The effect of visual notifications on user performance in an augmented reality environment: a distribution of attention between exogenous and endogenous stimuli

Schelvis, Kasper

Universiteit Leiden

Psychologie
Faculteit der Sociale Wetenschappen

The effect of visual notifications on user performance in an augmented reality environment: a distribution of attention between exogenous and endogenous stimuli.

Kasper Helair Schelvis

Master Thesis Clinical Neuropsychology
Faculty of Behavioural and Social Sciences – Leiden University
January 2022
Student number: 1572849
First examiner: Ineke van der Ham,
Section: Health, Medical and Neuropsychology

Abstract

This study examined the interface design of an augmented reality (AR) system that was being developed by the Dutch Police Force to assist police officers on horseback in navigating unknown terrain. The main research objective was to investigate the effect of visual notifications on the officers' responsiveness to navigation-assisting stimuli (i.e. 'user performance'). These stimuli consisted of buzzer sounds and direction indicators. Since navigation support was the primary goal of the interface, attention focused on navigation-supporting stimuli was regarded endogenous. Because information provision was a secondary goal, attention drawn to notifications was regarded exogenous. To investigate the influence of exogenous stimuli on the quality of endogenous information processing, a virtual environment was created. In this environment, ninety-nine participants walked both a route with notifications and a route without notifications. (Endogenous) response times of both conditions were compared to determine the effect of the exogenous stimuli. Subsequently, both the role of timing and the effect of endogenous-exogenous competition on travel speed were investigated. Several repeated measures analyses of variance have been conducted. Exogenous stimuli were found to have a significant negative effect on user performance, $F(1,87) = 11.193$, $p = .001$, $\eta 2 = .114$. In addition, the range between approximately 600 and 1000 milliseconds before the appearance of endogenous stimuli is probably the region in which endogenous user performance starts to be prone to exogenous stimuli, $F(1,9) = 10.005$, $p = .011$, $\eta 2 = .526$. Lastly, it turned out that notifications caused participants to run faster, $F(1,86) = 8.162$, $p < .05$, $\eta 2 = .087$. This study showed that stimuli in AR interfaces can enhance the travel speed of users. This is a desirable effect, since it is important for police officers to arrive at their destination as quickly as possible. This study also showed that exogenous stimuli can decrease user performance, as a result of which they could jeopardize users and others in the (traffic) environment. However, this study also provided an indication of the timing range in which exogenous stimuli are most likely to cause this undesired effect. Based on this range, timing-related blockages of distracting stimuli can be built into AR systems in an effective and efficient way, through which the performance-reducing effect of exogenous stimuli could be avoided.

Layman's abstract

In deze studie is onderzoek gedaan naar een 'augmented reality' (AR) navigatie systeem dat de politie wil gebruiken bij evenementen. Met de AR technologie kan door middel van een digitale bril een virtuele laag over het gezichtsveld van politieagenten worden geplaatst. Deze laag bestaat deels uit richtingaanwijzers en deels uit notificaties. Hierdoor kunnen politieagenten worden geholpen met het vinden van de weg en kunnen zij daarnaast worden geïnformeerd over de omgeving of noodsituaties.

Het effect van notificaties op de 'gebruikersprestatie', die aan de hand van reactietijden is gemeten, stond centraal in dit onderzoek. Het idee hierachter is dat de gebruikersprestatie iets zegt over de mate waarin iemand zich kan concentreren op de richtingaanwijzers en het verkeer. Dit is onderzocht aan de

hand van een virtuele omgeving, waarin participanten zowel een route met notificaties als een route zonder notificaties hebben gelopen.

Het onderzoek heeft aangetoond dat de snelheid waarmee de participanten door de virtuele omgeving liepen door de notificaties werd verhoogd. Dit is een gewenst effect, omdat het in noodsituaties van belang is dat politieagenten snel ter plaatse zijn. Ook is gebleken dat het tonen van notificaties de gebruikersprestatie verlaagt, hetgeen een ongewenst effect is omdat het in het kader van de navigatiedoelstelling en de verkeersveiligheid belangrijk is dat politieagenten snel op richtingaanwijzers en hun omgeving kunnen reageren. Echter kwam uit het onderzoek ook naar voren dat de gebruikersprestatie minder sterk werd beïnvloed wanneer een notificatie minimaal 1000 milliseconden na een navigatie-ondersteunend signaal werd weergegeven dan wanneer een notificatie maximaal 600 milliseconden na een dergelijk signaal werd weergegeven. Dit resultaat stelt ontwerpers van AR-systemen in staat om te voorkomen dat notificaties de gebruikersprestatie verlagen, omdat zij op basis van deze informatie een specifiek kader hebben waarmee zij notificaties afhankelijk van hun timing tijdelijk kunnen blokkeren. Zo kan op een effectieve en efficiënte manier worden voorkomen dat agenten op kwetsbare momenten worden afgeleid, zonder dat dit ten koste gaat van tijdige communicatie van informatie die de agenten nodig hebben om hun overige taken uit te voeren.

Introduction

Augmented reality (AR) is a relatively new technique that enables the user to see the real world, with virtual objects superimposed upon or composited with the real world (Hughes, 2015). In recent years, AR has offered new possibilities for a wide range of industries and institutions, such as gaming, architecture, and education. An institution that now wanted to investigate whether AR could also be of service to them is the Dutch Police Academy.

At the time of writing this article, the Dutch Police force was developing an AR system for police officers who are present at events on horseback. By using AR glasses, virtual route indicators can be projected over the visual field of view of police officers. In this way, the AR layer meets a supporting need, allowing police officers to navigate in unfamiliar territory without having to explore the area in advance. In addition to its supportive function in navigation processes, the AR technology enables visual notifications to be displayed in the visual field of view of the officers. In this way, the AR layer meets a supporting need, reminding officers of their surveilling duties. For instance, officers can be alerted about the closing time of a particular pub, or about the characteristics of a person or a vehicle that is on the run.

In the present study, the user interface that was being developed by the Police Force has been examined in a simulated setting. Because both route indicators and notifications are added to the usual information flow to be processed by the officers, the extent to which people can process information from both sources has been the focus of this study.

