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Visual perception of mobile displays depending on the combination of the luminance of the display and the lighting conditions

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Abstract

Mobile displays are used across a wide range of lighting conditions. Readability and visual comfort vary greatly depending on the surrounding light environment as well as the luminance of the display. To evaluate effects of the light environment, we developed a two-booth experimental system capable of independently manipulating three factors: the illuminance on display surface, the luminance behind the display and the ambient illuminance in the user's space. Participants viewed black text on a white screen of a smartphone under various light conditions, rating its readability, discomfort glare, and screen comfort across multiple luminance levels. The results demonstrated that all three factors affect visual perception. Especially, the illuminance on the screen had the most powerful effect on readability, while the factors interacted, offsetting each other's effects. In addition, we confirmed that such effects depend on the observer's light-dark adaptation state. These findings indicate that visual perception of mobile displays can be determined not by individual factors, but by their complex combination.

1. Introduction

Displays have become an indispensable information interface in modern life. In particular, mobile displays are used across a wide range of light environments, from dark places such as bedrooms at night to outdoors in direct sunlight. Readability and visual comfort vary significantly depending on the lighting environment. While previous studies have investigated the impact of lighting factors on screen perception, most have simplified complex lighting environment into a single indicator, such as "room illuminance". However, real-world viewing environments involve a complex interplay of multiple lighting factors. How these factors influence and interact with display perception remains an underexplored issue.

In this study, we reduced the light environment factors that affect display visibility into three factors. The first factor is illuminance on the display surface, such as that produced by ceiling lights or sunlight. This factor physically declines screen contrast and is a major cause of impaired visual performance in bright environments. The second one is the luminance of light emitted from behind the display. This light is assumed when viewing a display against a bright background, such as a window or a wall. Previous research [1] has shown that the brightness in the peripheral field of view can alter the perceived brightness of the central visual target. When viewing a display against a bright window or wall, the high-luminance background strongly influences perceived screen brightness. The third factor is ambient illumination, which determines the adaptation level of the visual system. In real-world settings, situations can occur where the observer is in a bright area while the display is in shadow. Therefore, we treat the ambient illuminance as a distinct factor from the projected illuminance.

In addition to the three factors mentioned above, we investigated the influence of dark adaptation. Since human sensitivity to light increases significantly in dark environments, the perception of display screens may also change substantially.

The objective of this study is to classify lighting environment factors in mobile display viewing into three elements: screen luminance, background luminance, and ambient illuminance, and to quantitatively evaluate their effects on the subjective perception of readability and comfort through psychophysical experiments with and without dark adaptation.

2. Apparatus

Figure 1 illustrates a schematic diagram of two-booth experimental system we developped. This was partitioned into a display booth and an observer booth, separated by a blackout curtain to prevent light leakage between the two environments. Therefore, three lighting factors: screen illuminance, background luminance, and ambient illuminance can be controled independently. Photographs of these booths are shown in Figs. 2 and 3.

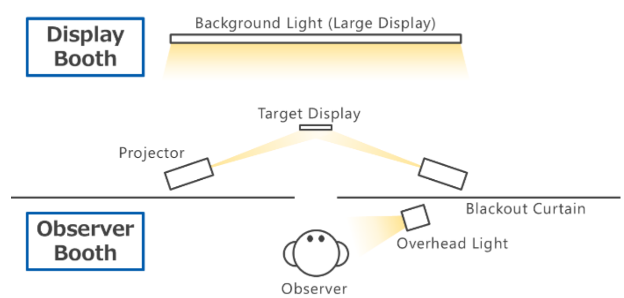

Figure 1. *Schematic of the two-booth experimental system designed to independently control projected screen illuminance, background luminance, and ambient illuminance in the observer booth.*

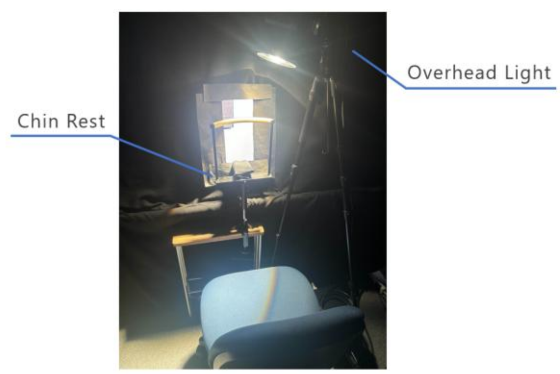

Figure 2. *Photo of the observer booth. The observer can peer into the display booth located at the rear through the central aperture.*

