

Human Reaction Times as a Response to Delays in Control Systems - Notes in vehicular context

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Summary

In this paper various aspects of human perception of delays and causality are reviewed. General reaction times are introduced so that the delay and its effects have some perspective of significance. Value that could be used as a “golden rule” for the maximum delay in different kind of systems related to three main senses in vehicular control (sight, hearing and touch) is in the range of **50 - 60ms** has been distilled from the reviewed material. This value has several advantages over higher values; In most of the cases it might be noticed but it does not affect the perception of the causality nor the performance, humans can easily adapt to it, it works with several senses simultaneously, and it has very low impact on the performance in the control tasks and other systems affected by the human perception capabilities.

Tiivistelmä

Tässä työssä käydään lävitse ihmisen viiveiden ja kausaliteetin havaintokykyyn liittyviä asioita. Yleiset reaktioajat esitellään jotta viiveiden ja niiden vaikutusten suuruus saataisiin esille. Läpikäydystä materiaalista on löydetty **50 – 60ms:n** arvo jota voidaan käyttää rajana ajoneuvoihin liittyvien ohjaustehtävien viiveissä. Tämän arvoalueen etuna hitaampiin viiveisiin ovat ainakin seuraavat seikat; Tämä viive voidaan havaita joissain tapauksissa eri aistein, mutta sillä ei ole merkitystä tehtävistä suoriutumisen tai kausaliteetin havainnointiin, tällaiseen viiveeseen on helppo sopeutua, toimii useiden aistien suhteen, ja sillä on hyvin pieni vaikutus suorituskykyyn ohjausjärjestelmien hallinnannassa tai muissa järjestelmissä joissa ihmisen havaintokyvyllä on merkitystä.

Background

This literature review was done as a part of the Vehicular Information Systems (VIS) development program. Aim of this study was to find out

- what kind of delays humans notice in control systems
- how fast humans can react in control tasks
- how the delay affects the reaction time and the control efficiency of the humans

The control tasks in this paper means a task which is done in a closed control-loop. In closed control-loop the effect of the input force to the result is monitored and adjusted accordingly continuously, e.g. driver turns the steering wheel and monitors how the car is turning on the road as a response to his movement. If there are any problems he can change the force applied to the wheel immediately. most control-systems in vehicular context are based on the closed control-loop, one notable exception being the teleoperated

systems. In open-loop controller applies force, and waits until he sees if it was enough or too much. After this period of waiting he can apply the correctional force and wait again for the result.

So, why all these delays matter in the closed control-loop? Basic reason for this is that because slow reaction time to events while in control of some form of machinery is dangerous in the context of moving objects. **If the speed of the object is 88km/h it translates roughly to the speed of 25m/s which means that every 0.2s of time is about 5 meters worth of movement** (example converted from Green, 2000). Other reason where knowledge of the limits can be used is the development of the new technical solutions that are used in vehicles.

Many of these solutions use computational parts that need time to do their tasks (e.g. computation and adjustments of vehicle parameters based on sensors), and these cause delays between the person acting as the operator and the control movement. Especially this affects the vehicles using so called X-by-Wire – solutions where aspects like braking, steering and throttling are dispatched through communication network instead of the classical mechanical link. If the delays in these systems get too long and problematic, the paradigm of closed control-loop gets changed eventually to the open control-loop.

Literature material to which this work is based ranges from scientific articles to computer game journalism. This stems from the diversity of studied fields and the fact that on some fields the scientific studies are not done in from the same perspective that we were looking for during this survey. Mostly the material comes from the areas of physiology, vehicular systems, transportation, different forms of the teleoperation, computer gaming and human-computer interaction (HCI) studies. Also the sources of research differ depending on the focus of the original research as some of the studies are coming from industry and military organizations while majority of the material is coming from the research institutes.