Endogenous and exogenous attention

As users of the AR interface need to keep their attention on the road, but at the same time keep an eye on notifications, it was evident that the cognitive model relevant to the police force's design was one that assumed a distribution between two kinds of attention. Because users have to focus their attention on the direction indicators, through which they perform their navigation task in a targeted manner, this form of attention was considered endogenous. This kind of attention is often described as top-down (goal oriented) and voluntary (Chica et al., 2013; Mayer et al., 2004; Theeuwes, 1991). Since navigating was regarded as the initial goal to which attention should be remained, momentary attention that is drawn to the notifications was considered involuntary and stimulus-driven, also known as exogenous (Chica et al., 2013; Mayer et al., 2004; Theeuwes, 1991). Since both forms of information processing rely on different neural circuits, it can be assumed with some certainty that they are fundamentally different (Chica et al., 2013; Mayer et al., 2004; Petersen et al., 1994).

The dichotomy between endogenous and exogenous attention was central to this study. Since attention would not exist without entities to which it can be directed or drawn to, endogenous attention is directed to endogenous stimuli and exogenous attention is drawn to exogenous stimuli. One of the interface designs the Police Force envisioned was one in which users are not only exposed to direction indicators, but also to a buzzer sound that is audible whenever users approach an intersection. This buzzer sound is intended to prompt the user to display a direction indicator by means of an act yet to be determined, which supports the navigation process. In this design, both visuo-spatial and auditive attention is oriented endogenously to relevant auditive and spatial stimuli. Visuo-spatial attention is also oriented exogenously, as users sometimes receive notifications while they are navigating. These notifications could either be embedded and appear based on the user's location, for example when they entail information regarding surveillance tasks. However, a notification could also be novel and acute, for example when they entail characteristics of an emergency or a wanted person.

Both endogenous and exogenous attention are believed to serve a particular purpose. On the one hand, endogenous oriented attention allows one to act purposefully, because it enables the person to select incoming stimuli through a framework that entails certain expectations. Stimuli that are expected are thereby detected and processed more easily (Chica et al., 2013; Posner, 1980). On the other hand, one must be able to process exogenous stimuli as well, for important stimuli which were not anticipated to be relevant should also be noticed (Chica et al., 2013). Therefore, both endogenous attention and exogenous attention enable us to deal with a dynamic environment. In the case of the police, navigation performance is supported by endogenous attention, since navigation can be regarded top-down and endogenous attention has been shown to contribute to perceptual orientation (Yeshurun & Tkacz-Domb, 2021). In addition, endogenous attention allows the officers to monitor the traffic situation and, since it has been shown to increase response performance, it contributes to the safety of themselves and other road users (Posner, 1980; Saunier & Sayed, 2008; Zheng et al., 2014). It can therefore be stated that in this case, navigation and traffic safety fall under the same endogenous category that could be referred to as 'user performance'. On the other hand, exogenous attention ensures that the officers can be made aware of their remaining tasks, since attention focused on stimuli that are not relevant to the endogenous task (e.g. notifications) can be classified as stimulus driven (Chica et al., 2013; Hoekstra-Atwood, 2015).

Exploring the interplay between endogenous and exogenous attentional processing was the main objective of this study, which was divided into its effect on user performance and its effect on travel speed. Its effect on user performance was subdivided into a timing-independent and a timing-dependent effect.

Competition and user performance

As the interface design presented by the Police Force is one that is unique and arose directly from practice, it was not clear how exactly the interplay between notifications and user performance would manifests itself. However, there are several studies that have investigated the interplay between endogenous and exogenous attention in alternative settings.

One of these studies is a study of Meeter et al. (2010). In this study, the effect of distractors on saccadic response times was examined. It was found that whenever a visual target and a visual distractor were presented simultaneously after an attentional fixation, saccade latency occurred with regard to the target. This experiment also showed that this latency depended on the (spatial) distance between the target and the distractor: latency occurred when the distance between the target and the distractor was relatively large. This study showed that exogenous stimuli can delay the attentional shift towards an endogenous target (Meeter et al., 2010).

Hickey et al. (2010) discuss similar findings. In their study, rapid deployment of attention was found to be associated with slow response times on an endogenous response task. This was because attention needed to be redeployed to the target location after it had been deployed to the distractor. Hickey et al. (2010) state that their findings and the findings of Meeter et al. (2010) are in line with Godijn and Teeuwes' competitive integration model. This model describes how integration of endogenous and exogenous factors in a common retinotopic salience map determines the programming of saccadic eye movement (Teeuwes & Godijn, 2002). Hickey et al. (2010) concluded that competition between relatively distant activation loci on the retinotopic map caused them to inhibit each other, whereas relatively close activation caused 'summation'. As a result, exogenous influences on the map occurred rapidly, while the accrual of endogenous information took time.

So even though endogenous and exogenous attention appear to be necessary to deal with a dynamic environment, it has been shown that the relationship between the two can be one of competitive nature (Hickey et al., 2010; Meeter et al., 2010). It is therefore quite possible that the relationship between the two processes, as reflected in the design of the Police Force, could also be explained in competitive terms. Besides, it is relatively easy to imagine a situation in which someone interacting with the AR interface is experiencing an incident that could be explained by such a competitive model. Take for example an officer who is approaching an intersection while he is navigating during an event. At such a moment, the officer's endogenous attention is fixated on the intersection, at which he knows a direction indicator is about to appear. Also, his endogenous attention is fixated on the intersection because he has to monitor the traffic situation. When at such crucial moment a notification appears, it could attract his attention. In the midst of this situation, endogenous attention must suddenly compete with the notification that draws attention exogenously. Based on the results of Meeter et al. (2010), which demonstrated that exogenous stimuli can cause saccadic latency with regard to an exogenous task, and Hickey et al. (2010), which demonstrated that exogenous stimuli can cause slower response times on an endogenous task, it was expected that adding notifications to the navigation task would result in slower response times with regard to the endogenous task.