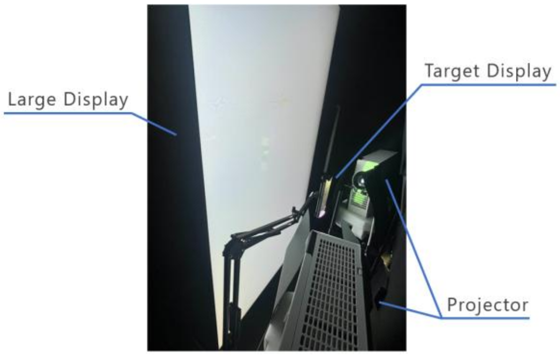

Figure 3. *Photo of the display booth. The target display is fixed at the center by an arm.*

In the display booth, an OLED smartphone (Samsung Galaxy S24 Ultra) was installed as test display. Participants viewed to evaluate factors such as readability and visual comfort subjectively. To control the lighting environment, a 65-inch high-brightness display (DynaScan, DS653LT5) was installed behind the smartphone to serve as a controlled background light source. Additionally, two high-brightness projectors (Panasonic, PT-VMZ82J) were employed to precisely manipulate the illuminance incident on the smartphone surface.

In the observer booth, an overhead lighting system (TSUBOSAKA ELECTRIC, SOL-600-01T05) was employed to regulate the ambient illuminance in the observer booth. A chin rest was used to fix the viewing distance to the test smartphone at 30 cm, ensuring consistent viewing conditions across all participants.

3. Experiment I: Visual Assessment across Broad Lighting Levels

Experiment I focused on visual performance under conditions simulating a wide range of environments, from slightly dim indoors to high illuminance outdoors.

Method

The specific levels of each parameter are summarized in Table 1. The experimental design consisted of six levels of ambient illuminance (ranging from 0 to 100000 lx), two patterns of projected illuminance (either 0 lx or matching the ambient illuminance), and five levels of background luminance (ranging from 0 to 4000 cd/m^2). Among these, the condition where all three factors were zero was excluded from Experiment I, as it was reserved for Experiment II which focused on dark environments. Consequently, the total number of unique conditions, calculated from all combinations of the three factors, was (5×2+1)×5−1=54.

The specific values for each factor were determined as follows. The ambient illuminance was measured at the observer's eye level at the center of the chin rest. For the projected illuminance, the 10 lx and 100 lx levels were achieved by attenuating the projector light with ND16 filters. Background luminance was measured as the average luminance across the entire screen using a 2D spectroradiometer.

For each condition, an image of black text on a white background was presented on the smartphone for 5 seconds. The screen luminance, defined as the luminance of the white background area, consisted of ten levels ranging from 1.2 to 749.3 cd/m^2, which were presented in a randomized order. After each presentation, participants rated their experience on three scales: a six-point scale of readability (1: not at all readable – 6: very easy to read), a nine-point scale of discomfort glare from the screen (1: imperceptible – 9: intolerable) and a seven-point scale of screen comfort (1: intolerably dark – 4: just right – 7: intolerably bright). These items were developed with reference to [2], [3], and [4]. The participants were 20 students in their 20s from Yokohama National University, all of whom possessed normal color vision.

Table 1. Experimental conditions for Experiment I.

Parameter	Levels
Ambient Illuminance [lx]	0, 10, 100, 1000, 10000, 100000
Projected Illuminance [lx]	0 or equal to ambient illuminance
Background Luminance [cd/m^2]	0, 10, 100, 1000, 4000
Target Display Luminance [cd/m^2]	1.2, 4.6, 9.5, 30.0, 76.5, 150.9, 251.1, 398.3, 548.3, 749.3

Results

Figure 4 shows the results for conditions where both ambient and projected illuminances were 0 lx while the background luminance ranged from 10 to 4000 cd/m^2. These results represent the isolated impact of background luminance among the three factors. As background luminance increases, the ratings for readability, discomfort glare, and screen comfort all show a downward trend, indicating that higher background luminance makes the screen appear relatively darker.

