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(54) **ELECTRONIC DEVICE WITH AMBIENT-ADAPTIVE DISPLAY**

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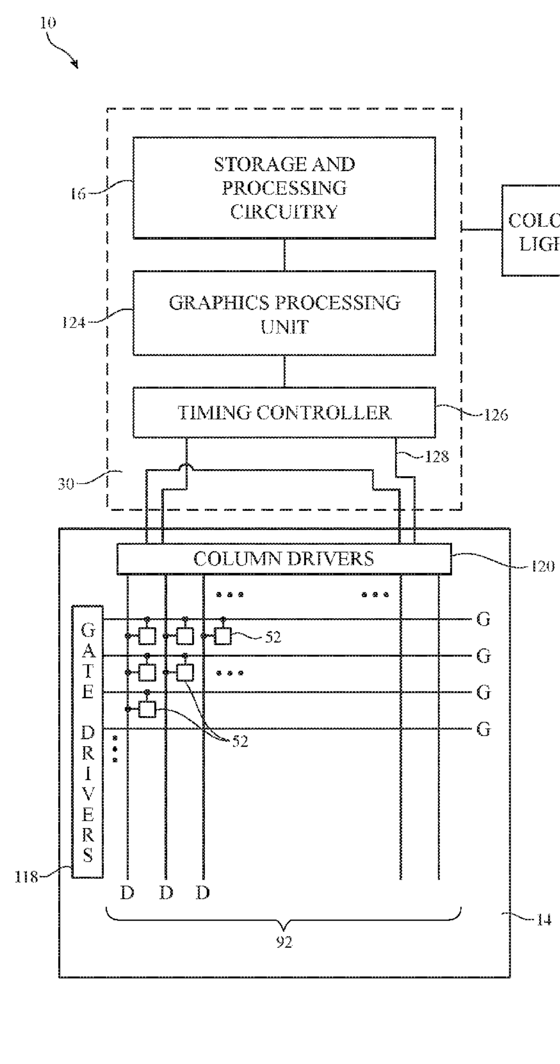
(57) **ABSTRACT**

An electronic device may be provided with a display, display control circuitry that operates the display, and a color ambient light sensor that gathers ambient light information. Display color cast may be adjusted based on the ambient light information. When the color of ambient light is within an acceptable range of colors, the color cast of the display may be adjusted to more closely match the color of ambient light. When the color of ambient light is outside of the acceptable range of colors, display control circuitry may determine an adjusted ambient light color that is within the acceptable range. The adjusted ambient light color may have the same color temperature as the measured ambient light color. After determining an adjusted ambient light color that is within the acceptable range, the color cast of the display may be adjusted to more closely match the adjusted ambient light color.