Timing dependency

In a study of Grubb et al. (2014) the interaction between endogenous and exogenous attention was also investigated, but they added another layer. In this study, it was found that the perceptual consequences of the interaction between endogenous and exogenous spatial attention was timing dependent (Grubb et al., 2014). More specifically, it was discovered that endogenous information accrual and performance was significantly modulated by exogenous cues when there was a forced response delay period of 600 milliseconds, while the impact of task-irrelevant distractors on the endogenous task could be regarded negligible when the response was forced to take place after 1000 milliseconds. This timing effect was found both when endogenous attention was pre-allocated to the target location and when it was distributed across the visual scene. This finding showed that exogenous stimuli are less likely to interfere with an endogenous task when the interval between them is larger (Grubb et al., 2014). Based on the study of Grubb et al. (2014), which demonstrated a timing-dependent relationship between exogenous cues and endogenous performance, it was expected that there would exist a timing-dependent relationship between notifications and user performance.

Travel speed

Besides the fact that it is possible for an exogenous stimuli to affect endogenous performance, research from Wu et al. (2011) and Qiao et al. (2015) indicate that notifications might decrease travel speed.

Workload has been shown to have a negative impact on driving speed during a navigation task (Wu et al., 2011). This effect was found in native American-English people who were navigating in an unfamiliar country in a driving simulator. A higher driver workload was shown to be experienced by drivers when they had to use Chinese street signs, compared to when they had to use street signs in their native language (Wu et al., 2011). Additionally, it was found that driving speed was also affected in the condition with Chinese street signs, which caused Wu et al. (2011) to postulate a tendency to avoid collisions as an underlying explanation for this effect. Due to the increased workload caused by the Chinese street signs, they said, the drivers drove slower to continue to meet this need.

A study of Qiao et al., (2015) investigated the effect of warning messages on driving behavior on four safety measures (headway distance, headway time, speed, and deceleration/acceleration). As drivers need to pay most attention to visual stimuli in order to drive safe, it was found that visual warning messages deteriorated driving behavior of participants because they got distracted from the road. Additionally, it was found that this effect was correlated with subjective workload, based on which it could be concluded that modally congruent stimuli, in this case visual stimuli, increased the subjective workload. In contrast to this effect, auditive warning messages turned out to improve driving safety (Qiao et al., 2015).

Qiao et al. (2015) have not only demonstrated that, in accordance with the findings of Wu et al. (2011), an increase in workload results in less endogenous attention, but also that this increase in workload can be a consequence of visual stimuli. Based on the study of Wu et al. (2011), which demonstrated a negative correlation between workload and driving speed, and the study of Qiao et al. (2015), which demonstrated an increase in workload through visual messages, it was expected that adding notifications to the navigation task would result in slower travel speed.

To summarize, competition between endogenous and exogenous attention has been investigated at two levels. First, the influence of exogenous stimuli was examined in relation to endogenous user performance without considering the role of the timing of exogenous stimuli. Simply put, it has been investigated whether showing notifications during a navigation task generally affects user performance. At a more detailed level, it was investigated whether the timing of exogenous stimuli would mediate the relationship between exogenous stimuli and user performance. This was considered relevant, because it might say something about when exactly notifications affect user performance, and when they do not. With this knowledge, navigation interfaces such as the Police Force's could be customized in a way that allows officers to get informed without having their user performance compromised. Lastly, it has been investigated whether notifications affect travel speed. This was considered relevant, because it is crucial for officers to arrive on time in case of emergency.

Based on what has been discussed in the introduction, it was expected that user performance would be worse when users receive notifications during the navigation task, compared to when users do not receive notifications. This gave rise to the hypothesis that the average response time of the notification condition would be significantly higher than the average response time of the non-notification condition (hypothesis 1a). It was also expected that user performance would be worse at intersections where the onset of the buzzer would be relatively simultaneous with the onset of a notification than at intersections where the onset of a buzzer is relatively separated from the onset of a notification. This gave rise to the hypothesis that the average response time to 'notification-simultaneous buzzers' would be significantly higher (i.e. slower) than the average response time to 'notification-separated buzzers' (hypothesis 1b). Because of the initial uncertainty that existed with regard to the way in which the data would be registered, the goal to explore the temporal range in which the hypothesized effect of notifications on user performance, and the uncertainty regarding the way in which the timing classifications would be distributed among participants because of the experiment's design that caused the timing variable to have no fixed subdivisions, hypothesis 1b was exploratively investigated. Lastly, it was expected that notifications would reduce the speed with which participants walk through the virtual environment. This gave rise to the hypothesis that the average travel speed of the non-notification condition would be significantly higher compared with the average travel speed of the notification condition (hypothesis 2).

Methods

Design

The experiment was conducted in the context of an overarching study investigating several cognitive performances in different interface designs of the Police Force's AR system. It had a within-subject design and it contained four experimental conditions. These conditions were created on the basis of two within-subject factors: way of presenting direction indicators (direct of indirect) and notifications (present or absent). In this study, the direct presentation conditions (A and C) were not subject to investigation. To account for a learning-effect, participants were assigned to one out of four sequence versions in a pseudorandom order, based on the order of registration. These versions were A-B-C-D (version 1), B-A-D-C (version 2), C-D-A-B (version 3) or D-C-B-A (version 4).

Participants

Ninety-nine Dutch speaking students have participated in this study (M = 19.83 , SD = 1.99, 75 women and 24 men). Most of the participants studied Psychology at the University of Leiden and were recruited in exchange for study-related credits. There were also a number of students from other studies, such as medicine and marine technology. A few of them studied at another university. Participants were excluded if they had a neurological or psychiatric disorder. They were also excluded if their age was not between the range of 18 and 30 years old. Before the participants took part in the experiment, informed consent was granted.

Measures and instruments

Navigation task

The experiment consisted of two online environments that the participants had to switch between. One of these environments was called the ‘instruction environment’, which was created with Qualtrics. Qualtrics is a web-based survey tool to conduct survey research, evaluations, and other data collection activities (Bosch & Duong, 2020). In the present study, Qualtrics was used to register demographical data of the participants, but also to display instructions about the experiment. The second environment that was created was called the ‘virtual environment’. This environment consisted of a Unity-based 3D Virtual Reality web application that had been created by a programmer who worked at the Dutch Police Force. This was the environment in which participants walked the routes. Figure 1 shows a screenshot taken while going through one of the routes.