Figure 5 illustrates the results when the background luminance was 0 cd/m^2. In this case, the ambient illuminance ranged from 10 to 100000 lx and the projected illuminance was either 0 lx or equal to the ambient illuminance. These results demonstrate the effects of ambient and projected illuminances without the influence of background luminance. Regarding readability, there was little difference between 10 and 1000 lx. However, readability began to decline slightly at 10000 lx of ambient illuminance and showed a significant drop at 100000 lx. Projected illuminance brought a similar effect but was more severe. While there was no major difference up to 1000 lx, projected illuminance caused a large decline at 10000 lx and a very sharp decrease at 100000 lx. This is because projected illuminance above 10000 lx significantly reduces the contrast of the characters on the display. In terms of discomfort glare, the evaluation values decreased as the ambient illuminance increased. This occurs because a higher adaptation level of the observer's visual system increases their tolerance to intense light. For projected illuminance, the evaluation values were higher when the projected illuminance matched the ambient illuminance compared to when it was 0 lx. This is because the light reflected off the display increases the total intensity of light reaching the eyes. The evaluation of screen comfort generally decreased as ambient illuminance increased, which shows a tendency for the screen to be perceived as darker. The decline was moderate up to 10000 lx but became much larger at 100000 lx. In terms of projected illuminance, ratings at 10 and 100 lx were higher than those at 0 lx. This suggests that up to 100 lx, the perceived brightness increases without negatively affecting the contrast. However, at 10000 lx and 100000 lx, the ratings were significantly lower than the 0 lx condition. This is likely because the substantial loss of contrast at these high levels causes the screen to be perceived as both dark and uncomfortable.

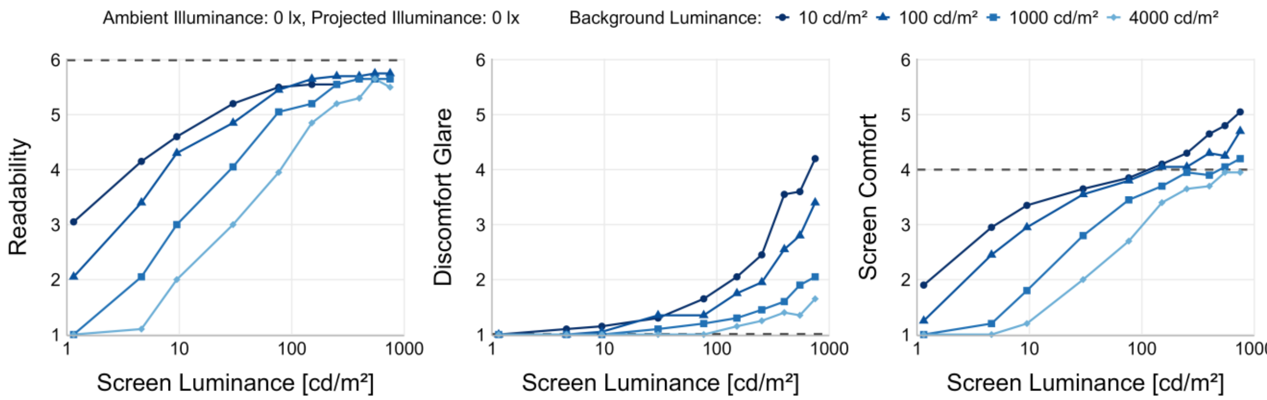

Figure 4. *Results of Experiment I under conditions of 0 lx ambient and projectes illuminance, with background luminance ranging from 0 to 4000 cd/m^2. Each plotted value represents the mean score across all participants. The dashed lines indicate the optimal score for each evaluation metric (Readability: 6, Discomfort glare: 1, Screen comfort: 4).*