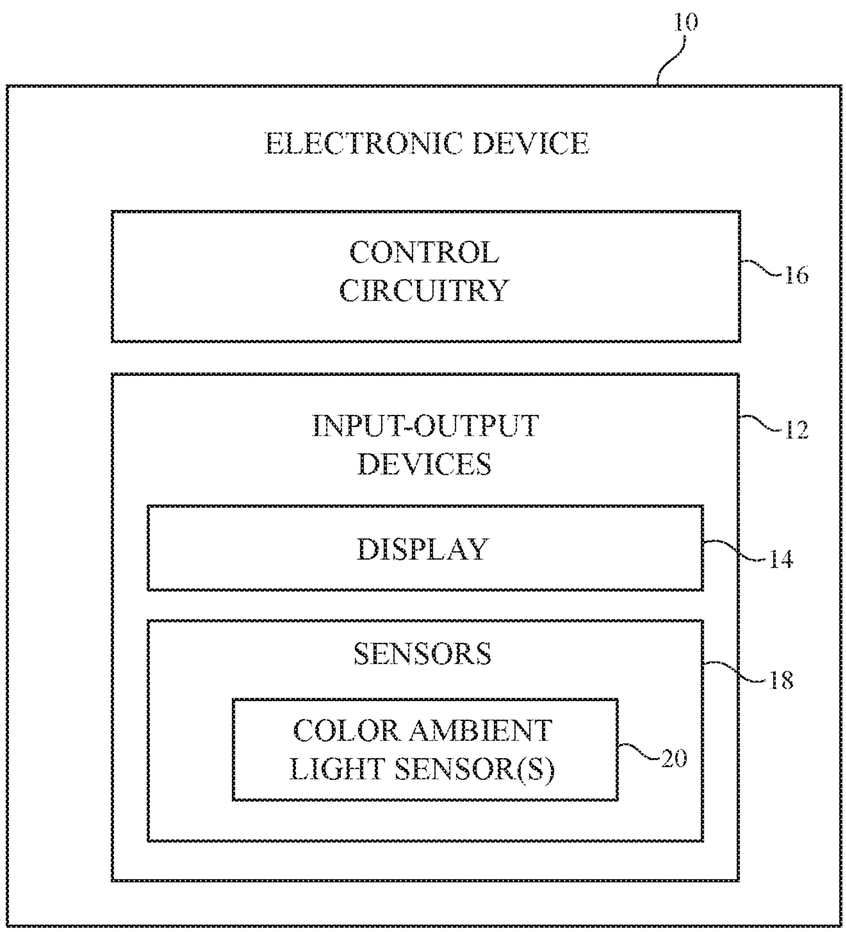

10
ELECTRONIC DEVICE
CONTROL CIRCUITRY
16
INPUT-OUTPUT DEVICES
12
DISPLAY
14
SENSORS
18
COLOR AMBIENT LIGHT SENSOR(S)
20

FIG. 1

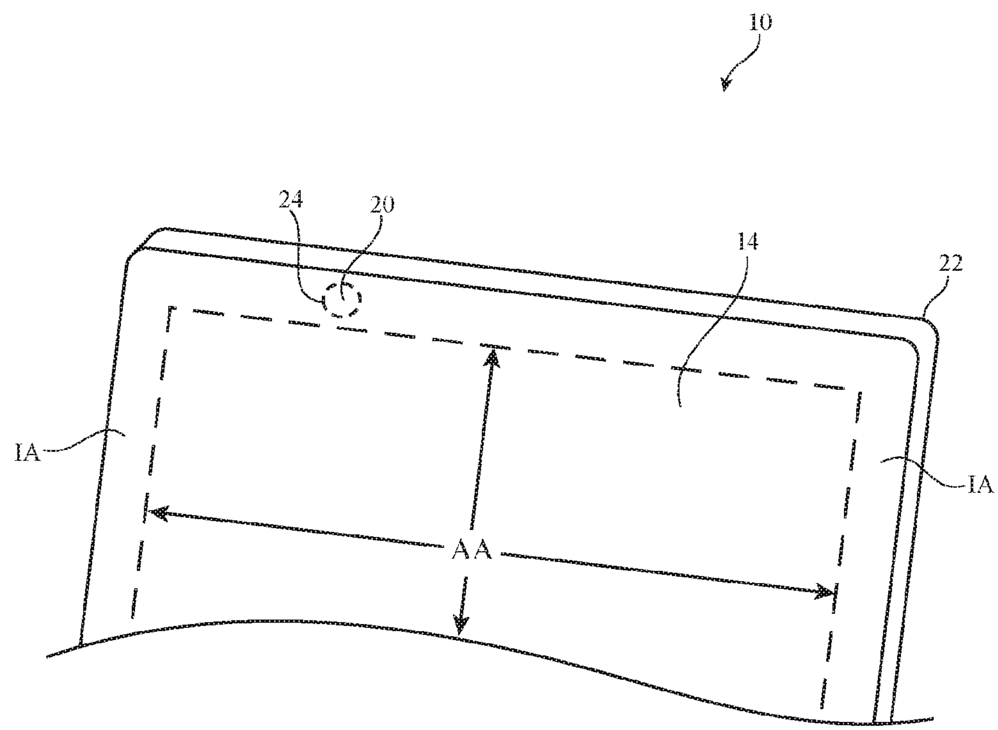


FIG. 2

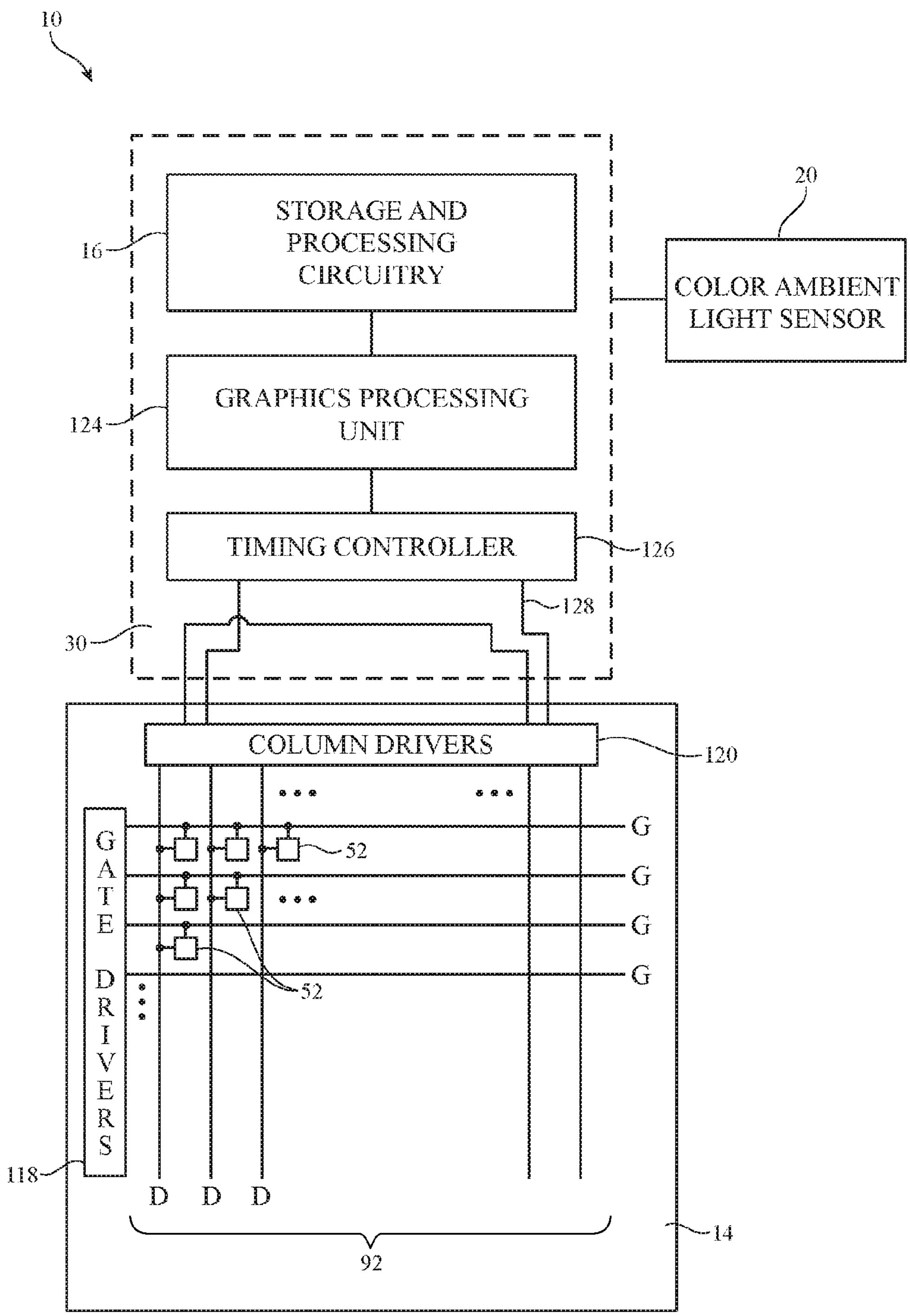

10
STORAGE AND PROCESSING CIRCUITRY
16
20
COLOR AMBIENT LIGHT SENSOR
GRAPHICS PROCESSING UNIT
124
TIMING CONTROLLER
126
128
30
COLUMN DRIVERS
120
G
G
G
G
52
52
GATE DRIVERS
118
D D D
14
92