Figure 1

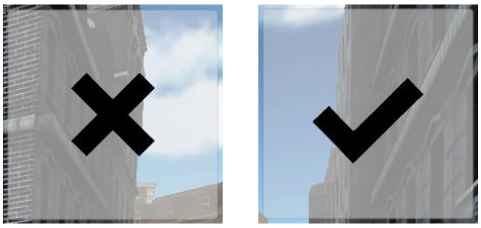
Virtual environment

Notifications

In condition D, notifications were presented in the form of GO-NOGO cues. The appearance of a ‘V’ on the (right side of the) screen counted as a GO-cue and the appearance of an ‘X’ counted as a NOGO-cue. Both notifications are shown in Figure 2. Whenever a subject identified a notification as a GO-cue, he had to press the ‘F’ key. Whenever a subject identified a notification as a NOGO-cue, he had to refrain from pressing the ‘F’ key. These notifications were programmed to be displayed consecutively with an interval of 5 seconds.

Figure 2

Notifications



User performance

Response time was used as a measure for user performance. These response times were measured on a single-response task (in milliseconds). In condition B and D, participants had to respond to a 'buzzer' sound that was audible when the participant reached a certain distance to the intersection. The response times to these buzzers were representative of the participant’s user performance, because they reflect how well the participants succeeded in retaining their attention at the place where traffic and navigation-assisting information originate. This focus was indicative of endogenous attention: the faster the response time, the more their attention was directed endogenously. Average response times were calculated without response time on the fist buzzer the participants encountered, as the first buzzer occurred immediately when the route started. As a result, five reaction times per condition were used for each participant.

Timing dependency

Participants walked through the virtual environment by means of the ‘WASD-keys’ and a computer mouse. This locomotion feature accounted for variation in the speed at which routes were traversed. As a result of this variance in speed, the timing of notifications varied with respect to the occurrence of the buzzers. Because this study also investigated whether the relationship between notifications and driver performance was mediated by the timing of the notification, time stamps were created. For each occurrence of a notification, its moment in time was recorded. In addition, for each occurrence of a direction indicator, its moment in time was recorded as well. The moment in time of each occurrence of a buzzer was calculated by subtracting the corresponding response time from the direction indicator's time stamp. By juxtaposing the timestamps of the notifications and the buzzers, it was possible to determine for each buzzer its timing relative to the notifications and vice versa. For each buzzer, only its timing relative to the preceding notification and its timing relative to the succeeding notification were calculated. By means of several methods, that are discussed in the results section, it was determined for each buzzer whether it belonged to the group of the 'notification-simultaneous' buzzers or to the 'notification-separated' buzzers.

Travel speed

Another variable that was used, was travel speed. This variable was obtained through dividing the distance (in virtual meters) traveled by the time taken to complete the route (in seconds). The total distance of the route in condition B was 253,14 virtual meters. The total distance of the route in condition D was 256,57 virtual meters. The higher the outcome of this calculation, the higher the walking speed.

Procedure

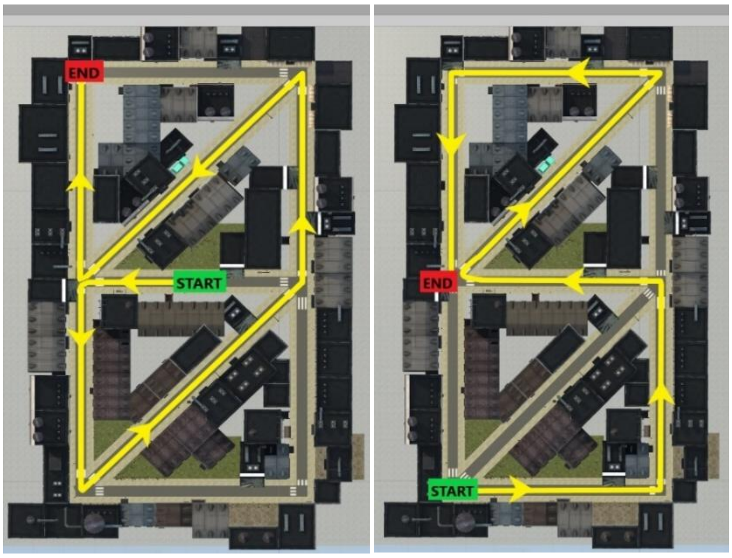
Each participant took part in the experiment in his own (private) environment. First, Participants received a personal email, in most cases after they signed up for the experiment via SONA (a participant management tool). In this email they could find a URL with which they could open the instruction environment assigned to them. Their personal login data were also included in the email. With these login data they had access to the virtual environment, which could be opened from the instruction environment. After opening the instruction environment with the URL, they were presented with some information about the study and an explanation about the procedure. After reading this information, they had to sign an informed consent and they were instructed to open the virtual environment in an additional tab in their browser by clicking on a URL (https://arvronderzoek.nl). They were also instructed to return to the instruction environment after they had opened the virtual environment. This way, the virtual environment could be loaded while the participant could report their subject number, age, and sex in the instruction environment. Subsequently, they were given some instructions about the tutorial they had to walk through once the virtual environment was fully loaded.

When the virtual environment was ready, participants logged in using their personal login data and started with the tutorial. Participants were instructed to enlarge their screen by pressing on an ‘enlarge’ button, so that the virtual environment went full screen. The tutorial consisted of a small virtual environment in which they were able to move around with the same controls they would need to move around during the experiment. They were taught how to walk and how to deal with notifications. After hey completed the tutorial, they were instructed to return to the instruction environment. Arriving there, they were told that they were going to switch between the two environments more often during the experiment. The reason for this was that their route knowledge was being tested in the instruction environment, but this data was not used for the present study. The last thing participants were shown before the experiment started, was the screen they would be presented with whenever they finish a route, accompanied by a message stating that the participant had to switch screens whenever they would see this screen. This was done to prevent participants from skipping questions.