Material also has wide range in publication years, as oldest papers that were reviewed are from the year 1899 and the latest ones are from the year 2009. Many of the basic values used in this field are also based on human nervous systems fixed values which do not change much even during decades or centuries so this explains some of the old material. Compared to the size of this paper there are quite a lot of references, but this is because of the previously mentioned material is from wide range and time scale and it has been distilled to this review. From this material the delay recommendation for the delay in the control systems or simulators has been distracted, This recommendation is the value of **50 - 60ms** as mentioned in the summary and the rest of the paper is telling the main points of the story behind this value.

At the first part we go through the basic reaction times, and then we will introduce what kinds of delays are noticed, and what kinds of delays do have an effect on the performance. Also the effects of the delays and reaction times to the performance are noted while these findings are presented, and if some affecting factors have been identified from the literature, those are also introduced in the text.

Delays base on the human nervous system

This chapter contains some of the basic information that explains why some of the delays and differences occur between the delays of different senses. Basically, three most important senses in the perspective of the VIS are ranked as follows:

- auditory stimulus only takes 8-10 ms to reach the brain (Kemp et al., 1973)
- visual stimulus takes 20-40 ms (Marshall et al., 1943)
- touch is intermediate, at 155 ms (Robinson, 1934)

These differences are partially explained by the fact that the nerve system has different kind of speeds for different sources of signals. Here are some examples of the travel times of the impulses in the nervous system:

- Muscles: 119m/s
- Touch : 76.2m/s
- Pain: 0.61m/s

This explains the baseline difference between senses. Also, human brain is somewhat visually oriented, 38% from sensory area is dedicated to visual stimulus (values are compiled from various sources, e.g. Chudler, Myers, and Kraus). Tactile/Haptic values have some contradictory values between sources as the Handbook of Perception and Human Performance (1986) says that tactile simple reaction time is 140ms, which contradicts with the slow travel rate.

Also, Keele reports that approximate delay on reacting on more haptic things, like tension of the spring changing is around the values of 110 - 160ms (1968). These results might be dependent on the location from which the tactile stimulus entered the nervous systems as e.g. toes are further away than fingers. Another interesting point is raised on the works of Eagleman, whose work is discussed bit more later on, about how brain processes data related the causality of the events.

Also, for the visual stimulus the area of eye which does the detecting changes the reaction times. As Brebner and Welford (1980) have noted, the central area of eye produces faster reaction times than the edges. Central area of eye is the area where detectors are cones, and in edges the rods are dominant ones. These parts also have different roles in visual perception as noted in Money's (1993) paper where the difference is summarized as:

- Central Vision, serves to answer the question "what"
- Peripheral Vision, serves to answer the question "where"

Other aspects of the stimulus also affect on its detection by human senses. Some of these are the contrast between stimulus and the background, conditions where the detection happens, and size and the strength of the stimulus. In example, very dim object might be detected during night, but not during day as its intensity does not meet the perceptual threshold of the retina compared to the other brigetrs objects on the field of vision.

Following values and other remarks are largely based on the work done by Green and Summala in their publications on the Transportation Human Factors during year 2000 (Green, 2000; Summala, 2000.) These findings are updated with additions from Green's website which has somewhat different version of the publication (Green, 2006). Also other sources are used to augment more information about specific

aspects. In the works of Green and Summala the main focus is in the drivers braking behavior and reaction times. Steering is also touched upon, but mostly the other aspects besides braking come from these other sources.

Following information about the response (braking) and reaction time to the stimulus is presented using steps Green uses in his works (2000; 2006).

1. Mental processing (perception time) contains all the phases which happen during and after sensory processing inside the brain.

- Sensation is the phase where we notice that something is happening in our surrounding. This mostly happens in the non-conscious part of the awareness.
- Perception e.g. we notice that it is a person who is on the road, not just a “something”.
 - It takes **190 - 215ms for light stimuli** to be processed.
 - As noted, **sound stimuli is bit faster at 160ms.**
(For these see e.g. Galton, 1899; Fieandt et al., 1956; Welford, 1980; Brebner and Welford, 1980.)
- Situational awareness is the phases were driver combines the perception and his own situation, e.g. someone is on the road, and because that is the direction to which he is driving, there will be a collision.
- Response selection and programming follows this understanding of the current situation. During this it is decided what should be done, and how it is done. These decisions are based on the situation, training, expectations and so on. **Choice adds 100 - 200ms** to the process (Laming, 1968; Boff et al, 1986, p. 30-5).
- This all takes around **500 to 800ms** depending on various variables as mentioned above.