FIG. 3

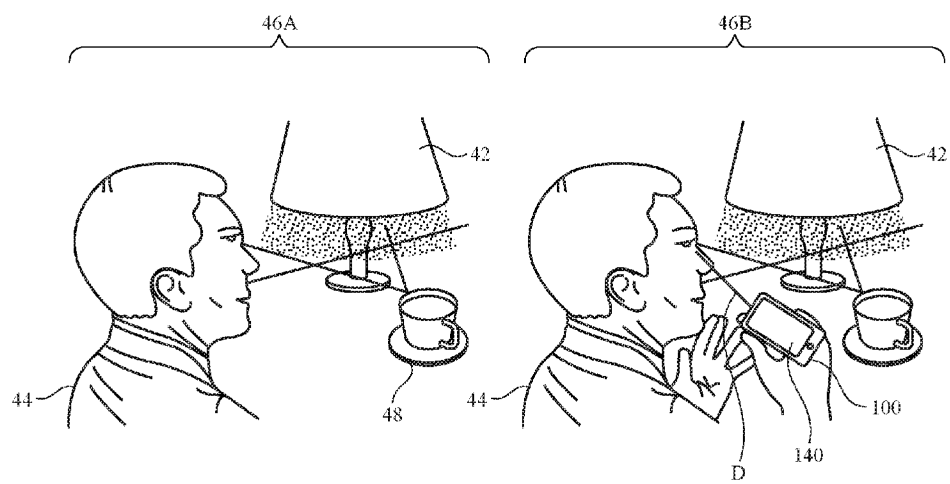


FIG. 4

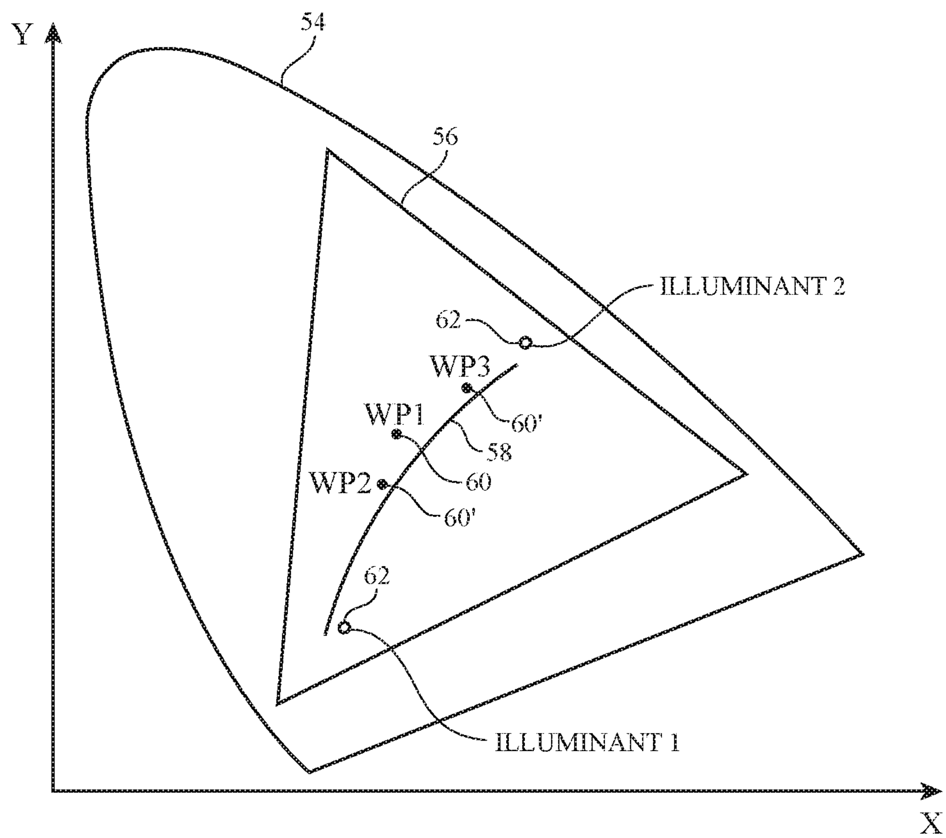


FIG. 5

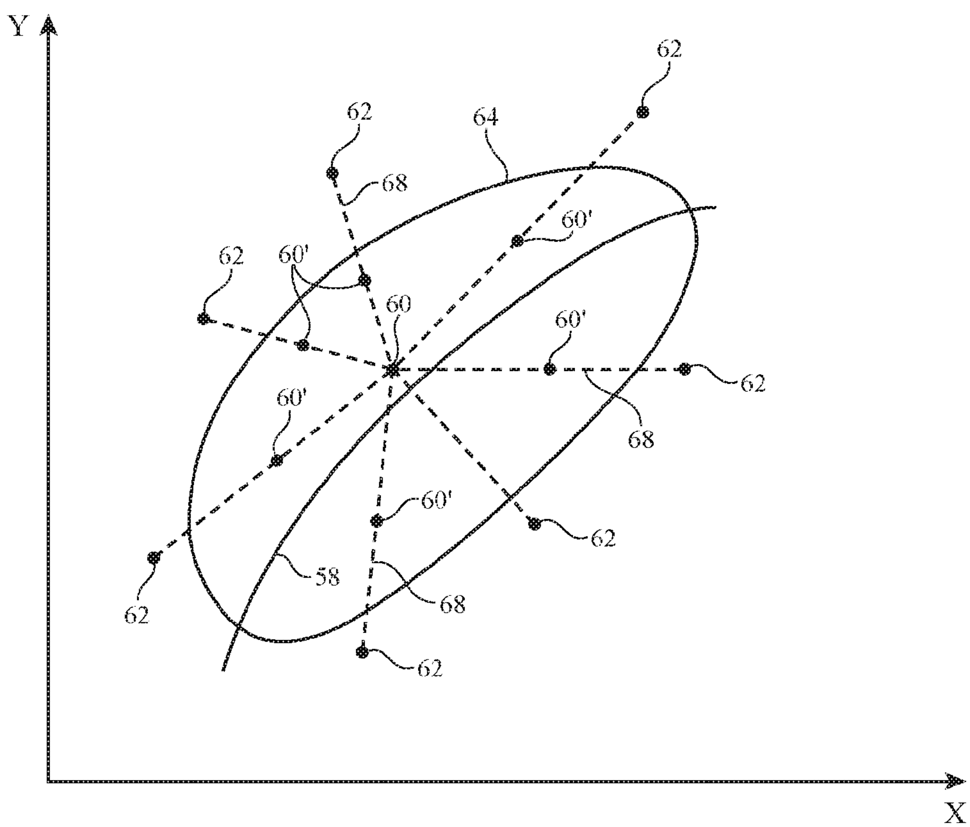


FIG. 6

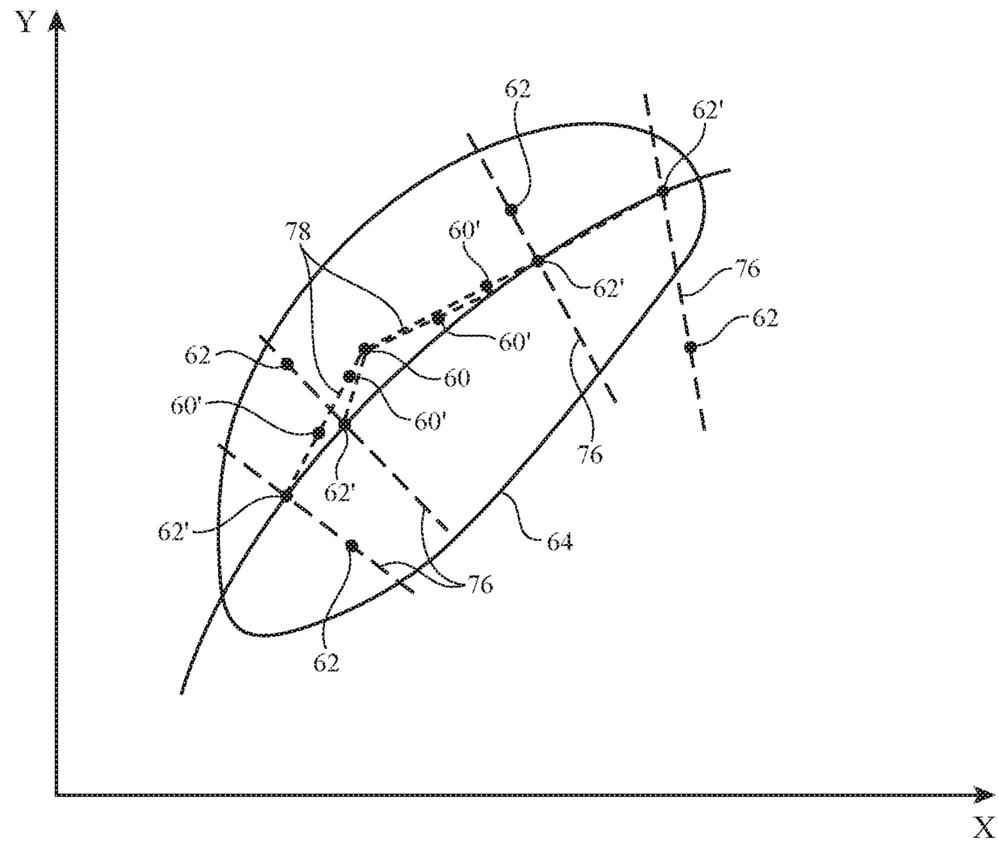


FIG. 7

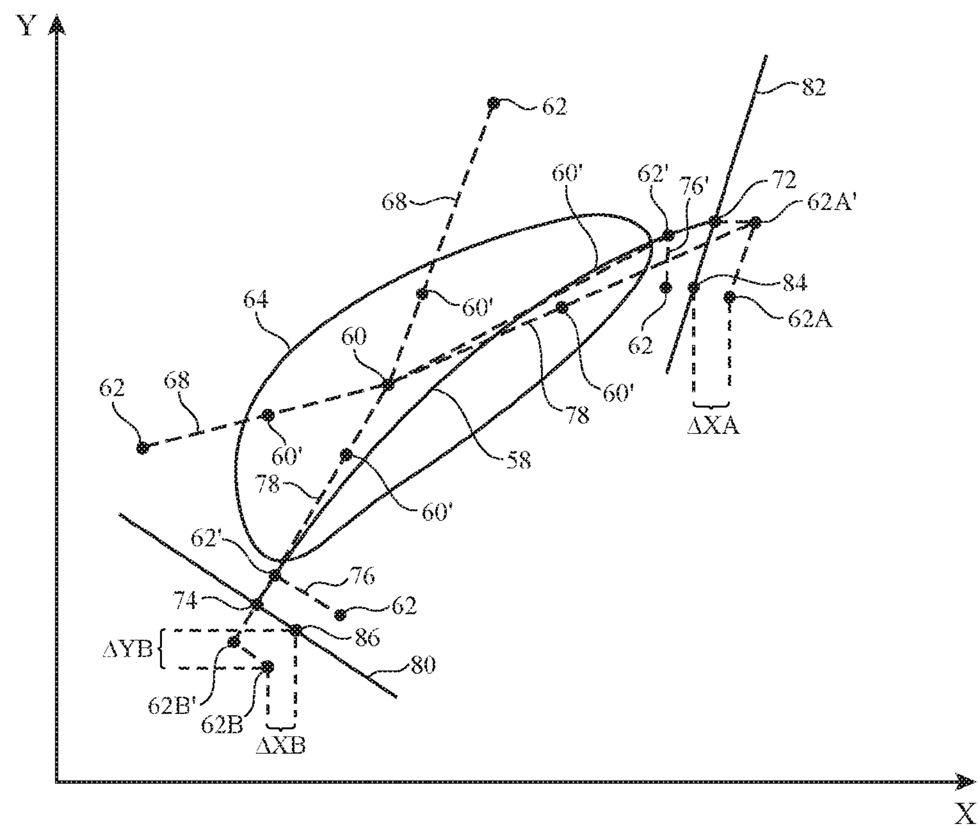

Y
X
62
82
68
60'
62'
76'
72
62A'
84
62A
64
60'
60
62
62
68
60'
78
60'
ΔXA
60'
58
78
60'
62'
76
74
62
86
ΔYB
80
62B'
62B
ΔXB