Each participant went through four conditions, each consisting of one route, in one out of four sequencies. Based on the sequence, login data and instruction environment URLs were linked, so that the questions matched the routes. In this way, participants walked through four unique, but comparable routes in different circumstances. Condition A consisted of walking through route one without interference of notifications, while direction indicators were being presented directly. Condition B consisted of walking through route two without interference of notifications, while direction indicators were being presented indirectly. Condition C consisted of walking through route three with interference of notifications, while direction indicators were being presented directly. Condition D consisted of walking through route four with interference of notifications, while direction indicators were being presented indirectly. Maps of routes two (condition B) and four (condition D) are shown in Figure 3. While going through each route, the participants encountered six intersections. Whenever this happened, a direction indicator appeared in the middle of the intersection. For condition A and C, these direction indicators were programmed to appear whenever a participant reached a fixed amount of distance to the intersection. For condition B and D, as presentation was indirect, the direction indicators were programmed to appear whenever the participant pressed the SPACE-button. The participants were able to press the SPACE button after hearing a buzzer sound, which was audible whenever the same distance to the intersection that was used in condition A and C was reached. After going through all the conditions, the participants were informed about the purpose of the study. The data of this study was collected between the 5th of March 2021 and the 25th of April. The ethical approval, METC, was granted by the ethics committee of Leiden University on July 17, 2020.

Figure 3

Maps of routes two (left) and four (right)



Statistical analyses

To test the hypotheses, several analyses of variance have been conducted through SPSS. The pairwise comparison tables and descriptive statistics tables were used to determine the direction of the effect.

Notification effect

To test the hypothesis that the average response time of the notification condition would be significantly higher than the average response time of the non-notification condition (hypothesis 1a), a Repeated measures ANOVA has been conducted. In this analysis, response time counted as the dependent variable. The presence of notifications (conditions B and D) was the independent variable.

Travel speed

To test the hypothesis that the average travel speed of the non-notification condition would be significantly higher than the average travel speed of the notification condition (hypothesis 1b), another Repeated Measures ANOVA has been conducted. Here, walking speed counted as the dependent variable. The independent variable was the presence of notifications.

Timing dependency

To test the hypothesis that the average response time to notification-simultaneous buzzers would be significantly higher than the average response time to notification-separate buzzers (hypothesis 2), several Repeated Measures ANOVA's have been conducted. Response time counted as the dependent variable in this test. The independent variable was the timing of the buzzer.

Results

In this study, the relationship between notifications and user performance has been investigated on the basis of three hypotheses. The hypotheses and their corresponding analyses are being discussed separately. There were ten participants whose data were excluded from the analyses of all hypotheses. This was either because response times of both conditions were not registered (seven participants), response times of both conditions were systematically reported in rounded numbers (one participant), mean response times in both conditions were regarded as outliers (one participant) or because the mean response time of condition D was regarded as an outlier (one participant). Additionally, two participants were excluded from the analyses of hypotheses 1a and 2. This was either because response times of condition B were not registered (one participant), or the mean response time of condition B was regarded as an outlier (one participant). Table 1 shows the descriptive statistics that apply to the analyses of hypotheses 1a and 2. Unfortunately, a significant number of notification time stamps, which were used to determine the exact timing of notifications, was lost. Those of 23 participants were stored, but because of unknown technical reasons, response times of three of these participants were not registered. As a result, the relationship between timing and response times (hypothesis 1b) could only be investigated in 20 participants. One participant was excluded from the analyses of hypothesis 1b, because its response times were considered as outliers in all analyses.

Table 1

Means and standard deviations between conditions

Variable	Mean	Standard deviation
RT without notifications (B)	1171 ms	418 ms
RT with notifications (D)	1321 ms	422 ms
Travel speed without notifications (B)	2,172 m/s	0,444 m/s
Travel speed with notifications (D)	2,316 m/s	0,5 m/s

Note. RT = response time.

Effect of notifications on user performance

The first effect that was expected, was that adding notifications to the interface would result in lower user performance (hypothesis 1a). User performance was measured by response times to the buzzer sound, which acted as a cue at intersections for the ability to enable the direction indicator. For this analysis, the difference in these response times between the condition without notifications and the condition with notifications has been examined. This difference turned out to be significant, $F(1,87) = 11.193$, $p = .001$, $\eta 2 = .114$. This means that participants responded faster to buzzers in the condition without notifications than in the condition with notifications.

Timing-dependent effect of notifications on user performance

The second effect that was expected, was that in the condition with notifications, the average response time to notification-simultaneous buzzers would be significantly higher than the average response time to notification-separated buzzers (hypothesis 1b). For this analysis, response times of notification-simultaneous buzzers have been compared with those of notification-separated buzzers. For explorative purposes, several criteria have been used to define both notification-simultaneous buzzers and notification-separated buzzers. Various analyzes have therefore been carried out. Table 2 shows the descriptive statistics that apply to these analyses. Due to the chosen design, which caused not every participant to have representative response times for each classification, the descriptive statistics did not only differ per group, but also depended on how much participants had at least one representative response time in each of two groups with which the analysis was performed.

Table 2

Mean response times and standard deviations of the timing analyses

Analysis (classifications)	Variable	Mean (ms)	Standard deviation (ms)	N
(1) Extremely simultaneous vs. Large inclusion separated	Simultaneous	1250	298	10
	Separated	1033	179	10
(2) Extremely simultaneous vs. Extremely separated	Simultaneous	1230	202	5
	Separated	1050	147	5
(3) Large inclusion simultaneous vs. Extremely separated	Simultaneous	1144	196	8
	Separated	1115	198	8
(4) Large inclusion simultaneous vs. Large inclusion separated	Simultaneous	1217	283	14
	Separated	1089	200	14

First, the buzzers were classified based on the timing distinction that was used in the experiment of Grubb et al. (2014). A buzzer was defined a notification-simultaneous buzzer when a notification was displayed up to 600 milliseconds prior to the onset of the buzzer. As it was likely that a notification could also have competed for attention when it was displayed slightly after a buzzer, buzzers that preceded a notification for up to 300 milliseconds were also regarded as notification-simultaneous buzzers. This group was called ‘extremely simultaneous buzzers’. In contrast, a buzzer was defined as a notification-separated buzzer when a notification was displayed at least 1000 milliseconds before the buzzer. Additionally, buzzers followed by a notification within a 1000 millisecond time frame were excluded. This group was called ‘large inclusion separated buzzers’. Using these definitions, response times of notification-simultaneous buzzers were significantly higher than those of notification-separated buzzers, $F(1,9) = 10.005$, $p = .011$, $\eta 2 = .526$.