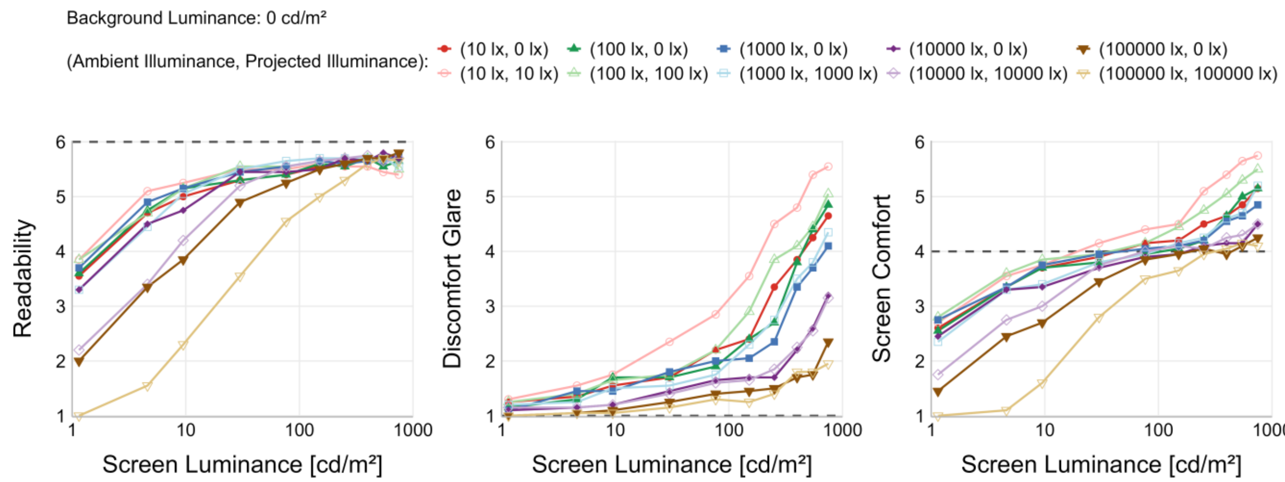

Figure 5. *Results of Experiment I with a background luminance of 0 cd/m^2. The ambient illuminance ranges from 10 to 100,000 lx, while the projected illuminance is either 0 lx or equal to the ambient illuminance. Each data point represents the mean score across all participants. The dashed lines indicate the optimal scores for each evaluation metric (Readability: 6, Discomfort Glare: 1, Screen Comfort: 4).*

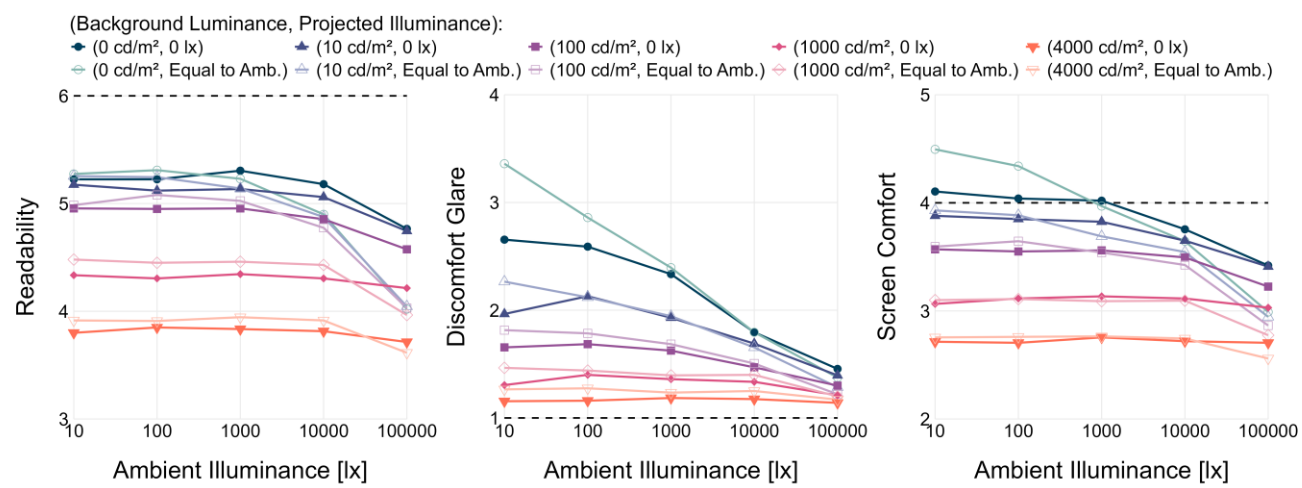

Figure 6. *Results of Experiment I showing evaluation scores as a function of ambient illuminance, with varying background luminance and projected illuminance. Each data point is the average score across screen luminance levels ranging from 1.2 to 749.3 cd/m^2 under each condition. The dashed lines indicate the optimal scores for each evaluation metric (Readability: 6, Discomfort Glare: 1, Screen Comfort: 4)*