FIG. 8

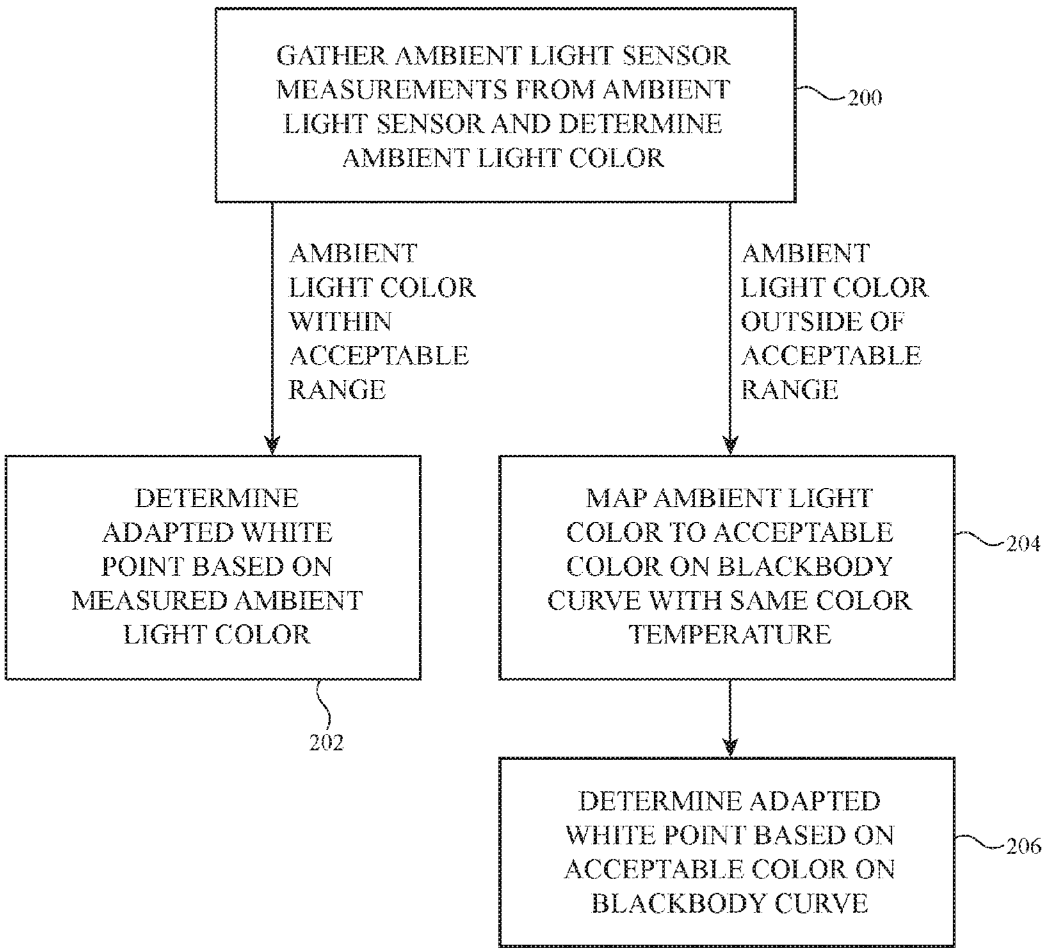

GATHER AMBIENT LIGHT SENSOR MEASUREMENTS FROM AMBIENT LIGHT SENSOR AND DETERMINE AMBIENT LIGHT COLOR
200
AMBIENT LIGHT COLOR WITHIN ACCEPTABLE RANGE
AMBIENT LIGHT COLOR OUTSIDE OF ACCEPTABLE RANGE
DETERMINE ADAPTED WHITE POINT BASED ON MEASURED AMBIENT LIGHT COLOR
202
MAP AMBIENT LIGHT COLOR TO ACCEPTABLE COLOR ON BLACKBODY CURVE WITH SAME COLOR TEMPERATURE
204
DETERMINE ADAPTED WHITE POINT BASED ON ACCEPTABLE COLOR ON BLACKBODY CURVE
206

FIG. 9

ELECTRONIC DEVICE WITH AMBIENT-ADAPTIVE DISPLAY

[0001] This application claims the benefit of provisional patent application No. 62/305,774, filed Mar. 9, 2016, which is hereby incorporated by reference herein in its entirety.

BACKGROUND

[0002] This relates generally to electronic devices, and, more particularly, to light sensors for electronic devices.

[0003] Electronic devices such as laptop computers, cellular telephones, and other equipment are sometimes provided with light sensors. For example, ambient light sensors may be incorporated into a device to provide the device with information on current lighting conditions. Ambient light readings may be used in controlling the device. If, for example bright daylight conditions are detected, an electronic device may increase display brightness to compensate.

[0004] Ambient light sensors can sometimes produce erroneous readings. For example, a user's finger or other external object may block an ambient light sensor. In this type of situation, the ambient light sensor may produce a reading that does not accurately reflect ambient lighting conditions. If care is not taken, this may lead to inappropriate display adjustments.

[0005] It would therefore be desirable to be able to provide improved systems for operating displays in electronic devices.

SUMMARY

[0006] An electronic device may be provided with a display and display control circuitry. A color ambient light sensor may make measurements of ambient light intensity and color through a window in an inactive border region of the display.

[0007] The white point and color cast of the display may be adjusted based on ambient light information. When the measured color of ambient light is within an acceptable range of ambient light colors, the display control circuitry may adjust the color cast of the display to more closely match the measured color of ambient light. When the measured color of ambient light is outside of the acceptable range of ambient light colors, the display control circuitry may determine an adjusted ambient light color that is within the acceptable range of ambient light colors. The adjusted ambient light color may have the same color temperature as the measured ambient light color, but may be less saturated than the measured ambient light color. The adjusted ambient light color may have chromaticity coordinates that are located on a Planckian locus.

[0008] After determining an adjusted ambient light color that is within the acceptable range, the color cast of the display may be adjusted to more closely match the adjusted ambient light color.

BRIEF DESCRIPTION OF THE DRAWINGS

[0009] FIG. **1** is a schematic diagram of an illustrative electronic device in accordance with an embodiment.

[0010] FIG. **2** is a front perspective view of a portion of an illustrative electronic device in accordance with an embodiment.

[0011] FIG. **3** is a schematic diagram of an illustrative electronic device having a display, display control circuitry, and a color ambient light sensor in accordance with an embodiment.

[0012] FIG. **4** is a diagram illustrating how conventional displays do not adapt to the color of ambient light and become unsightly to a user as a result.

[0013] FIG. **5** is a chromaticity diagram illustrating how the white point of a display may be adjusted based on the color of ambient light in accordance with an embodiment.

[0014] FIG. **6** is a chromaticity diagram illustrating how an ambient-adapted white point may be determined based on the measured ambient light color in accordance with an embodiment.

[0015] FIG. **7** is a chromaticity diagram illustrating how measured ambient light colors may be adjusted to less saturated ambient light colors before determining an ambient-adapted white point in accordance with an embodiment.

[0016] FIG. **8** is a chromaticity diagram illustrating how measured ambient light colors that fall outside of a predetermined range of colors may be adjusted to less saturated ambient light colors before determining an ambient-adapted white point in accordance with an embodiment.

[0017] FIG. **9** is a flow chart of illustrative steps involved in determining an ambient-adapted white point for a display using a technique of the type shown in FIG. **8** in accordance with an embodiment.

DETAILED DESCRIPTION

[0018] An illustrative electronic device of the type that may be provided with one or more light sensors is shown in FIG. **1**. Electronic device **10** may be a computing device such as a laptop computer, a computer monitor containing an embedded computer, a tablet computer, a cellular telephone, a media player, or other handheld or portable electronic device, a smaller device such as a wrist-watch device, a pendant device, a headphone or earpiece device, a device embedded in eyeglasses or other equipment worn on a user's head, or other wearable or miniature device, a television, a computer display that does not contain an embedded computer, a gaming device, a navigation device, an embedded system such as a system in which electronic equipment with a display is mounted in a kiosk or automobile, equipment that implements the functionality of two or more of these devices, or other electronic equipment.

[0019] As shown in FIG. **1**, electronic device **10** may have control circuitry **16**. Control circuitry **16** may include storage and processing circuitry for supporting the operation of device **10**. The storage and processing circuitry may include storage such as hard disk drive storage, nonvolatile memory (e.g., flash memory or other electrically-programmable-read-only memory configured to form a solid state drive), volatile memory (e.g., static or dynamic random-access-memory), etc. Processing circuitry in control circuitry **16** may be used to control the operation of device **10**. The processing circuitry may be based on one or more microprocessors, microcontrollers, digital signal processors, baseband processors, power management units, audio chips, application specific integrated circuits, etc.

[0020] Input-output circuitry in device **10** such as input-output devices **12** may be used to allow data to be supplied to device **10** and to allow data to be provided from device **10** to external devices. Input-output devices **12** may include buttons, joysticks, scrolling wheels, touch pads, key pads, keyboards, microphones, speakers, tone generators, vibrators, cameras, light-emitting diodes and other status indicators, data ports, etc. A user can control the operation of device **10** by supplying commands through input-output devices **12** and may receive status information and other output from device **10** using the output resources of input-output devices **12**.

[0021] Input-output devices **12** may include one or more displays such as display **14**. Display **14** may be a touch screen display that includes a touch sensor for gathering touch input from a user or display **14** may be insensitive to touch. A touch sensor for display **14** may be based on an array of capacitive touch sensor electrodes, acoustic touch sensor structures, resistive touch components, force-based touch sensor structures, a light-based touch sensor, or other suitable touch sensor arrangements.

[0022] Input-output devices **12** may also include sensors **18**. Sensors **18** may include an ambient light sensor such as color ambient light sensors **20** and other sensors (e.g., a capacitive proximity sensor, a light-based proximity sensor, a magnetic sensor, an accelerometer, a force sensor, a touch sensor, a temperature sensor, a pressure sensor, a compass, a microphone or other sound sensor, or other sensors).

[0023] Color ambient light sensor **20** for device **10** may have an array of detectors each of which is provided with a color filter. If desired, the detectors in ambient light sensor **20** may be provided with color filters of different respective colors. Information from the detectors may be used to measure the total amount of ambient light that is present in the vicinity of device **10**. For example, the ambient light sensor may be used to determine whether device **10** is in a dark or bright environment. Based on this information, control circuitry **16** can adjust display brightness for display **14** or can take other suitable action.

[0024] Ambient light sensors **20** may be used to make ambient light intensity (brightness) measurements. Ambient light intensity measurements, which may sometimes be referred to as ambient light luminance measurements, may be used by device **10** to adjust display brightness (as an example). Ambient light sensors **20** may be used to make measurements of ambient light color (e.g., color coordinates, correlated color temperature, or other color parameters representing ambient light color). Processing circuitry **16** may be used to convert these different types of color information to other formats, if desired (e.g., a set of red, green, and blue sensor output values may be converted into color chromaticity coordinates and/or may be processed to produce an associated correlated color temperature, etc.).