The second analysis was focused on analyzing extremes. For the representation of notification-simultaneous buzzers, the same group was used as in the first analysis: extremely simultaneous buzzers. However, a buzzer was considered a notification-separated buzzer when a notification was displayed at least 2000 milliseconds before the buzzer. Additionally, buzzers followed by a notification within a 2000 millisecond time frame were excluded. This group was called ‘extremely separated buzzers’. Using these definitions, response time did not differ significantly, $F(1,4) = 1.924$, $p = .238$, $\eta 2 = .325$.

Finally, a third and fourth analysis were performed to investigate whether including a higher number of buzzers would reveal a relationship between notification-simultaneous and notification-separated buzzers. However, to achieve this, classification criteria had to be broadened. First, only the criteria for determining notification-simultaneous buzzers have been broadened to ‘having a notification up to 1000 milliseconds prior to the onset of the buzzer’. The additional inclusion that has been used for extremely simultaneous buzzers; buzzers that precede a notification up to 300 milliseconds, was also applied here. This group was called ‘large inclusion simultaneous buzzers’. For the representation of notification-separated buzzers, the same group was used as in the second analysis: extremely separated buzzers. Using these definitions, response times did not differ significantly, $F(1,7) = 0.066$, $p = .804$, $\eta 2 = .009$. Subsequently, the groups that were determined by the hitherto most broadly formulated criteria; large inclusion simultaneous and large inclusion separated buzzers have been compared. Using these definitions, response times did not differ significantly, $F(1,13) = 3.676$, $p = .077$, $\eta 2 = .220$.

Effect of notifications on travel speed

The third effect that was expected, was that adding notifications to the interface would result in a lower travel speed (hypothesis 2). For this analysis, the travel speed in the condition with notifications has been compared with the travel speed in the condition without notifications. The difference between the two conditions turned out to be significant, $F(1,86) = 8.162$, $p < .05$, $\eta 2 = .087$. However, the effect was directed in the opposite direction to what was expected. This means that participants’ travel speed was higher in the condition with notifications than in the condition without notifications.

Discussion

The aim of this study was to investigate the cognitive effects of the Police Force’s AR interface design. Central to this was the processing quality of information from endogenous attention in the presence of exogenous stimuli. The analysis used to investigate this showed that the processing quality of endogenous information was decreased by exogenous stimuli. This corresponded with what was expected, as it implied a competition between endogenous and exogenous attention, and corresponded with previous findings (Hickey et al., 2010; Meeter et al., 2010). Subsequently, it was investigated whether the competition between endogenous and exogenous attention depended on the timing of exogenous stimuli. The first analysis that was used to examine this, in which conservative boundaries for the definition of ‘simultaneous’ and wide boundaries for the definition of ‘separate’ were handled, showed that endogenous attention encountered more competition from exogenous attention when the exogenous stimuli appeared simultaneous with the moment at which users were required focus their attention endogenously. This corresponded with what was expected based on earlier findings (Grubb et al., 2014). However, based on the corresponding analyses, timing appeared to play no role in the competition between endogenous and exogenous attention when the remaining timing classification-combinations were handled. Lastly, the relationship between endogenous-exogenous competition and travel speed was investigated. The analysis used to investigate this showed that the competition between endogenous and exogenous attention caused users to walk faster instead of slower. Before discussing the meaning and implications of these results separately, it should be stated that when interpreting the results, it should be taken into account that the population was relatively young and highly educated.

Competition

Because endogenous attention was partly auditory in this experiment, the finding about the effect of notifications on user performance may indicate that visual exogenous stimuli can compete not only with visual endogenous attention, but also with auditory endogenous attention. However, in the experiment visual and auditory attention were represented by the same measure, as a result of which they were inseparable. A future experiment, in which these two forms of attention are represented by different measures, should show whether this indication is correct.

Although this experiment revealed a competitive relationship between endogenous and exogenous attention, it is conceivable that this relationship is less expressed when the AR system is used in real life. This is because the notifications that were used in the experiment were stimuli to which the users were instructed to differentiate in order to choose to either respond or refrain from responding. Depending on the nature of the messages that eventually will be communicated through the AR interface of the Police Force, not all notifications might be designed this way. For example, notifications that remind officers of their surveillance duties may not require direct action from the users. In such notifications, response selection is not involved. Hypothetically, this absence of the immediate need for response selection could lead to a decreased demand for exogenous attention and performance, because this process takes time (Gajewski et al., 2007). In addition, because part of exogenous response performance consists of motor response time, such notifications could hypothetically reduce the demand for exogenous attention as well (Delmas et al., 2018). As a result of both these hypothetical reductions on the demand for exogenous attention and performance, the competition between endogenous and exogenous attention may be less in terms of impact, and perhaps also in terms of its sensitivity to timing. However, the opposite could also be the case, as in real life, users have to deal with a greater amount of complex external stimuli compared to the virtual environment used in the experiment. Such complex stimuli have been proven to increase workload and degenerate driver performance, because the processing of these stimuli requires a more controlled kind of processing mode (Paxion et al., 2014). Hypothetically, it could therefore be the case that the real-life negative effect on endogenous performance might actually be greater in terms of impact and timing sensitivity, because of an increase in the demand for exogenous attention that could be the result of this.