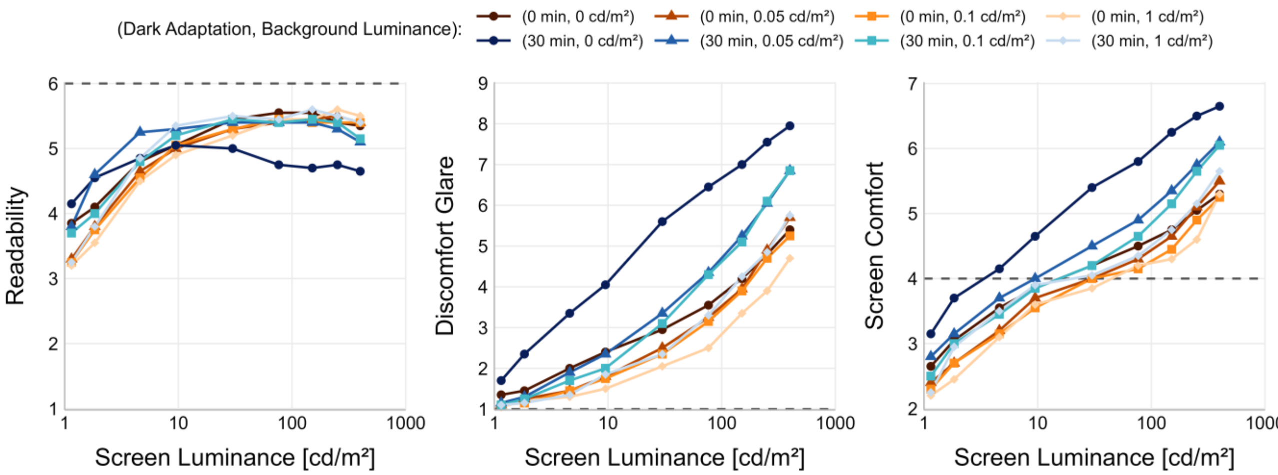

Figure 7. *Results of Experiment II. Each data point represents the mean score across all participants. The dashed lines indicate the optimal scores for each evaluation metric (Readability: 6, Discomfort Glare: 1, Screen Comfort: 4).*

After examining the independent effects of each factor, the interactions between background luminance, ambient illuminance, and projected illuminance were investigated. Figure 6 shows the changes in evaluation values relative to the ambient illuminance for each level of projected illuminance and background luminance. In this analysis, the evaluation values across ten levels of screen luminance ranging from 1.2 to 749.3 cd/m^2 were averaged. The graph indicates that while readability decreases as ambient and projected illuminances increase, the degree of this decline becomes less pronounced as background luminance increases. This suggests that an interaction exists between background luminance and the combined effects of ambient and projected illuminances, effectively mitigating their negative impact. Similar mitigating effects were also observed not only for readability but also for discomfort glare and overall comfort. These results demonstrate that the influences of these three lighting factors are not simply additive but instead involve complex interactions where each factor can modulate the effects of the others.

4. Experiment II: Visual Assessment with Dark Adaptation and Low Luminance Backgrounds

Experiment II specifically targets dark environments. Previous research [1] has demonstrated that peripheral light of 1 cd/m² or less can alter the perceived brightness of a visual target in central vision. When viewing a display in the dark, such subtle light may similarly influence perception. Furthermore, in dark settings, it is necessary to account for changes in the human eye's sensitivity to light resulting from dark adaptation. Experiment II investigates the impact of background light of 1 cd/m² or less and the presence or absence of dark adaptation on the subjective evaluation of displays.

Table 2. Experimental conditions for Experiment II.

Parameter	Levels
Background Luminance [cd/m^2]	0, 0.05, 0.1, 1
Dark Adaptation [min]	0, 30
Target Display Luminance [cd/m^2]	1.2, 1.8, 4.6, 9.5, 30.0, 76.5, 150.9, 251.1, 398.3

Method

Table 2 shows the experimental conditions for Experiment II. It included four low-luminance background levels ranging from 0 to 1 cd/m² and two dark adaptation conditions, specifically 0 minutes, representing no dark adaptation, and 30 minutes of dark adaptation. Both ambient and projected illuminances were set to 0 lx for all conditions.

In the 0-minute dark adaptation condition, the experiment commenced immediately after the lights were turned off to reach 0 lx in a room that initially had a floor illuminance of approximately 500 lx. For the 30-minute dark adaptation condition, participants moved from the 500-lx room to a darkroom and wore an eye mask for 30 minutes before beginning the session. This resulted in a total of eight experimental conditions, derived from the combination of the four background luminance levels and two adaptation states. Like Experiment I, an image of black text on a white background was presented on the test display under each condition. The screen luminance was set at nine levels ranging from 1.2 to 398.3 cd/m². Unlike Experiment I, these screen luminance levels were presented in ascending order starting from 1.2 cd/m². This specific order was employed because initial exposure to a bright screen could significantly disrupt the dark-adapted state of the observers. Consistent with Experiment I, the presentation duration for each stimulus was 5 seconds, after which participants evaluated the same three items. The participants were the same as in Experiment I.

