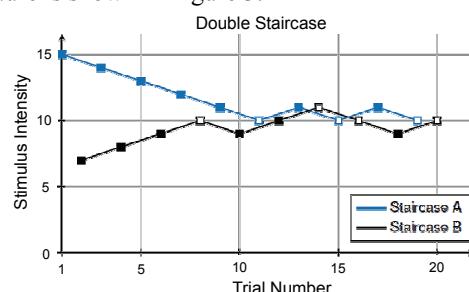


Figure 3. Double Staircase procedure

Due to the number of statistically required repetitions, and the presentation of very small stimulus differences, experiments in the field of psychophysical research are often an exhausting and monotonous process for subjects to undergo. To prevent negative effects on the results, a performance-based bonus/malus system was thus implemented in the experimental procedure. This should increase the motivation level for a disciplined experimental procedure and keep it high throughout the experiment. The subjects were given an imaginary account, in which a correct answer increased the balance while a wrong answer decreased it. When the experiment was completed, the final score was "paid off" with chocolate bars.

That's the methodological framework of the present study. The following subchapter will explain the procedure of defining the parameters to be investigated in the experiment.

Analyzing the acceleration process

At the beginning of this part, the acceleration process was analyzed and separated into the phases 1 to 3. Figure 4 shows the result of a measurement of a full throttle acceleration in the second gear from a constant driving speed of 20km/h.

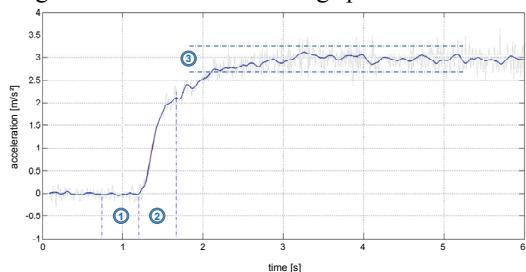


Figure 4. Acceleration separated in 3 phases

The process of acceleration was divided into the following phases:

Phase 1: Response Time. The response time is considered as the time between the actuation of the accelerator pedal and the first measurable response of the vehicle.

Phase 2: Acceleration gradient. The increase in acceleration over time is called acceleration gradient. This increase will be flatter or steeper depending on the performance of the vehicle. The measurement starts after the first measurable response of the vehicle and ends after reaching a certain percentage of the maximum acceleration.

Phase 3: Maximum acceleration. Depending on the performance of the vehicle, it will remain for a certain time at a certain level of maximum acceleration. The measured value of maximum acceleration is the mean average of acceleration for several seconds after having reached the highest value (e.g. here: 3m/s^2). Depending on the engine characteristics, but at the latest on reaching the maximum rpm, this phase will change over into the phase of a decrease of acceleration (not shown in Figure 4).

The respective phases are considered only for one gear stage. There is no gear shifting at any point in the experiment. The response time (phase 1) and the decrease of acceleration after the phase of maximum acceleration are not considered in this experiment.

The result of this analysis was to subdivide the investigation of just noticeable differences of longitudinal acceleration into two phases: the gradient and the level of maximum acceleration. These parameters are considered to influence the subjective perception essentially.

The next subchapter deals with the necessary focusing on these two kinds of stimuli.

Focusing and keeping constant

The following parameters which may interfere with an exclusive focus on the investigated stimuli should be kept as constant as possible:

Vehicle. To avoid interference from different vehicle classes, a special experimental vehicle was used for the experiment. With this vehicle it was possible to vary the parameter gradient and maximum acceleration using appropriate measuring and calibration equipment.

Course. The influence of lane width, number of lanes and objects next to the road (e.g. dense forest or plane open field) on the driver's peripheral visual flow can be experienced in everyday life and has also been shown in different studies (e.g. Edquist, 2009). To eliminate the effects of roadside environment on perception of own speed and acceleration, the study was conducted each time on the same flat, straight and little traveled rural road.

Engine Sound. The engine sound was kept constant by completing the same driving maneuver each time (acceleration from 1500 rpm to 5000 rpm, respectively 20 to 50km/h).

RESULTS

This chapter provides an overview of the obtained results based on the methodological framework presented. The results are divided into two experimental parts: maximum acceleration and acceleration gradient. For the statistical analysis t-tests were applied where appropriate. The relevant level of significance was determined by $\alpha = .05$.

Maximum acceleration

Since the accelerations were measured and recorded not only during the pre-tests but during the main experiment as well, it was possible to analyze the data more precisely and to check the reproducibility of the acceleration maneuvers. The maximum acceleration of the standard stimulus was 3.3m/s^2 ($SD=0.2\text{m/s}^2$) and quite good reproducible.