Timing

This study seems to show that the ‘boundary’ of the region in which endogenous performance is most prone to competition from exogenous stimuli is approximately between 600 and 1000 milliseconds before the appearance of an endogenous stimulus. This range is also plausible because research by Grubb et al. (2014) has previously demonstrated that exogenous stimuli that fall (precisely) on the left side of this range are more likely to influence exogenous performance than stimuli that fall (precisely) on the right side of this range. However, there are some limitations with regard to the underlying analyzes that generated the finding of the present study. For instance, during the experiment, it was not registered of each occurring notifications whether it was a GO-notification or a NOGO-notification. Since these notifications are different in the extent to which they are ought to be acted on, and notifications that differ in the extent to which they ought to be handled have shown to be processed by different brain areas, it could hypothetically be possible that they appeal to exogenous attention and interfere with endogenous processing to different degrees Mangun et al., 2000). This could especially have played a role in the investigation of the timing-dependence effect, because of the small number of observations that were used in the corresponding analyses, which is another limitation that was caused by missing data and underrepresentation of certain timing classifications. As a result, the groups that have been compared in the analyses related to this effect were prone to skewness in terms of “notification-type representation”. This applied most to analyses one and three, as in these analyses the difference in width through which response times have been filtered was largest, as a result of which the groups in these analyses were most unequal in the amount of response times that represented these classifications. It would therefore be good to label and investigate the effect of both types of notifications in a controlled setting in a future experiment. In addition, the effect of exogenous stimuli should be investigated under various timing conditions that are the same for every participant, by means of which underrepresentation is prevented. This way, future research could possibly confirm the range that has been found in this study, or show perhaps that it should be shifted, widened, or narrowed. The best analysis technique that can be used for the precise determination of the range might be a logistic regression, as it would provide the most insight into the effect of exogenous stimuli across multiple (individual) timing conditions (Stoltzfus, 2011). This could provide a more detailed insight in the trade-off between endogenous performance and timely information provision, allowing makers of AR interface designs to concretize their considerations. Another point a future study could take into account is that for each notification-simultaneous buzzer classification in this study, a criterion was used to include buzzers that are preceded by notification up to 300 milliseconds. This assumption should be tested in future research, because applying a different threshold may change the range in which exogenous influence is found to be exercised.

Traffic safety

One of the premises of this study was that endogenous attention, measured by user performance, represented the extent to which the users were able to focus their attention on the traffic situation. Endogenous attention was therefore also regarded as an indication of traffic safety. However, although this study provides strong implications for this effect, as response readiness is widely regarded as a traffic safety factor, a future study could investigate how this manifests itself in the specific case of agents on horseback (Saunier & Sayed, 2008; Zheng et al., 2014). In such a study, traffic safety should be measured in a less indirect way. In addition, in real-life use of the system, it is also theoretically possible that the desire not to collide, which was not invoked during the experiment due to the absence of traffic, would cause both the attention paid to the endogenous stimuli and the attention paid to the exogenous stimuli (notifications) to be overruled by the attention paid to the traffic situation. This would attribute a more dynamic or transcendent role to traffic safety in terms of endogenous-exogenous classification. In the context of traffic safety, this is also something that could be explored through future investigation.

When designing a system that blocks incoming notifications at certain times to improve traffic safety, it may also be important to weigh the form of the notification that would represent its underlying message. It may therefore also be useful to investigate to what extent different forms of notifications influence the processing of endogenous stimuli. However, it has been found previously that auditory stimuli endanger traffic safety less than visual stimuli, probably due to the fact that the modality of these stimuli is congruent with the information needed to drive safely (Qiao, et al., 2015). In the context of safety, it is therefore generally recommended to present notifications in auditory form when it is possible to do so. However, when messages are preferred to be (re)presented visually, blockages of these notifications can be built into the AR system. These blockages could be programmed based on the timing distinction that was found to be significant. For example, a blockage could be activated whenever a user is approaching an (automated) direction indicator within 1000 milliseconds. In addition, it could be deactivated at least 300 milliseconds after the direction indicator has appeared. However, this deactivation boundary still has a greater degree of uncertainty, because it was not tested explicitly in this study. Theoretically, these (de)activation functions could be created through calculations using GPS information, which the system already has access to. Lastly, if for some reason a message must not be delayed before communicating it in the midst of a crucial moment, it could be best communicated auditorily, but future research should show to what extent this applies to officers on horseback.

Travel speed

Hypothetically, it is possible that participants were faster in the notification condition because they were aroused and hounded by the notifications. In his case, this result could literally and metaphorically be regarded as a boost for the Police Force, because his would mean that the notifications increased the workload, achieving just the opposite effect to what was expected based on earlier findings (Qiao et al., 2015; Wu et al., 2011). In this case, participants' workload condition while walking through the route in which they were not exposed to notifications could be referred to as "underloaded". It could very well be that the participants experienced such an underload under these circumstances, as it has previously been shown to cause attentional resources to shrink and reduce performance in drivers (Young & Stanton, 2002; Young et al., 2015). In the case of the participants, the underload may have caused them to become less focused on performing their primary task, causing them to slow down. However, another explanation for the difference in travel speed could be that the notifications did not increase the workload enough to cause a so-called "overload", which has previously been shown to cause attentional lapses, performance degeneration and a reduction in travel speed in drivers (Paxion et al., 2014; Wu et al., 2011, Young et al., 2015). This would mean that it would still be possible for a high exposure to notifications to decrease travel speed through an increase in workload. Both explanations could be explored in a future experiment. Theoretically, this future experiment might show that both explanations are correct, which would mean that there is an optimal range in the amount of (exogenous) arousal that causes people to travel faster, but also a range that has a paralyzing effect. A measurement for (subjective) workload should be included in such a future study, as it was indeed previously shown that the two discussed explanatory effects can be jointly accounted for by means of an asymptotic function that displays the relationship between the extent of attentional resources and workload (Young et al., 2015).