2. Movement time (muscle reaction) is the time required to move limbs. This varies between different actions and muscles.

- **200 – 400ms** is the time needed to **move limbs** as a programmed response.

3. Device response time

Third part of the whole event is the device response time which is the result of environmental and technical issues. For this reason this topic is no discussed in depth here. Some notes that were discovered while reviewing the sources are brought up here.

In flying **100ms** is seen as a limit for a responsiveness of the plane which if exceeded will affect negatively on the performance of the pilot (US Military Standard as referenced in the Smith, R.E., and Sarrafian, 1986a; and Smith, R.E., and Sarrafian, 1986b). Levels of handling qualities in this standard are following:

- Level 1, satisfactory handling qualities: 100ms.
- Level 2, acceptable handling qualities: 200ms.
- Level 3, controllable handling qualities: 250ms.

These requirements for the short delay between controller and the device come from the nature of the work of the fighter pilots who require precise controls for many tasks, like the tasks related to flying, e.g. midair refueling and landing.

In vehicular context Society of Auto-motive Engineers determined **20ms** to be the **transfer delay** between nodes in CAN standard, but this does not include the computation time required in the nodes.

Things affecting the reaction time

In case of hands, these times do not vary much if the subject uses one or both hands: difference between their reaction times to **sound** is from **0 to 17 ms** and with the **visual** stimulus it ranges from **0 to 23ms**. (Blinkov, Nikandrov, 2002). Also it's noteworthy that our perception of our own hand movements is limited as visual feedback on arm movements ranges from 150 to 250ms (Yin et al, 2003). But at the same time, we have the sense of proprioception, which is the sense we use to detect the relative position of neighboring parts of the body, e.g. when police officer asks person to close eyes, and touch the nose with index fingere. This is achieved with the proprioception.

Interesting side note on the brake reaction time studies was that those with fast reaction time pressed the pedal to the floor faster than those with slower reaction times; 500ms vs. 800 – 1000ms (Barret, Kobayashi, & Fox, 1968).

Green (2000) has list of three separate value sets for combined response times in braking situations depending on how well the drivers were informed about what would be happening during the test.

- Expected: 700 – 750ms is the reaction time from detection to moving foot from gas to brake
- Unexpected: 1250ms
- Surprise: approximately 1500ms for braking, and app. 1200ms for steering as hands do not need to be moved from one place to another (Hankey, 1996; Green, 2000).

Impact of the usage of the mobile phone is to the reaction times starts from the value of 500ms due the higher cognitive load of the drivers as reported in many studies (e.g. Alm, Nilsson, 1994; Summala et al, 1998). In some cases this also might also help the reaction times if people acknowledge the fact that they are driving with limited cognitive resources when using phones, and adjust their driving behavior accordingly. Some diseases also have negative effect on reaction times, e.g. diabetes type II causes longer reaction times (as summarized in the work of Richerson, Robinson, & Shum, 2005) almost by doubling it in some cases.

As reported by McGehee, Mazzae and Bladwin (2000) in simulation results are 300ms faster than in real live situations. But it is not known how extensively this value is applicable.

If visual information changes rapidly the reaction time to this change, e.g. direction of the movement of the target, reaction time to this is 135-185ms. It takes 110ms to respond to a change in target position if the direction of the movement is known in advance (Soechting, Lacquaniti, 1983) and over 200ms if the direction is not known (van Sonderen, Denier van der Gon, & Gielen, 1988).

In almost every age group, males have faster reaction times than females, and female disadvantage is not reduced by practice (Noble et al., 1964; Welford, 1980; Adam et al., 1999; Dane and Erzurumluoglu, 2003; Der and Deary, 2006). Barral and Debu (2004) found that while men were faster than women at aiming at a target, the women were more accurate. Visser et al. (2007) found that training on a complex task both shortened reaction time and improved accuracy.