[0025] Color information and brightness information from color sensing ambient light sensor **20** can be used to adjust the operation of device **10**. For example, the color cast of display **14** may be adjusted in accordance with the color of ambient lighting conditions. If, for example, a user moves device **10** from a cool lighting environment to a warm lighting environment (e.g., an incandescent light environment), the warmth of display **14** may be increased accordingly, so that the user of device **10** does not perceive display **14** as being overly cold. If desired, the ambient light sensor may include an infrared light sensor. In general, any suitable actions may be taken based on color measurements and/or total light intensity measurements (e.g., adjusting display brightness, adjusting display content, changing audio and/or video settings, adjusting sensor measurements from other sensors, adjusting which on-screen options are presented to a user of device **10**, adjusting wireless circuitry settings, etc.).

[0026] A perspective view of a portion of an illustrative electronic device is shown in FIG. **2**. In the example of FIG. **2**, device **10** includes a display such as display **14** mounted in housing **22**. Housing **22**, which may sometimes be referred to as an enclosure or case, may be formed of plastic, glass, ceramics, fiber composites, metal (e.g., stainless steel, aluminum, etc.), other suitable materials, or a combination of any two or more of these materials. Housing **22** may be formed using a unibody configuration in which some or all of housing **22** is machined or molded as a single structure or may be formed using multiple structures (e.g., an internal frame structure, one or more structures that form exterior housing surfaces, etc.).

[0027] Display **14** may be protected using a display cover layer such as a layer of transparent glass, clear plastic, sapphire, or other clear layer. Openings may be formed in the display cover layer. For example, an opening may be formed in the display cover layer to accommodate a button, a speaker port, or other components. Openings may be formed in housing **22** to form communications ports (e.g., an audio jack port, a digital data port, etc.), to form openings for buttons, etc.

[0028] Display **14** may include an array of display pixels formed from liquid crystal display (LCD) components, an array of electrophoretic pixels, an array of plasma pixels, an array of organic light-emitting diode pixels or other light-emitting diodes, an array of electrowetting pixels, or pixels based on other display technologies. The array of pixels of display **14** forms an active area AA. Active area AA is used to display images for a user of device **10**. Active area AA may be rectangular or may have other suitable shapes. Inactive border area IA may run along one or more edges of active area AA. Inactive border area IA may contain circuits, signal lines, and other structures that do not emit light for forming images. To hide inactive circuitry and other components in border area IA from view by a user of device **10**, the underside of the outermost layer of display **14** (e.g., the display cover layer or other display layer) may be coated with an opaque masking material such as a layer of black ink. Optical components (e.g., a camera, a light-based proximity sensor, an ambient light sensor, status indicator light-emitting diodes, camera flash light-emitting diodes, etc.) may be mounted under inactive border area IA. One or more openings (sometimes referred to as windows) may be formed in the opaque masking layer of IA to accommodate the optical components. For example, a light component window such as an ambient light sensor window may be formed in a peripheral portion of display **14** such as region **24** in inactive border area IA. Ambient light from the exterior of device **10** may be measured by ambient light sensor **20** in device **10** after passing through region **24** and the display cover layer.

[0029] FIG. **3** is a diagram of device **10** showing illustrative circuitry that may be used in displaying images for a user of device **10** on pixel array **92** of display **14**. As shown in FIG. **3**, display **14** may have column driver circuitry **120** that drives data signals (analog voltages) onto the data lines D of array **92**. Gate driver circuitry **118** drives gate line signals onto gate lines G of array **92**. Using the data lines and gate lines, display pixels **52** may be configured to display images on display **14** for a user. Gate driver circuitry **118**

may be implemented using thin-film transistor circuitry on a display substrate such as a glass or plastic display substrate or may be implemented using integrated circuits that are mounted on the display substrate or attached to the display substrate by a flexible printed circuit or other connecting layer. Column driver circuitry **120** may be implemented using one or more column driver integrated circuits that are mounted on the display substrate or using column driver circuits mounted on other substrates.

[0030] During operation of device **10**, storage and processing circuitry **16** may produce data that is to be displayed on display **14**. This display data may be provided to display control circuitry such as timing controller integrated circuit **126** using graphics processing unit **124**.

[0031] Timing controller **126** may provide digital display data to column driver circuitry **120** using paths **128**. Column driver circuitry **120** may receive the digital display data from timing controller **126**. Using digital-to-analog converter circuitry within column driver circuitry **120**, column driver circuitry **120** may provide corresponding analog output signals on the data lines D running along the columns of display pixels **52** of array **92**.

[0032] Storage and processing circuitry **16**, graphics processing unit **124**, and timing controller **126** may sometimes collectively be referred to herein as display control circuitry **30**. Display control circuitry **30** may be used in controlling the operation of display **14**.

[0033] Pixels **52** may include color pixels such as red (R) pixels, green (G) pixels, blue pixels (B) pixel, white (W) pixels, and/or pixels of other colors. Arrangements in which pixels **52** include a pattern of red, green, and blue pixels are sometimes described herein as an illustrative example. Color pixels may include color filter elements that transmit light of a particular color or color pixels may be formed from emissive elements that emit light of a particular color

[0034] Display control circuitry **30** and associated thin-film transistor circuitry associated with display **14** may be used to produce signals such as data signals and gate line signals for operating pixels **52** (e.g., turning pixels **52** on and off, adjusting the intensity of pixels **52**, etc.). During operation, display control circuitry **30** may control the values of the data signals and gate signals to control the light intensity associated with each of the display pixels and to thereby display images on display **14**.

[0035] Display control circuitry **30** may produce red, green, and blue pixel values (sometimes referred to as RGB values or digital display control values) corresponding to the color to be displayed by a given pixel. The RGB values may be converted into analog display signals for controlling the brightness of each pixel. The RGB values (e.g., integers with values ranging from 0 to 255) may correspond to the desired pixel intensity of each pixel. For example, a digital display control value of 0 may result in an "off" pixel, whereas a digital display control value of 255 may result in a pixel operating at a maximum available power and brightness.

[0036] If desired, each color channel may have eight bits, six bits, or any other suitable number of bits. In arrangements where each color channel has eight bits, the digital display control values that control each pixel may be integers ranging from 0 to 255. In arrangements where each color channel has six bits, the digital display control values that control each pixel may be integers ranging from 0 to 64. Arrangements in which each color channel has eight bits are sometimes described herein as an illustrative example.

[0037] Display control circuitry **30** may gather ambient light sensor data from color ambient light sensor **20** to adaptively determine how to adjust display light and display colors based on ambient lighting conditions. If desired, display control circuitry **30** may control display **14** using other information such as time information from a clock, calendar, and/or other time source, location information from location detection circuitry (e.g., Global Positioning System receiver circuitry, IEEE 802.11 transceiver circuitry, or other location detection circuitry), user input information from a user input device such as a touchscreen (e.g., touchscreen display **14**) or keyboard, etc.

[0038] Ambient light sensors **20** may be used to measure the color and intensity of ambient light. Display control circuitry **30** may adjust the operation of display **14** based on the color and intensity of ambient light. In adjusting the output from display **14**, display control circuitry **30** may take into account the chromatic adaptation function of the human visual system. This may include, for example, adjusting the white point of display **14** based on the color and/or brightness of ambient light measured by ambient light sensor **20**. If, for example, a user moves device **10** from a cool lighting environment (e.g., outdoor light having a relatively high correlated color temperature) to a warm lighting environment (e.g., indoor light having a relatively low correlated color temperature), the "warmth" of display **14** may be increased accordingly by adjusting the white point of display **14** to a warmer white (e.g., a white with a cooler color temperature), so that the user of device **10** does not perceive display **14** as being overly cold.

[0039] FIG. **4** is a diagram illustrating the effects of using a conventional display that does not take into account the chromatic adaptation of human vision. Conventional displays such as display **140** of device **100** typically have a fixed target white point such as D65 (a standard illuminant defined by the International Commission on Illumination). In scenario **46**A, user **44** observes external objects **48** under illuminant **42** (e.g., an indoor light source that generates warm light). The vision of user **44** adapts to the color and brightness of the ambient lighting conditions. Scenario **46**B represents how a user perceives light from display **140** of device **100** after having adapted to the color and brightness of illuminant **42**. Because the white point of display **140** remains fixed at D65, device **100** does not account for the chromatic adaptation of human vision, and display **140** appears bluish and unsightly to user **44** as a result.

[0040] To avoid the perceived discoloration of display **14**, display control circuitry **30** of FIG. **3** may control the white point and color cast of display **14** based on the color (and intensity, if desired) of ambient light. This may include, for example, adaptively adjusting the white point of display **14** to have a color that more closely matches the color of ambient light.