Conclusion

This study has shown that it is possible for exogenous stimuli, such as notifications, to negatively influence response readiness in humans navigating using an AR system. This means that, based on the findings of this study, AR navigation interfaces could benefit from modifications that prevent notifications or other types of exogenous stimuli to compromise user performance. For example, this could be done through the incorporation of timing-related blockages of distracting stimuli. Such blockages would ensure that distracting notifications are put on hold whenever a short-lasting crucial moment occurs, through which the performance-reducing effect of exogenous stimuli is avoided. For example, when a police officer is approaching an intersection (at high speed), at which the traffic situation is most complex and direction indicators are being displayed, his attentional resources should be fully utilizable. If potential distracting notifications are blocked within the right timing interval, it would enable the officer to utilize his attentional resources for the right purposes, so that he would be able to process route information and react quickly to potentially dangerous situations. The moment the police officer has passed the timing interval in which he is prone to distraction from crucial information, this blockage can be lifted, causing the notifications to be displayed. However, the benefits of exogenous stimuli should also be explored and weighed in the process of creating such blockages. Given the current pace at which technology is evolving, it is for instance conceivable that augmented stimuli could entail safety enhancing information in the future. For example, it would be theoretically possible, by means of the incorporation of artificial intelligence, to enable an AR system to identify potential hazards. These hazards could be pointed out by means of visual ‘attention-guiding stimuli’, which have been proven to guide drivers’ attention and improve driver performance. (Kim et al., 2018). Keeping this in mind, it could be possible for the importance of displaying such stimuli to sometimes outweigh the safety afforded by the absence of virtual exogenous stimuli. It is therefore conceivable that mechanisms will be needed to allow attention-guiding stimuli to escape from blockages at short lasting crucial moments, but research should validate the effect of such stimuli in different driver circumstances. In addition, further research should show with more certainty when and to what extent exogenous stimuli threaten user performance, so that adaptations could be programmed into these systems in the most effective way. If this can be achieved, the safety of AR navigation interface operators (such as police officers) could be effectively increased without compromising the speed with which users are being informed. Through adequate application of blockages in a broader range of industries, it could even be a step towards more safety in general, as the exploration of application possibilities of AR interfaces is still in its infancy.

References

Bosch, E., & Duong, K. (2020, March 2). *Research Guides: Qualtrics: What is Qualtrics?* California State University. Retrieved December 28, 2021, from https://csulb.libguides.com/qualtrics.

Chica, A. B., Bartolomeo, P., & Lupiáñez, J. (2013). Two cognitive and neural systems for endogenous and exogenous spatial attention. *Behavioural Brain Research, 237*, 107–123.

Delmas, S., Casamento-Moran, A., Park, S. H., Yacoubi, B., & Christou, E. A. (2018). Motor planning perturbation: muscle activation and reaction time. *Journal of Neurophysiology, 120*(4), 2059–2065.

Gajewski, P. D., Stoerig, P., & Falkenstein, M. (2007). ERP—Correlates of response selection in a response conflict paradigm. *Brain Research, 1189*, 127–134.

Godijn, R., & Theeuwes, J. (2002). Programming of endogenous and exogenous saccades: evidence for a competitive integration model. *Journal of Experimental Psychology: Human Perception and Performance, 28*(5), 1039–1054.

Grubb, M. A., White, A. L., Heeger, D. J., & Carrasco, M. (2014). Interactions between voluntary and involuntary attention modulate the quality and temporal dynamics of visual processing. *Psychonomic Bulletin & Review, 22*(2), 437–444.

Hickey, C., van Zoest, W., & Theeuwes, J. (2010). The time course of exogenous and endogenous control of covert attention. *Experimental Brain Research, 201*(4), 789–796.

Hoekstra-Atwood, L. (2015). Driving under involuntary and voluntary distraction: individual differences and effects on driving performance. *ProQuest Dissertations Publishing*.

Hughes, R. (2015). *Augmented reality: Developments, technologies and applications.* Nova Publishers.

Kim, H., Gabbard, J. L., Anon, A. M., & Misu, T. (2018). Driver behavior and performance with augmented reality pedestrian collision warning: an outdoor user study. *IEEE Transactions on Visualization and Computer Graphics, 24*(4), 1515–1524.

Meeter, M., van der Stigchel, S., & Theeuwes, J. (2010). A competitive integration model of exogenous and endogenous eye movements. *Biological Cybernetics, 102*(4), 271–291.

Mangun, G. R., Hopfinger, J. B., & Buonocore, M. H. (2000). The neural mechanisms of top-down attentional control. *Nature Neuroscience, 3*(3), 284–291.

Mayer, A. R., Dorflinger, J. M., Rao, S. M., & Seidenberg, M. (2004). Neural networks underlying endogenous and exogenous visual–spatial orienting. *NeuroImage, 23*(2), 534–541.

Paxion, J., Galy, E., & Berthelon, C. (2014). Mental workload and driving. *Frontiers in Psychology, 5*(1344), 1344–1344.

Petersen, S., Corbetta, M., Miezin, F., & Shulman, G. (1994). PET Studies of parietal involvement in spatial attention. *Canadian Journal of Experimental Psychology, 48*(2), 319–338.

Qiao, F., Rahman, R., Li, Q., Yu, L., & Kuo, P. (2015). Smart phone based forward collision warning messages in work zones to enhance safety and reduce emissions. *Transportation Research Record, 94*.

Saunier, N., & Sayed, T. (2008). Probabilistic framework for automated analysis of exposure to road collisions. *Transportation Research Record, 2083*(1), 96–104.

Stoltzfus, J. C. (2011). Logistic regression: a brief primer. *Academic Emergency Medicine, 18*(10), 1099–1104.

Theeuwes, J. (1991). Exogenous and endogenous control of attention: The effect of visual onsets and offsets. *Perception and Psychophysics, 49*(1), 83–90.

Wu, C., Zhao, G., Lin, B., & Lee, J. (2013). Navigating a car in an unfamiliar country using an internet map: effects of street language formats, map orientation consistency, and gender on driver performance, workload and multitasking strategy. *Behaviour & Information Technology, 32*(5), 425–437.

Yeshurun, Y., & Tkacz-Domb, S. (2021). The time-course of endogenous temporal attention – Super fast voluntary allocation of attention. *Cognition, 206*, 104506–104506.

Young, M. S., Brookhuis, K. A., Wickens, C. D., & Hancock, P. A. (2015). State of science: mental workload in ergonomics. *Ergonomics, 58*(1), 1–17.

Young, M. S., & Stanton, N. A. (2002). Malleable attentional resources theory: a new explanation for the effects of mental underload on performance. *Human Factors, 44*(3), 365–375.

Zheng. L., Ismail, K., & Meng, X. (2014). Traffic conflict techniques for road safety analysis: open questions and some insights. *Canadian Journal of Civil Engineering, 41*(7), 633–641.