
Volume 33, issue 2, April 2012
ISSN NO 0141-9382
ELSEVIER
Displays
Assessing comfortable 3D visual environment based on human factors – Including Regular Articles
Guest Editor: Makoto Yoshizawa

Displays 33 (2012) 98–102

Contents lists available at SciVerse ScienceDirect

Displays

journal homepage: www.elsevier.com/locate/displa

Change of the observed binocular disparity of the moving 3D object in 3D technology based on the time-division

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ARTICLE INFO

Article history:
Received 29 September 2010
Received in revised form 18 August 2011
Accepted 5 October 2011
Available online 15 October 2011

Keywords:
3 Dimensional display
Shutter glass
Binocular disparity
Sub-frame
Time-sequential
Time-division

ABSTRACT

In 3D technology based on the time-division, the time difference exists between the observed images of the left and the right eye. When the moving 3D image is displayed, this time difference can cause the change of the observed binocular disparity and the perceived depth, compared with those of the static 3D images. The amount of the disparity change is investigated in consideration of 3D display and 3D capturing device. Detailed effect and methods of preventing this change are described.

1. Introduction

Nowadays, 3D applications are becoming more popular. And many products based on the various kinds of 3D technology are on market. Some of these 3D products are based on time-division of the left and the right images while other 3D products provide the left and the right images simultaneously [1–4]. In case of 3D product based on the time-division, each frame of duration of 1/60 s consists of two sub-frames for the left and the right images. As the left and the right images are displayed sequential for the duration of each sub-frame, the time difference of 1/120 s exists between the left and the right images. It is preferred to provide the similar 3D experience irrespective of the applied 3D technologies. Yet, Mach-Dvorak illusion had been known that the moving object appears displaced in depth when alternately observed by the two eyes [5]. And its effects on the stereoscopic display system had been reported to cause the artifact related to the depth perception [6,7].

In this paper, the phenomenon caused by this time difference is investigated in consideration of the sequence of the left and the right images for 3D display and the 3D capturing device. First, the change of observed binocular disparity due to this time difference is investigated for moving 3D object. The effect on the perceived depth with respect to the imaging display is considered for the cases where 3D object is in front of the screen or behind the imaging display. Secondly, the method of reducing the change of the perceived depth is proposed where 3D source image is modified in consideration of movement of 3D object.

2. Phenomenon

For the 3D display and 3D capture device, technologies based on the time-division as well as no time-division had been reported [1–3]. As an example of no time-division, the left and the right images are displayed simultaneously in case of 3D display using polarization eyeglass. On the other hand, in case of 3D display using the shutter glass (SG 3D), the left and the right image are displayed sequentially with the time difference of 1/120 s as shown in Fig. 1a. As for 3D capturing device, two cameras can be used simultaneously to capture the images at the left and the right viewing directions as shown Fig. 1b. Or only one camera can be used where the capturing directions or positions are alternated in time. These capturing devices will generate 3D image source without or with the time difference between the left and the right images. While it is difficult to predict which technologies will be dominant in the future, the products of SG 3D and 3D camera using two cameras are currently quite popular in market [4]. Hence, it is assumed in the following analysis that the left and the right images are captured at the same time and are displayed by SG 3D with the time difference of 1/120 s.

In 3D, the horizontal spatial difference between the positions L and R of the left and right images is generally called as the binocular disparity and induces the perception of depth as illustrated in Fig. 2. Perceived depth is determined by the intersection of two

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doi:10.1016/j.displa.2011.10.001