[0041] A chromaticity diagram illustrating how display **14** may have an adaptive white point that is determined at least partly based on ambient lighting conditions is shown in FIG. **5**. The chromaticity diagram of FIG. **5** illustrates a two-dimensional projection of a three-dimensional color space (sometimes referred to as the 1931 CIE chromaticity diagram). The color generated by a display such as display **14** may be represented by chromaticity values x and y. The chromaticity values may be computed by transforming, for example, three color intensities (e.g., intensities of colored light emitted by a display) such as intensities of red, green, and blue light into three tristimulus values X, Y, and Z and normalizing the first two tristimulus values X and Y (e.g., by computing x=X/(X+Y+Z) and y=Y/(X+Y+Z) to obtain normalized x and y values). Transforming color intensities into tristimulus values may be performed using transformations defined by the International Commission on Illumination (CIE) or using any other suitable color transformation for computing tristimulus values.

[0042] Any color generated by a display may therefore be represented by a point (e.g., by chromaticity values x and y) on a chromaticity diagram such as the diagram shown in FIG. **5**. Bounded region **54** of FIG. **5** represents the limits of visible light that may be perceived by humans (i.e., the total available color space). The colors that may be generated by a display are contained within a subregion of bounded region **54**. For example, bounded region **56** may represent the available color space for display **14** (sometimes referred to as the color gamut of display **14**).

[0043] Display **14** may be characterized by various calibration settings such as gamma and color temperature. The color temperature of display **14** determines the color cast of display **14**. Although the color temperature setting of a display can affect the appearance of all colors, the color temperature setting of a display is sometimes referred to as the "white point" of the display because it is defined by the white color produced when all of the pixels in a display are operated at full power (e.g., when R=G=B=255). The white point of display **14** may be defined by an illuminant (e.g., D65, D50, or other illuminant), a color temperature (e.g., 6500 degrees Kelvin (K), 5000 K, or other color temperature), or a set of chromaticity coordinates. The color temperature of a light source refers to the temperature at which a theoretical black body radiator would emit radiation of a color most closely resembling that of the light source. Curve **58** illustrates the range of colors that would radiate from an ideal black body at different color temperatures and is sometimes referred to as the Planckian locus or black body locus. The color temperatures on black body curve **58** range from higher temperatures on the left (e.g., near the cooler hues around Illuminant **1**) to lower temperatures on the right (e.g., near the warmer hues around Illuminant **2**).

[0044] Display control circuitry **30** of FIG. **3** may operate display **14** in an ambient-adaptive mode and a non-adaptive mode. In ambient-adaptive mode, display control circuitry **30** may adaptively adjust the white point of display **14** based on the color of ambient light. In non-adaptive mode, the white point of display **14** may remain fixed at a default white point such as WP**1** (represented by point **60** of FIG. **5**). Display control circuitry **30** may switch between ambient-adaptive mode and non-adaptive mode automatically and/or a user may manually adjust the settings of display **14** to switch between ambient-adaptive mode and non-adaptive mode.

[0045] The default white point WP**1** of display **14** may be any suitable white point. For example, white point WP**1** may be D65, D50, or any other suitable white color. If desired, white point WP**1** may be selected and/or adjusted by the user. When operating in non-adaptive mode, the white point of display **14** may remain fixed at WP**1** even as the ambient lighting conditions change.

[0046] In ambient-adaptive mode, however, display control circuitry **30** may automatically adjust the white point of display **14** based on the color of ambient light. There may be certain ambient lighting situations where the default white point WP**1** is appropriate. For example, when ambient light is neither overly cool nor overly warm, default white point WP**1** may be a close match to the ambient light and may therefore be agreeable to the user's eyes. However, under other ambient lighting conditions (e.g., under different illuminants such as illuminants **62** of FIG. **5**), display control circuitry **30** may adjust the white point of display **14** to an ambient-adaptive white point (e.g., one of ambient-adaptive white points **60'** of FIG. **5**).

[0047] For example, under a first ambient illuminant **62** such as Illuminant **1**, control circuitry **30** may adjust the white point of display **14** to ambient-adapted white point WP**2** (represented by one of points **60'**). Ambient-adapted white point WP**2** more closely matches the color of Illuminant **1** than default white point WP**1**. Under a second ambient illuminant **62** such as Illuminant **2**, control circuitry **30** may adjust the white point of display **14** to ambient-adapted white point WP**3** (represented by another one of points **60'**). Ambient-adapted white point WP**3** more closely matches the color of Illuminant **2** than default white point WP**1**.

[0048] By adjusting the white point of display **14** based on the color of ambient light, the color cast of display **14** will adapt to the different ambient lighting conditions just as the user's vision chromatically adapts to different ambient lighting conditions. For example, Illuminant **2** may correspond to an indoor light source having a warm hue, whereas Illuminant **1** may correspond to daylight having a cool hue. Illuminant **2** may have a lower color temperature than Illuminant **1** and may therefore emit warmer light. In warmer ambient light (e.g., under Illuminant **2**), display control circuitry **30** can adjust the white point of display **14** to ambient-adapted white point WP**3**, which in turn adjusts the color cast of display **14** to produce warmer light (i.e., light with a lower color temperature) than that which would be produced if the default white point WP**1** were maintained as the display white point.

[0049] In addition to helping avoid perceived color shifts in different ambient lighting conditions, this type of adaptive color adjustment may also have beneficial effects on the human circadian rhythm. The human circadian system may respond differently to different wavelengths of light. For example, when a user is exposed to blue light having a peak wavelength within a particular range, the user's circadian system may be activated and melatonin production may be suppressed. On the other hand, when a user is exposed to light outside of this range of wavelengths or when blue light is suppressed (e.g., compared to red light), the user's melatonin production may be increased, signaling nighttime to the body.

[0050] Conventional displays do not take into account the spectral sensitivity of the human circadian rhythm. For example, some displays emit light having spectral characteristics that trigger the circadian system regardless of the time of day, which can in turn have an adverse effect on sleep quality.

[0051] In contrast, by using the color cast adjustment method described in connection with FIG. **5**, the ambient-adapted white point of display **14** may become warmer in warmer ambient lighting conditions (e.g., may be adjusted to white point WP**3** or other suitable warm white). Thus, when a user is at home in the evening (e.g., reading in warm ambient light), blue light emitted from display **14** may be suppressed (e.g., relative to other colors) as the display adapts to the warm ambient lighting conditions. The reduction in blue light may in turn reduce suppression of the user's melatonin production (and, in some scenarios, may increase the user's melatonin production) to promote better sleep.

[0052] FIG. **6** shows an illustrative method of determining an ambient-adaptive white point **60'** using measured ambient light data **62**. Each data point **62** represents chromaticity coordinates associated with a measured ambient light color. For example, in arrangements where ambient light sensor **20** has a red detector, a green detector, and a blue detector, sensor **20** may output red, green, and blue values corresponding to measured ambient light. Display control circuitry **30** may convert these red, green, and blue sensor values to corresponding tristimulus values X, Y, and Z, which in turn may be converted to chromaticity coordinates represented by data points **62** in FIG. **6**.

[0053] After measuring the color of ambient light, display control circuitry **30** may determine an ambient-adapted neutral point **60'** based on the color of measured ambient light **62** and the default target white point **60**. The ambient-adapted white point may be located along line **68** between default white point **60** and measured ambient light color **62**. Although line **68** is shown in CIEXYZ color space, line **68** may be a line between default white point **60** and ambient light color **62** in any suitable color space. In one illustrative example, line **68** may represent a line between default white point **60** and ambient light color **62** in CIELAB color space. If desired, other color spaces may be used (LMS color space, CIELUV color space, CIEXYZ color space, or other suitable color space).

[0054] The location of ambient-adapted white point **60'** on line **68** may depend on various factors. In some configurations, the white point may be adjusted to be the same as or close to the ambient light color **62**. However, some ambient light colors may be too far from default white point **60** and would therefore appear unsightly to a user. In order to avoid having the color cast of display **14** appear too yellow or too blue, display control circuitry **30** may impose constraints on the distance between default white point **60** and ambient-adapted white point **60'**. These constraints are represented by bounded region **64**. Line **64** represents the furthest acceptable distance that an ambient-adapted white point **60'** may be from default white point **60**. This is, however, merely illustrative. If desired, display control circuitry **30** may match ambient-adapted white point **60'** to ambient light **62** without imposing any constraints (e.g., ambient-adapted white point **60'** may be located outside of boundary **64**, if desired).