Results

The experimental results are shown in Fig. 7. To clarify the statistical differences between the background luminance and dark adaptation conditions, a three-way repeated-measures ANOVA was conducted with display luminance as the third factor, followed by Holm's post-hoc tests. The significance level was set at 0.05.

Regarding readability, no significant main effects were found for background luminance or dark adaptation. However, a significant main effect was observed for display luminance. Under most conditions, the readability scores reached 5 ("moderately easy to read") at a display luminance of approximately 10 cd/m^2. In the condition with 0 cd/m^2 background luminance and 30 minutes of dark adaptation, readability scores decreased as display luminance increased beyond this level, likely due to excessive glare. Similarly, in other conditions, readability slightly declined when display luminance exceeded approximately 250 cd/m^2 due to the influence of glare.

For discomfort glare, significant main effects were observed for all three factors. Discomfort glare was found to be significantly higher after 30 minutes of dark adaptation compared to the non-adapted state. Post-hoc comparisons revealed a trend where discomfort glare significantly decreased as background luminance increased. Specifically, the discomfort glare ratings at 0 cd/m^2 background luminance were significantly higher than in all other background luminance conditions 0.05, 0.1, and 1.0 cd/m^2. While no significant difference was found between 0.05 and 0.1 cd/m^2, a significant difference was observed between the 0.05 and 1.0 cd/m^2 conditions. These results confirm that even a slight amount of background light mitigates glare, and higher background luminance significantly suppresses perceived discomfort.

Similarly, for screen comfort, significant main effects were found for all three factors. Screen comfort scores were significantly higher after 30 minutes of dark adaptation compared to the non-adapted state. Post-hoc tests showed significant differences between all pairs of background luminance conditions, indicating that higher background luminance leads to lower screen comfort scores. In the condition with 0 cd/m^2 background luminance and 30 minutes of dark adaptation, both discomfort glare and screen comfort were the highest, indicating that the display was perceived as extremely dazzling.

These findings suggest that displays are perceived as more dazzling when the observer is adapted to dark environments. Furthermore, the results indicate that even a minimal background luminance of 1.0 cd/m^2 or lower can effectively suppress screen glare in such dark conditions.

Conclusions

The results in this study quantitatively demonstrated that the visual perception of mobile displays can be determined by the complex interplay of three environmental lighting factors, including ambient illuminance, projected illuminance, and background luminance. Projected illuminance most significantly impacts readability, and it causes a sharp decline above 10000 lx due to reduced contrast. Increased ambient illuminance and background luminance enhance light tolerance and mitigate discomfort glare by raising the visual adaptation level. It also became clear that these factors interact with one another and offset each other's effects. Furthermore, it was found that dark adaptation significantly intensifies perceived discomfort glare in dark environments. On the other hand, even a minimal background luminance of less than 1.0 cd/m^2 can effectively suppress discomfort glare from the display. These findings emphasize that considering the three lighting elements in conjunction with the observer's adaptation state is essential for evaluating optimal display performance under diverse real-world lighting conditions.

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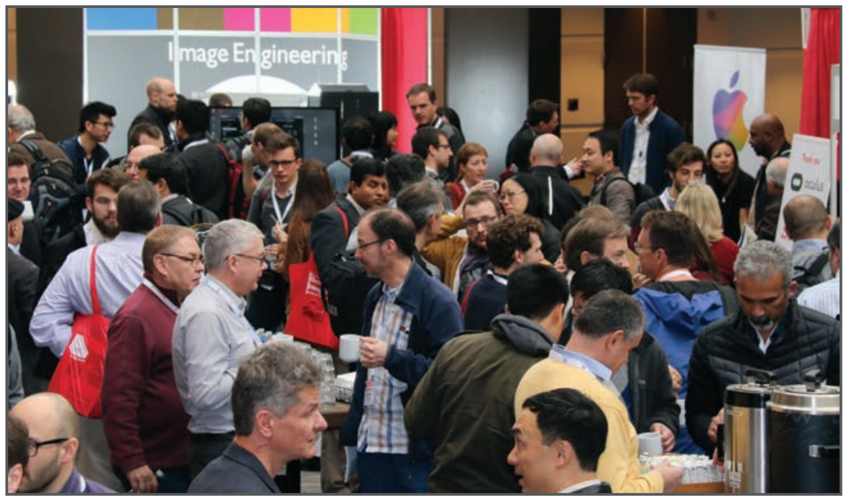

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