Noticeable delays and their effect in control

Visual

Studies of Virtual Environments show that people are generally able to **detect latencies as low as 10 to 20ms** (Ellis, Mania, Adelstein, & Hill, 2004). Delay of **25ms did not** have a measurable effect on the performance, but **69-75ms** delay starts to show an effect (McKenzie, 1993; Jay, Hubbold, 2005). This might be affected by the fact that in visual stimulus, **30 - 40ms** delay is short enough to be perceived as a smooth motion (Mateo, 2007).

Kemeny (2000) who works in the PSA Peugeot-Citroën's simulation center has used the value of **50ms** in his works as a limit to which should not be exceeded in delays. He also cites following works and values as typical acceptable values for simulator transport delays as **150 ms for civil flight simulators** (FAA, 1995), **50 ms for conventional driving simulators** (*not found, Park, 1992*; but same values in Blana, 1996), up to **20 ms for head-mounted display** applications (Bloche et al., 1997). Same 50ms is also the highest response time reported by Chapron and Colinot (2007) of the motional base of the PSA Peugeot-Citroën's own driving simulator.

Shorter delays as degrading factors have been also reported, e.g. delays as small as **40 milliseconds significantly impair** rapid visually guided behaviors like pursuit tracking which is important aspect in the fighter planes (Warrick, 1949, 1955). In another study concentrating on the tracking tasks is by MacKenzie and Ware (1993) where they demonstrated that movement times increased by 64% and error rates increased by 214% when latency was increased from **8.3ms to 225ms** in target task. Values of 25ms and 75ms were also studied, but their effect on the movement times and the error rates were 10% or under.

In one study, (Loschky and McConkie, 2000) it was found that a **45 ms delay did not** affect search performance but did increase fixation durations for the eye movement. In other studies done by Loschky (2000, 2007) delays of **80 ms** in the updating of the graphics **significantly increased detection** of image blur that was otherwise almost never detected. Shortest delays found during this review were also reported by Loschky, as in one study (2002) he reports that test subjects were able to detect the resolution change in the picture with delays **between 5ms and 30ms** depending on which point of the saccade movement the eye was.

Reaction times **deteriorate after 80ms** in simulators, e.g. if the difference between visual stimulus outside the flying simulator and the cabin itself is at this level or over it (Boff et al, 1986). In a simulated driving task, driver's **vehicle control was found to be significantly degraded with a latency of 170 ms** (Frank, Casali, & Wierwille, 1988).

Sound

10-20ms delay does not cause the effects in most cases with auditory stimulus, musicians are specialist group with tighter requirements. Approximately **50ms causes** differences on the performance. **Lower than 100ms is required** to satisfy the requirements for most cases (Hämäläinen, Mäki-Patola, Pulkki & Airas, 2004). Immediate **causality** is observed if the delay is **under 50ms** (Michotte, report by Card, Moran & Newell, 1983) and perception of causality **degrades** if the delay is **over 55ms** (Dahl & Bresin, 2001).

In monkey studies conducted by Barone et al. (BMC Neuroscience, 2008) it is reported that if there is an auditory stimulus connected with the location of the weak visual stimulus, e.g. low contrast as in the source, the response time of the visual cortex drops by 5-10%. In other cases this effect was not noticed.

Touch

Vogels (2004) demonstrated that people were able to detect asynchrony between a visual and haptic stimulus at about **45ms**. Adelstein (2003) measured Just Noticeable Difference (**JND**) of **24ms**. Haptic feedback can lower the demands for visual stimuli and lower the reaction time by 18ms as demonstrated in the work of Griffiths and Gillespie (2004). **Effect for performance is noticeable around 200ms delay** (Jay & Rubhold, 2005).