[0055] The ambient-adapted white point **60'** may therefore be located anywhere along line **68** between default white point **60** and boundary line **64**. The location of the ambient-adapted white point **60'** along line **68** may be determined based on various factors. Since display **14** is itself illuminant, a user's chromatic adaptation may be affected by both display light from display **14** and ambient light from other light sources (e.g., the sun, a light bulb, etc.). Display control circuitry **30** may use an adaptation factor ranging from 0 to 1 to determine how heavily the display light should be weighted relative to other ambient light sources when determining ambient-adapted white point **60'**. When a user's vision is assumed to be completely adapted to display light without adapting to ambient light from surrounding light sources (e.g., when a user is viewing display **14** in a dark room), the adaptation factor may be equal to one. Conversely, when a user's vision is assumed to be completely adapted to the surrounding ambient light without adapting to the display light, the adaptation factor may be equal to zero. Adaptation factors between 0 and 1 may indicate that the user's vision is adapting to a mix of display light and other ambient light sources.

[0056] In some arrangements, display control circuitry **30** may use a look-up table (LUT) that is stored in device **10** to determine ambient-adapted white point **60'** based on ambient light color **62**. The look-up table may have output ambient-adapted white points **60'** that are indexed by measured ambient light **62**. If desired, the output ambient-adapted white points **60'** may be indexed by other variables such as the adaptation factor described above, the time of day, user preferences, or other suitable factors. If desired, equations or other mapping methods may be used instead of or in addition to look-up tables to determine an ambient-adapted white point **60'** based on measured ambient light color **62**.

[0057] When display control circuitry **30** is operating display **14** in ambient-adaptive mode, care must be taken to ensure that the ambient-adaptive white point of display **14** is not overly red or blue. There may be scenarios in which the output from ambient light sensor **20** does not accurately represent the color of ambient light. For example, a user's hand may be covering ambient light sensor **20**, or a red shirt may be directly in front of ambient light sensor **20**. If display control circuitry **30** were to adjust the white point of display **14** to match these types of sensor readings, the color cast if display **14** may appear too yellow or red to the user.

[0058] FIG. **7** illustrates a method of adjusting the white point of display **14** in a way that compensates for less accurate ambient light sensor readings. The chromaticity coordinates of most ambient light sources are located on or close to black body curve **58**. Colors that are further from black body curve **58** may be more saturated than colors on black body curve **58**. For example, colors below black body curve **58** may be more intensely red saturated than colors on curve **58**. Thus, to ensure that display control circuitry **30** does not adjust the white point of display **14** to match a sensor reading **62** that is overly saturated and not representative of the actual ambient light color, display control circuitry **30** may map ambient light sensor readings **62** to black body curve **58** before determining an appropriate ambient-adapted white point **60'**.

[0059] Each line **76** represents a range of colors that share the same color temperature (sometimes referred to as an iso-CCT line). Point **62'** represents the point on black body curve **58** with a color temperature that matches the color temperature associated with ambient light sensor reading **62**. When display control circuitry **30** receives an ambient light sensor reading **62**, it can convert the sensor output values to a color temperature. Display control circuitry **30** may then determine the point **62'** on black body curve **58** that has the same color temperature as the measured ambient light color **62**. After mapping ambient light colors **62** to acceptable ambient light colors **62'** on black body curve **58**, display control circuitry **30** may determine an appropriate ambient-adapted white point **60'** for display **14** using ambient light color **62'** as the ambient light color.

[0060] Display control circuitry **30** may, for example, use a method of the type described in connection with FIG. **6** to determine an ambient-adapted white point **60'** based on the adjusted ambient light color **62'** and the default white point **60**. For example, the ambient-adapted white point **60'** may be located along line **78** between default white point **60** and adjusted ambient light color **62'**. Line **78** may be a line between CIEXYZ color space, CIELAB color space, LMS color space, CIELUV color space, or other suitable color space. If desired, display control circuitry **30** may impose certain constraints to ensure that the ambient-adapted white point **60'** is located within an acceptable distance from default white point **60** (e.g., so that ambient-adapted white point **60'** is located within bounded region **64**).

[0061] The example of FIG. **7** in which all ambient light sensor readings **62** are mapped to colors of equal color temperature on black body curve **58** is merely illustrative. If desired, control circuitry **30** may only adjust ambient light sensor readings **62** that lie outside of an acceptable range of colors before determining an ambient-adapted white point **60**. This type of arrangement is described in FIG. **8**.

[0062] FIG. **8** illustrates a method of determining an ambient-adapted white point for display **14** in which some ambient light sensor readings **62** are processed using the method of FIG. **6** and other ambient light sensor readings **62** are processed using the method of FIG. **7**. This type of hybrid approach allows display control circuitry **30** to adjust the color cast of display **14** to closely match ambient light surroundings while still avoiding overly harsh adjustments that may make the display appear too yellow or red.

[0063] For example, when ambient light sensor **20** is covered by a user's hand or a red shirt, ambient light sensor **20** may produce ambient light data **62** with chromaticity coordinates below black body curve **58**. It may therefore be desirable to map ambient light sensor readings **62** that are located below black body curve **58** to a color on black body curve **58** with equal color temperature, as described in connection with FIG. **7**. Colors on black body curve **58** may be less saturated than colors below black body curve **58**. As another example, if users tend to dislike displays with overly yellow color casts, ambient light sensor readings **62** that are overly yellow may be mapped to black body curve **58** prior to determining an ambient-adapted white point **60'**. In general, ambient light sensor readings of any given color or within any given region of the color spectrum may be mapped to black body curve **58** prior to determining an ambient-adapted white point **60'**.

[0064] In the example of FIG. **8**, ambient light sensor readings **62** that are located below black body curve **58** on the chromaticity diagram are mapped to an acceptable color on black body curve **58** and are processed using the method of FIG. **7**. Ambient light sensor readings **62** that are located above black body curve **58** on the chromaticity diagram are deemed to be acceptable and are processed using the method of FIG. **6**.

[0065] There may be scenarios in which ambient light sensor measurements correspond to a highly saturated color that does not have a matching color temperature on black body curve **58**. For example, blackbody curve **58** may range from about 2,248 K at point **72** on black body curve **58** to 15,000 K at point **74** on black body curve **58**. Line **82** represents a range of colors that share the 2,248 K color temperature and is sometimes referred to as the 2,248 K iso-CCT line. Line **80** represents a range of colors that share the 15,000 K color temperature and is sometimes referred to as the 15,000 K iso-CCT line. Some ambient light sensor measurements such as measurements **62**A and **62**B may have color temperatures that are outside of the 2,248 K to 15,000 K temperature range. Display control circuitry **30** may apply special processing steps to these outlier measurements to determine an acceptable ambient light color that is less saturated than the measured ambient light color **62**A or **62**B.

[0066] For ambient light sensor measurements below 2,248 K such as measurement **62**A, display control circuitry **30** may determine the x-component ΔXA of the distance between point **62**A and the closest point **84** on 2,248 K iso-CCT line **82**. The adjusted ambient light color **62**A' for this measurement may then be determined by adding ΔXA to the x-component of point **72** (the 2,248 K temperature location on black body curve **58**). Adding only to the x-component of point **72** may help ensure that the adjusted ambient light color **62**A' does not shift downward into the red portion of the color spectrum. In effect, black body curve **58** is extended in the x-direction beyond point **72** to determine an appropriate ambient light color for color temperatures lower than 2,248 K. This is, however, merely illustrative. If desired, ambient light color **62**A' may be determined by adding to point **72** both the x-component and the y-component of the difference between point **62**A and point **84**.

[0067] For ambient light sensor measurements above 15,000 K such as measurement **62**B, display control circuitry **30** may determine the x-component ΔXB and the y-component ΔYB of the distance between point **62**B and the closest point **86** on 15,000 K iso-CCT line **80**. The adjusted ambient light color **62**B' for this measurement may then be determined by adding ΔXB to the x-component of point **74** (the 15,000 K temperature location on black body curve **58**) and by adding ΔYB to the y-component of point **74**. In effect, black body curve **58** is extrapolated using the tangent slope of curve **58** at point **74** to determine an appropriate ambient light color for color temperatures higher than 15,000 K.

[0068] Ambient light sensor measurements **62** that are within the acceptable portion of the color space (e.g., measurements **62** above black body curve **58**) may be processed using the method described in connection with FIG. **6**. For example, for measurements **62** above black body curve **58**, ambient-adapted white point **60'** may be located along line **68** between default white point **60** and ambient light color **62**. Line **68** may be a line between CIEXYZ color space, CIELAB color space, LMS color space, CIELUV color space, or other suitable color space. If desired, display control circuitry **30** may impose certain constraints to ensure that the ambient-adapted white point **60'** is located within an acceptable distance from default white point **60** (e.g., so that ambient-adapted white point **60'** is located within bounded region **64**). If desired, a look-up table may be used to determine ambient-adapted white point **60'** based on ambient light color **62**.