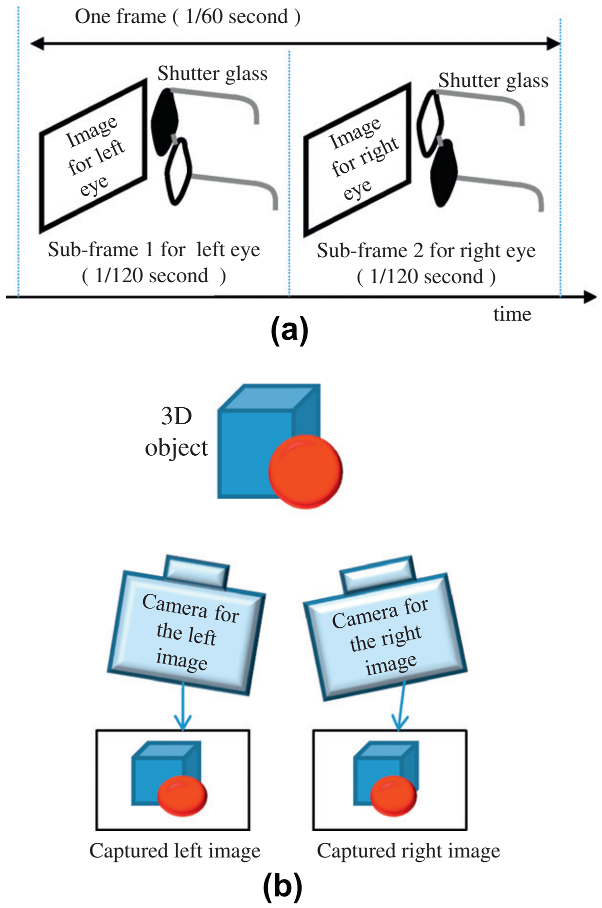

Fig. 1. (a) An example of time-division 3D display using the shutter glass where the left and the right images are displayed sequentially in synchronization with the ON/OFF of the shutter glass. These are observed sequentially by each side of the eye with the time difference of 1/120 s. (b) An example of 3D capturing device where two cameras capture the left and the right images simultaneously.

lines connecting each eye to 3D objects in the left and right images on the 3D display.

For the static 3D object with zero disparity, the left and the right image are displayed on the same positions, L and R. But for the moving 3D object with zero disparity, 3D object are displayed at the different position for each sub-frame. Fig. 3a illustrates the example of the moving 3D object that moves from the left side to the right side of the display along the horizontal direction. In SG 3D, the left and the rights images are displayed with the time difference of 1/120 s at the sub-frame 1 and 2, respectively as shown in Fig. 3b. At each sub-frame, only one eye can observe the displayed images and the other eye is blocked by the non-transparent state of shutter glass. If the eye movement is ignored and each eye in the blocked condition is assumed to watches the position L or R of the previous sub-frame, the distance between position L(N) and R(N) at sub-frame 1, L(N)–R(N) is different from the distance between position R(N) and position L(N + 1) at sub-frame 2, R(N)–L(N + 1). Thus, ignorance of the eye movement results in two binocular disparities which do not accord with the known 3D display performance.

It is known that the eye follows the movement of object steadily for the moving object [8]. In case of Flat Panel Display (FPD) where each image is renewed discretely in each frame, the eye of the observer is reported to watch the intermediate position between the positions of the two adjacent frames as the eye follows the movement of discretely displayed images [9–11]. When the moving 3D object is displayed on the 3D display, the same analysis can be applied. Hence, it is assumed that each eye follows the movement even when the eyes are blocked by the non-transparent shutter glasses. This assumption is also in accordance with the explanation of Mach-Dvorak illusion [5–7]. Fig. 4 represents the observed position at each sub-frame under this assumption. At the time of the sub-frame 2 of frame N that the right image is being displayed, the left eye watches the intermediate position L′of the positions L of frame N and N + 1, not watching positions L of frame N or N + 1. Similarly, the right eye watches the intermediate position R’ at the time of sub-frame 1 in which the left image is being displayed. The binocular disparity at sub-frame 1 is the distance between positions L and R′. The binocular disparity at sub-frame 2 is the distance between positions L′ and R. And the sizes of these two disparities are equal. So this is defined as the observed binocular disparity in this paper. Yet, this is different from the binocular disparity of original 3D image which is the distance between L and R.

3. Analysis and discussion

In case that the left and the right images are captured at the same time and are displayed by SG 3D sequentially, the difference of the observed and the original binocular disparity is equal to the half of moving distance between the adjacent two frames. This difference can cause the perceived depth to be different from the intended depth. How the perceived depth is affected by this difference, is illustrated in Fig. 5. It shows that the perceived depth of 3D object can be