In summary, haptic feedback has been seen as supportive information which is not necessarily needed as visual information has so dominant position in human perception. For this reason researchers have designed haptic devices as tools that could pass more information to the controller, e.g. the drift direction of the helicopter through a haptic vest as this information would not hamper the performance of the pilot, but could provide him information that he otherwise would not notice so easily.

Delay of control in computer games

This information has been gathered from small set of sources, namely articles from Gamasutra which is game news and resource site mainly targeting game developers, and from Eurogamer which is targeting gamers. In the field of computer gaming the delay in the control-loop is called "response lag", "input lag" or "controller latency/lag", or just "lag" depending on the case. It equals well with the meaning of control latency in other fields. Research papers found during this review were all from sources that were concentrating on the virtual environment side of responsiveness or to the latency effect of the network connection or graphical displays rather than to the control latency.

Based on this data, in games the target for control latency is in the range of **50 - 66.7ms**. In practice most of the games are in the range of 66.7-150ms. One of the exceptions is the PlayStation 3 user interface which has the delay of **50ms**. In practice this means that the delays last for 3 – 4 frames in the case of 60fps game, e.g. display refresh rate is 60Hz, as this translates to refresh rate of 16.67ms per frame. This value is in the same range that is reported in other fields. In practice players complain around 100 or 150ms, but this depends a lot on the game context, e.g. latency requirements between the firing actions of the bow firearm are different.

Fixed vs. changing delay

Watson et al. (1998) found that when the standard **deviation of latency was above 82 ms**, performance degraded, especially for the placement task, which required more frequent visual feedback. It was suggested that a **short variable lag could be more detrimental than a longer fixed one** (Lane et al., 2002). Over-actuation (e.g., over-steering and repeated command issuing) is also common when system delay is unpredictable (Kamsickas, 2003; Malcolm & Lim, 2003). This is explained by the fact that static and possibly known latency can be compensated by the adaptation coming from the experience and the training. Deviations can't be anticipated or adapted so this causes problems for the controller.

As general rule of thumb: after delay grows **to or over the 1000ms** operators switch from continuous control **to "move and wait" control** (Lane et al., 2002; Mateo, 2007), e.g. control-systems switches from closed-loop to open-loop.

Notes

In studies of steering, simulation is commonly used technique. Human model used in these models typically has the reaction time of 400ms (e.g. Card et al, 1986). In games the reported golden rule is in the area of **50 – 66.7ms**. This is lower than the widely cited quotation from Jacob Nielsen, who has said in the

“Response Times: The Three Important Limits”: "The basic advice regarding response times has been about the same for almost thirty years (Miller 1968; Card et al. 1991): **0.1 second** is about the limit for having the user feel that the system is reacting instantaneously, meaning that no special feedback is necessary except to display the result.”

This 100ms might be fast enough for utility software, but in the domain of games it might already cause problems with users. Of course the domain differences have to be notified here, Nielsen’s rules are for generic software and HCI studies where people are using information system to produce something, but in the games and other entertainment software humans are usually in control of some kind of a system or a virtual vehicle, so the shorter delays are seen as a necessity for proper feel of control and causality.

Training and adaptation have huge impact on the effect of the delays. In work of Cunningham, Billock, and Tsou (2001) the constant delay of 235ms was compensated by practicing between 5 to 20 minutes before experiments, e.g. operators adapted to the delay in system without significant effect on the performance. In another study conducted by Cunningham et al (2001) delay of 130ms was not causing problems for drivers, but delays of 230ms and 430ms had significant effect, and especially the group with the 230ms delay improved their performance significantly by practice.

It has been also observed that brain might delay the processing of some stimulus to wait for slower ones to arrive. These kinds of results have been reported in the works of Eagleman (2009). Based on his findings it might be so that in near field of the perception, near meaning closest 30 meters to the person, brain does some kind of a synchronization of the events to get a better view of them. According to him “this seems to occur because the system perceptually synchronizes signals that arrive less than 80ms apart (past 30 meters, the difference between the speeds of light and sound exceed this window)”. But this field is new, and the meaning of the possibilities of such a artificial delay on the real world, and in the simulated environments is not studied further yet.

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