Table 1 shows the results of the obtained JNDs of maximum acceleration averaged over all 15 subjects. The data for one subject had to be excluded from the interpretation because the analysis of the measurement plots showed that this subject did not perform the driving maneuver correctly.

Table 1: Results for the JND of maximum acceleration

	Mean	SD
Threshold (approaching from below)	0.08 m/s^2	0.077 m/s^2
Mean average	0.09 m/s^2	0.086 m/s^2
Threshold (approaching from above)	0.10 m/s^2	0.095 m/s^2
95% confidence interval	from 0.04 m/s^2 to 0.13 m/s^2	

The following chart shows an approach for a group-specific interpretation of the collected data. Referring to the hypothesis mentioned in the introduction, the influence of power reduction or power enhancement to perceptual performance of the subject is analyzed. The stepwise approaching to the standard stimulus from above represents the power reduction, the approaching to the standard stimulus from below represents the power enhancement. Figure 5 compares the resulting JNDs.

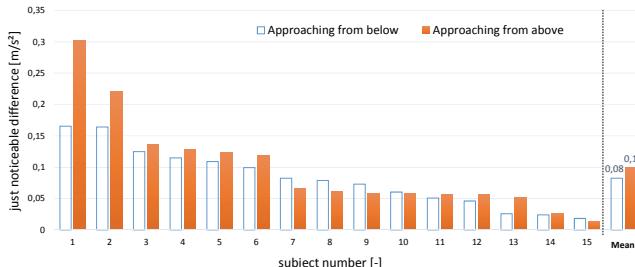


Figure 5. Comparison of JNDs approaching from below and above

The JND reveals no significant influence of the direction of approach direction ($t(14)=-1,642$, $p=.123$). Thus the hypothesis that the direction of approaching the difference threshold has a significant influence for the value of the threshold could not be confirmed.

Acceleration gradient

The measurements of the acceleration gradient have also been recorded. The gradient of the standard stimulus was 8.5 m/s^3 ($SD=0.7\text{m/s}^3$). The averaged results over 15 subjects are shown in Table 2. The relatively high standard deviations in Table 2 indicate the technically not fully satisfactory reproducibility of the factor *gradient*. Using the results of measurements it was possible to perform the analysis anyway.

Table 2: Results for the JND of acceleration gradient

	Mean	SD
Threshold (approaching from below)	0.52 m/s^3	0.72 m/s^3
Mean average	0.53 m/s^3	0.83 m/s^3
Threshold (approaching from above)	0.53 m/s^3	0.93 m/s^3
95% confidence interval	from 0.07 m/s^3 to 1.0 m/s^3	

The mean variation can in part be explained by the different way some subjects were doing the driving maneuver. The input requirement was to hold down the accelerator pedal to 100% as quickly as possible. Since the measured gradient is quite sensitive to even slight variations in this procedure, such effects lead to interferences of reproducibility. For this reason we define the JND for the acceleration gradient as the upper threshold of the 95% confidence interval (1m/s^3).

DISCUSSION AND CONCLUSION

The research presented in this paper is related to the research topic of Rockwell and Snider from the 1960s. Thanks to technological capabilities, it was possible to design the experiment to be far more specific and to analyze the results and the measurements in much greater detail. Nevertheless, the results of the investigation of thresholds for the level of maximum acceleration seem to be in close context to the

results of Rockwell und Snider (1965). However, in Rockwell's experiment the experimenter was controlling and also performing the vehicle's acceleration. To investigate absolute threshold the subjects just had to report their perception via pressing a button. The study presented here, however, divides the acceleration maneuver into its main parts and is investigating their thresholds under much more controlled and standardized conditions. Giving the subject the chance to perform the acceleration maneuver by itself, is an important factor to relate the results to realistic situations, where noticeable differences of accelerations can become relevant. Both the found results and the applied method and technical implementation can help developing e.g. upcoming technologies for personalized and customized driving characteristics. Also the perceptual influences of power degradation of electric vehicles are associated with the presented research and should be seriously considered and investigated before bringing them to the market.

Next steps

Because we identified the maximum acceleration level to be a dominating, easy adjustable and good reproducible factor for perceiving vehicle's acceleration, subsequent studies will focus on this part of the acceleration process. The next studies will investigate the dependence of the existing thresholds on the driven speed. The effect of different psychophysical methods and the influence of engine sound will also be investigated, while keeping E-Mobility in mind.

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