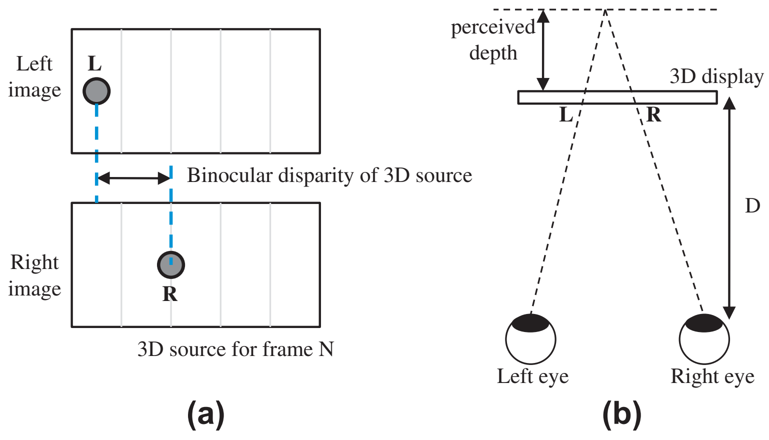

Fig. 2. (a) Binocular disparity of 3D source. (b) Relation between the perceived depth and the binocular disparity. L and R represent the position of 3D object for the left and the right eyes. *D* is the distance between the user and the 3D display.

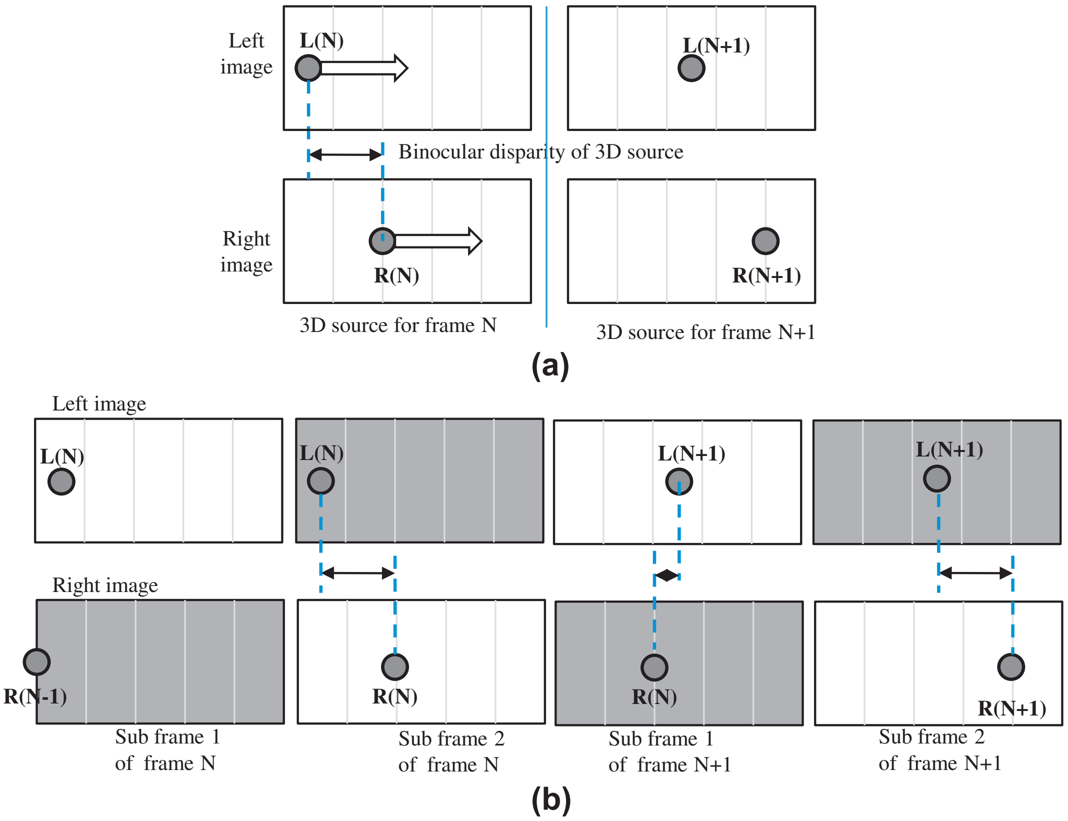

Fig. 3. Observations of the moving images under the assumption that each eye of the blocked state watches the position of the previous sub-frame. (a) An example of the moving 3D object which moves horizontally from the left side of the imaging display to the right side. (b) Positions of 3D object at each sub-frame. Upper and lower box represent the images for the left and the right eyes, respectively. At sub-frame 1, the right eye of the user is blocked by non-transparent state of shutter glass. At sub-frame 2, the left eye of the user is blocked. Solid circles represent the positions of the 3D object at each sub-frame.

either nearer or farther than the intended depth, depending on the moving direction. The difference between the intended and perceived depth can be written as follows.

$$\text{Depth difference} = \frac{\Delta \cdot D \cdot \mathrm{IOD}}{(\mathrm{IOD} + LR)(\mathrm{IOD} + LR - \Delta)} \qquad (1)$$

In Eq. (1), IOD (Inter Ocular Distance) represents the distance between two eyes where 65 mm is generally used. D represents the distance between the user and 3D display. LR represents the binocular disparity of 3D image source. Δ represents the change of the binocular disparity.