[0069] Ambient light sensor measurements **62** that are not within the acceptable portion of the color space (e.g., measurements **62** below black body curve **58**) may be processed using the method described in connection with FIG. **7**. For example, display control circuitry **30** may first map these ambient light sensor measurements **62** to acceptable ambient light colors **62'** by determining the point on curve **58** with the same color temperature as ambient light color **62**. Display control circuitry **30** may then use the adjusted ambient light color **62'** to determine ambient-adapted white point **60**. Ambient-adapted white point **60'**

may be located along line **78** between default white point **60** and adjusted ambient light color **62'**. Line **78** may be a line between CIEXYZ color space, CIELAB color space, LMS color space, CIELUV color space, or other suitable color space. If desired, display control circuitry **30** may impose certain constraints to ensure that the ambient-adapted white point **60'** is located within an acceptable distance from default white point **60** (e.g., so that ambient-adapted white point **60'** is located within bounded region **64**). If desired, a look-up table may be used to determine ambient-adapted white point **60'** based on adjusted ambient light color **62'**.

[0070] FIG. **9** is a flow chart of illustrative steps involved in determining an ambient-adapted white point for display **14** based on the color of ambient light.

[0071] At step **200**, display control circuitry **30** may use color ambient light sensor **20** to gather intensity information and color information on ambient light. Color information (i.e., color ambient light sensor color data) may be gathered as color coordinates, correlated color temperature (CCT) readings, or using other suitable color sensing parameters. During the operations of step **200**, the ambient light sensor measurements may be processed. For example, red, green, and blue sensor output values may be converted to chromaticity coordinates (e.g., chromaticity coordinates **62** of FIGS. **6**, **7**, and **8**) representing the color of ambient light.

[0072] During the operations of step **200**, display control circuitry **30** may determine whether the ambient light color is within a predetermined acceptable range of colors. For example, ambient light colors that are located above black body curve **58** may be deemed "acceptable," whereas ambient light colors that are located below black body curve **58** may be too red and may need adjustment to a less saturated color before being used to determine an ambient-adapted white point for display **14**. The use of black body curve **58** to separate acceptable ambient light colors from unacceptable ambient colors that need to be adjusted is merely illustrative. Whether an ambient light color is acceptable may be based on other factors or constraints. For example, some ambient light colors below black body curve **58** may be deemed acceptable, whereas other colors below curve **58** (e.g., saturated red colors) may be deemed unacceptable and in need of adjustment.

[0073] If it is determined during step **200** that the ambient light color is within the acceptable range of colors, display control circuitry **30** may process the ambient light sensor data using the operations of step **202**. At step **202**, display control circuitry **30** may determine an ambient-adapted white point **60'** based on the ambient light color **62** measured in step **200**. This may include, for example, applying an equation, look-up table (e.g., a 1D LUT, a 3D LUT, or other suitable LUT), or other mapping method using ambient light color **62** to determine an ambient-adapted white point **60'** that more closely matches ambient light color **62**. In some scenarios, the ambient-adapted white point **60'** may have a color that matches ambient light color **62**. In other scenarios, the ambient-adapted white point **60'** may be a color between default white point **60** and ambient light color **62** (e.g., in CIELAB color space or other suitable color space).

[0074] If it is determined during step **200** that the ambient light color is not within the acceptable range of colors, display control circuitry **30** may process the ambient light sensor data using the operations of step **204**. At step **204**, display control circuitry **30** may adjust the measured ambient light color **62** to an acceptable ambient light color **62'**. This may include, for example, determining the color temperature associated with the measured ambient light color **62** and then determining the color **62'** on black body curve **58** with that same color temperature. The adjusted ambient light color may, for example, be less saturated than the measured ambient light color. For ambient light colors that do not have a matching color temperature on black body curve **58** (e.g., measurements with color temperatures outside of the 2,248 K to 15,000 K range such as measurements **62**A and **62**B of FIG. **8**), the measured ambient light color may be mapped to a color on an "extended" or extrapolated portion of black body curve as described in connection with FIG. **8** (e.g., acceptable colors **62**A' and **62**B' of FIG. **8**).

[0075] At step **206**, display control circuitry **30** may determine an ambient-adapted white point **60'** based on the adjusted ambient light color **62'** determined in step **204**. This may include, for example, applying an equation, look-up table, or other mapping method using adjusted ambient light color **62'** to determine an ambient-adapted white point **60'** that more closely matches adjusted ambient light color **62'**. In some scenarios, the ambient-adapted white point **60'** may have a color that matches adjusted ambient light color **62'**. In other scenarios, the ambient-adapted white point **60'** may be a color between default white point **60** and adjusted ambient light color **62'** (e.g., in CIELAB color space or other suitable color space).

[0076] The foregoing is merely illustrative and various modifications can be made by those skilled in the art without departing from the scope and spirit of the described embodiments. The foregoing embodiments may be implemented individually or in any combination.

What is claimed is:

1. A method of operating a display in an electronic device having a color ambient light sensor that receives ambient light and having display control circuitry, comprising:

with the display control circuitry, gathering ambient light sensor data using the color ambient light sensor;

with the display control circuitry, processing the ambient light sensor data to determine a measured color of the ambient light;

with the display control circuitry, determining an adjusted ambient light color based on the measured color, wherein the adjusted ambient light color is different from the measured color; and

with the display control circuitry, adjusting a white point of the display based on the adjusted ambient light color.

2. The method defined in claim **1** wherein processing the ambient light sensor data to determine the measured color comprise processing the ambient light sensor data to determine a color temperature of the ambient light.

3. The method defined in claim **2** wherein determining the adjusted ambient light color based on the measured color comprises determining the adjusted ambient light color based on the color temperature of the ambient light.

4. The method defined in claim **2** wherein the adjusted ambient light color has a color temperature that matches the color temperature of the ambient light.

5. The method defined in claim **4** wherein the adjusted ambient light color has chromaticity coordinates that are located on a Planckian locus on a chromaticity diagram.

6. The method defined in claim **5** wherein the measured color has chromaticity coordinates that are located below the Planckian locus on the chromaticity diagram.

7. The method defined in claim **2** wherein determining the adjusted ambient light color based on the measured color comprises determining whether the color temperature of the ambient light falls within a predetermined range of color temperatures.

8. The method defined in claim **7** wherein the display control circuitry determines the adjusted ambient light color by extrapolating from a Planckian locus when the color temperature of the ambient light falls outside of the predetermined range of color temperatures.

9. The method defined in claim **7** wherein the predetermined range of color temperatures comprises color temperatures between 2,248 K and 15,000 K.

10. The method defined in claim **1** wherein the adjusted ambient light color is less saturated than the measured color.

11. The method defined in claim **1** wherein adjusting the white point of the display comprises automatically adjusting the color cast of the display based on the adjusted ambient light color.

12. The method defined in claim **1** wherein adjusting the white point of the display comprises shifting the white point of the display from a first white point to a second white point, wherein the second white point more closely matches the adjusted ambient light color than the first white point.

13. A method of operating a display in an electronic device having a color ambient light sensor and display control circuitry, comprising:

with the display control circuitry, gathering ambient light sensor data using the color ambient light sensor;

with the display control circuitry, determining a measured ambient light color based on the ambient light sensor data;

with the display control circuitry, determining whether the measured ambient light color is within an acceptable range of ambient light colors; and

with the display control circuitry, determining an ambient-adapted white point for the display based on the measured ambient light color and based on whether the measured ambient light color is within the acceptable range of ambient light colors.

14. The method defined in claim **13** further comprising:

in response to determining that the measured ambient light color is outside of the acceptable range of ambient light colors, determining an acceptable ambient light color based on the measured ambient light color, wherein the acceptable ambient light color is within the acceptable range of ambient light colors.

15. The method defined in claim **14** wherein the acceptable ambient light color has chromaticity coordinates that are located on a Planckian locus on a chromaticity diagram.

16. The method defined in claim **14** wherein the acceptable ambient light color and the measured ambient light color have the same color temperature.

17. The method defined in claim **14** wherein determining the ambient-adapted white point for the display comprises adjusting a color cast of the display to more closely match the acceptable ambient light color.

18. The method defined in claim **13** wherein determining the ambient-adapted white point for the display comprises adjusting a color cast of the display to more closely match the measured ambient light color in response to determining that the measured ambient light color is within the acceptable range of ambient light colors.

19. An electronic device, comprising:

a display;

a color ambient light sensor that gathers ambient light data; and

display control circuitry that determines a measured color of ambient light based on the ambient light data, determines an adjusted color based on the measured color, and adjusts a color cast of the display based on the adjusted color, wherein the adjusted color is less saturated than the measured color.

20. The electronic device defined in claim **19** wherein the display control circuitry adjusts the color cast of the display to more closely match the adjusted color.

21. The electronic device defined in claim **19** wherein the color ambient light sensor comprises a red detector that outputs red values, a green detector that outputs green values, and a blue detector that outputs blue values, wherein the display control circuitry determines a color temperature of the ambient light based on the red, green, and blue values, and wherein the adjusted color has a color temperature that matches the color temperature of the ambient light.

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