An example of the depth difference is calculated using Eq. (1) and shown in Fig. 6. *D* of 2 m and 3D TV of the diagonal size of 55 in. and the pixel pitch of 0.63 mm is assumed. 3D object is assumed to move horizontally from the left side to the right side with the speed of 10 pixels per frame. In this example, the change of the binocular disparity, Δ is $5 \times 0.63\ \text{mm} = 3.15\ \text{mm}$. Fig. 6 shows that the amount of the depth distortion increases for 3D object behind position of 3D display. The horizontal movement of 3D object will cause users to perceive 3D object of zero depth to be in front of the imaging display. As the moving speed determines the amount of the distortion, 3D object of the different moving speed and the same binocular disparity will be perceived to be located at the different depth.

While the above analysis is performed for 3D display of time-division and the 3D capturing device of no time-division, similar phenomena can happen for the other situations. The effects on the observed binocular disparity for the various combinations of the time-division and no time-division of 3D display and 3D capturing device are summarized in Table 1. In time-division method, the left image may occur before or after the right image. So these two cases are represented as 'left image first' and 'right image first'. These two cases have the different effect on the observed binocular disparity. If the sequence of the left and the image are opposite in 3D capturing device and the 3D display, the disparity change will increase further.

If the movement of 3D object in each frame can be estimated, this distortion can be reduced by the image modification where the left or the right images are shifted by the amount of Table 1. Estimating the movement of the images between two adjacent frames have been already used in FPD TV of higher than 120 Hz frame rate where the image sources of 24 or 60 Hz frame rate are converted into the images of higher frame rate [12]. Fig. 7b illustrates an example where the positions of 3D object of the right images are modified. When the modified images are displayed, the right eye following the motion of 3D object watches the positions R'_m as shown in Fig. 7c. The distance between the positions L and R'_m at sub-frame 1 is equal to the distance between the positions L' and R_m at sub-frame 2. This distance is also equal to the binocular disparity of the 3D image source. Therefore, the depth distortion of the moving 3D object illustrated in Figs. 4 and 5 can be prevented.

4. Conclusion

When either 3D capturing device or 3D display is based on time-division, the time difference of the 3D source and 3D display can cause the depth perception of the moving 3D object different from the intended one. This distortion of depth perception is re-

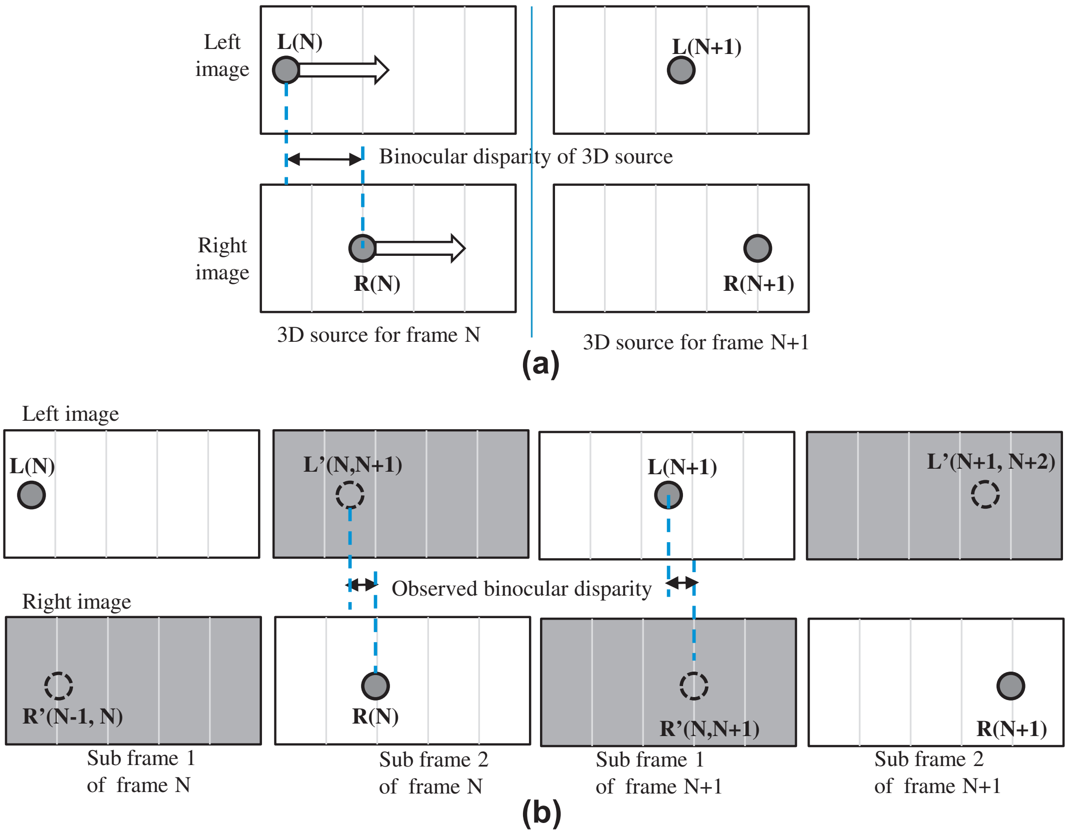

Fig. 4. Observations of the moving images under the assumption that each eye of the blocked state follows the movement of the 3D object. (a) Example of the moving 3D object. (b) Positions of 3D object at each sub-frame. Solid circles represent the positions of the 3D object at each sub-frame. Dotted circles represent the position on the 3D display that one eye watches at the time of the sub-frame that the image for the other eye is being displayed.

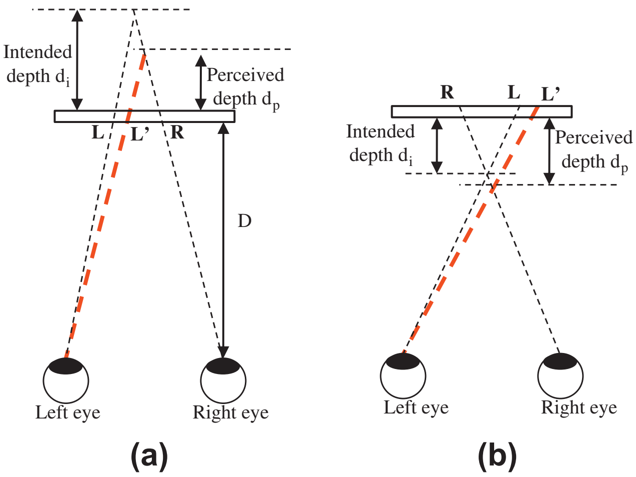

Fig. 5. Distortion of the perceived depth for 3D object that moves from left to right for the cases where. (a) 3D object is behind the screen and (b) 3D object is in front of the screen. For moving 3D object, left eye watches not the position L, but the position L′ at the time of the sub-frame 2 where the right image are being displayed. Hence, the perceived depth is different from the intended depth of 3D source. *D* is the distance between the user and the 3D display.

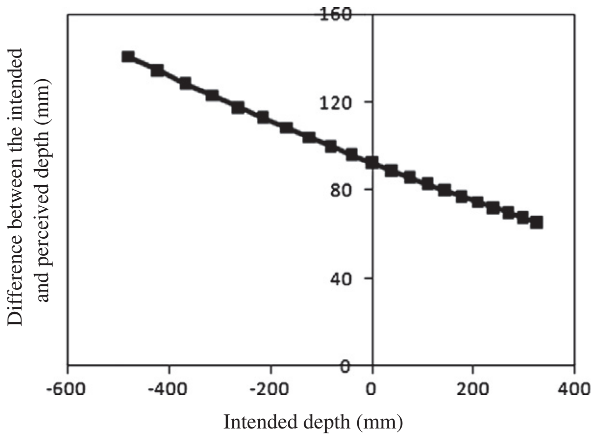

Fig. 6. Calculated differences between the intended and the perceived depth where 3D object moves with the scroll speed of 10 pixels per frame from the left side to the right side of the imaging display. (+) and (−) of the intended depth represent 3D object behind and in front of the screen, respectively.

Table 1
Disparity change due to the time difference of the left and the right images for 3D capturing device and 3D display.

	3D Capturing device		
	Time-division (left image first)	Time-division (right image first)	No time-division
3D display			
Time-division (left image first)	0	2Δ	Δ
Time-division (reft image first)	2Δ	0	Δ
No time-division	Δ	Δ	0

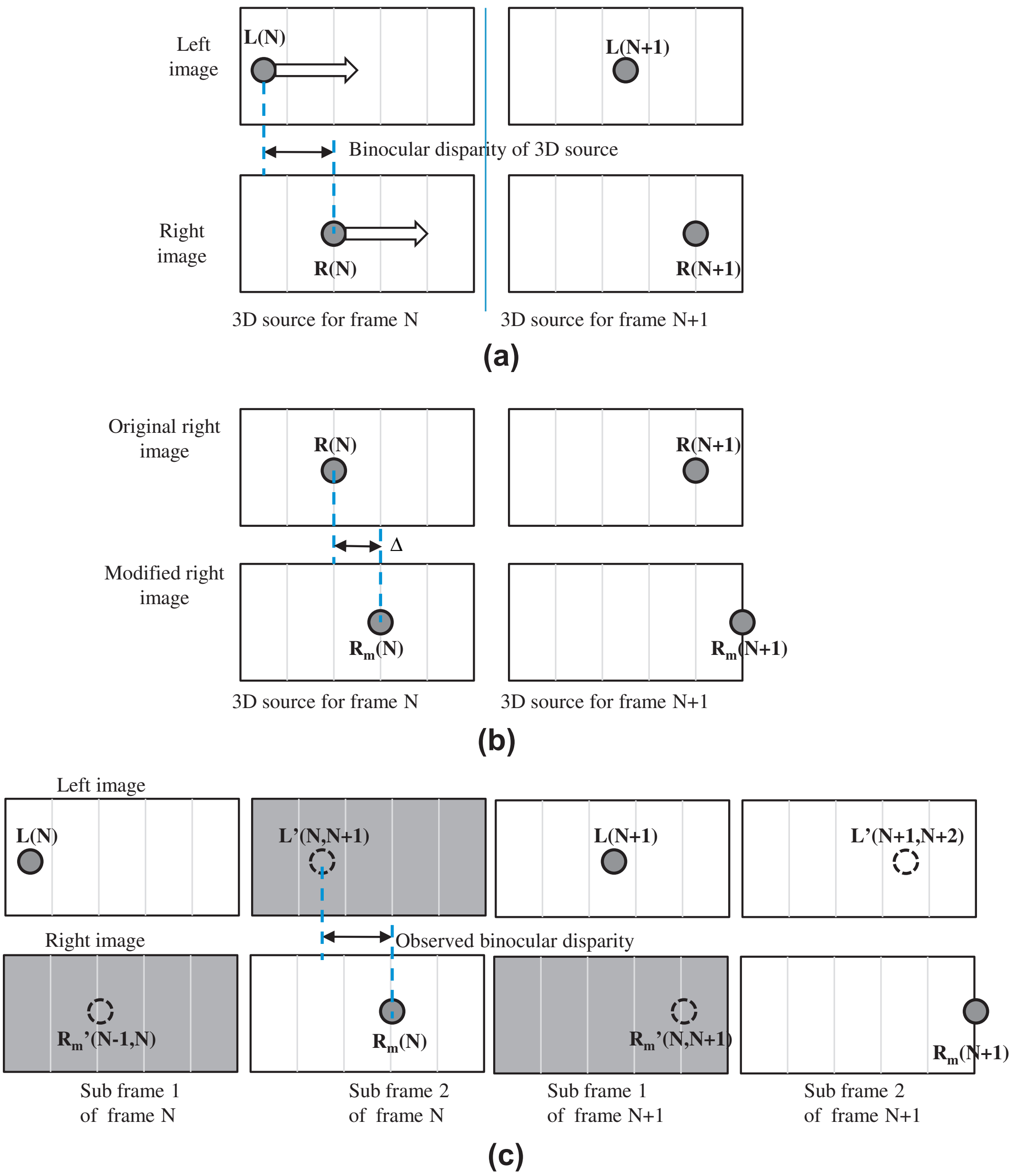

Fig. 7. 3 (a) Example of the moving 3D object which moves from the left side of the imaging display to the right side. (b) Modification of the right image to compensate the observed binocular disparity of Fig. 4c. Observed binocular disparity which is equal to that of the original 3D source. Dotted circles represent the position on the screen that one eye watches when the image for the other is being displayed.

lated the moving speed and the initial binocular disparity of 3D object.

When the movement between the adjacent frames is estimated and 3D image sources are modified in consideration of this movement, the distortion of depth perception can be prevented.

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