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Hierarchical Cellular Automata for Visual Saliency

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Abstract
Saliency detection, finding the most important parts of an image, has become increasingly popular in computer vision. In this paper, we introduce Hierarchical Cellular Automata (HCA)—a temporally evolving model to intelligently detect salient objects. HCA consists of two main components: Single-layer Cellular Automata (SCA) and Cuboid Cellular Automata (CCA). As an unsupervised propagation mechanism, Single-layer Cellular Automata can exploit the intrinsic relevance of similar regions through interactions with neighbors. Low-level image features as well as high-level semantic information extracted from deep neural networks are incorporated into the SCA to measure the correlation between different image patches. With these hierarchical deep features, an impact factor matrix and a coherence matrix are constructed to balance the influences on each cell's next state. The saliency values of all cells are iteratively updated according to a well-defined update rule. Furthermore, we propose CCA to integrate multiple saliency maps generated by SCA at different scales in a Bayesian framework. Therefore, single-layer propagation and multi-scale integration are jointly modeled in our unified HCA. Surprisingly, we find that the SCA can improve all existing methods that we applied it to, resulting in a similar precision level regardless of the original results. The CCA can act as an efficient pixel-wise aggregation algorithm that can integrate state-of-the-art methods, resulting in even better results. Extensive experiments on four challenging datasets demonstrate that the proposed algorithm outperforms state-of-the-art conventional methods and is competitive with deep learning based approaches.

Keywords Saliency detection · Hierarchical Cellular Automata · Deep contrast features · Bayesian framework

1 Introduction

Humans excel in identifying visually significant regions in a scene corresponding to salient objects. Given an image, people can quickly tell what attracts them most. In the field of computer vision, however, performing the same task is very challenging, despite dramatic progress in recent years. To mimic the human attention system, many researchers focus on developing computational models that locate regions of interest in the image. Since accurate saliency maps can assign relative importance to the visual contents in an image, saliency detection can be used as a pre-processing procedure to narrow the scope of visual processing and reduce the cost of computing resources. As a result, saliency detection has raised a great amount of attention (Achanta et al. 2009; Goferman et al. 2010) and has been incorporated into various computer vision tasks, such as visual tracking (Mahadevan and Vasconcelos 2009), object retargeting (Ding et al. 2011; Sun and Ling 2011) and image categorization (Siagian and Itti 2007; Kanan and Cottrell 2010). Results in perceptual research show that contrast is one of the decisive factors in the human visual attention system (Itti and Koch 2001; Reinagel and Zador 1999), suggesting that salient objects are most likely in the region of the image that significantly differs from its surroundings. Many conventional saliency detection methods focus on exploiting local and global con-

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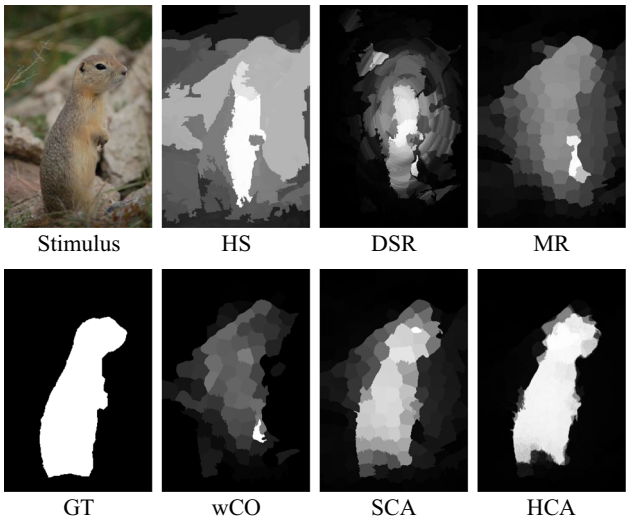


Fig. 1 An example illustrates that conventional saliency detection methods based on handcrafted low-level features fail in complex circumstances. From top left to bottom right: stimulus, HS (Yan et al. 2013), DSR (Li et al. 2013), MR (Yang et al. 2013), ground truth, wCO (Zhu et al. 2014), and our method SCA and HCA

trast based on various handcrafted image features, e.g., color features (Liu et al. 2011; Cheng et al. 2015), focusness (Jiang et al. 2013c), textual distinctiveness (Scharfenberger et al. 2013), and structure descriptors (Shi et al. 2013). Although these methods perform well on simple benchmarks, they may fail in some complex situations where the handcrafted low-level features do not help salient objects stand out from the background. For example, in Fig. 1, the prairie dog is surrounded by low-contrast rocks and bushes. It is challenging to detect the prairie dog as a salient object with only low-level saliency cues. However, humans can easily recognize the prairie dog based on its category as it is semantically salient in high-level cognition and understanding.

In addition to the limitation of low-level features, the large variations in object scales also restrict the accuracy of saliency detection. An appropriate scale is of great importance in extracting the salient object from the background. One of the most popular ways to detect salient objects of different sizes is to construct multi-scale saliency maps and then aggregate them with pre-defined functions, such as averaging or a weighted summation. In most existing methods (Wang et al. 2016; Li and Yu 2015; Li et al. 2014a; Zhou et al. 2014; Borji et al. 2015), however, these constructed saliency maps are usually integrated in a simple and heuristic way, which may directly limit the precision of saliency aggregation.

To address these two obvious problems, we propose a novel method named Hierarchical Cellular Automata (HCA) to extract the salient objects from the background efficiently. A Hierarchical Cellular Automata consists of two main components: Single-layer Cellular Automata (SCA) and Cuboid Cellular Automata (CCA). First, to improve the features, we use fully convolutional networks (Long et al. 2015) to extract deep features due to their successful application to semantic segmentation. It has been demonstrated that *deep features* are highly versatile and have stronger representational power than traditional handcrafted features (Krizhevsky et al. 2012; Farabet et al. 2013; Girshick et al. 2014). Low-level image features and high-level saliency cues extracted from deep neural networks are used by an SCA to measure the similarity of neighbors. With these hierarchical deep features, the SCA iteratively updates the saliency map through interactions with similar neighbors. Then the salient object will naturally emerge from the background with high consistency among similar image patches. Secondly, to detect multi-scale salient objects, we apply the SCA at different scales and integrate them with the CCA based on Bayesian inference. Through interactions with neighbors in a cuboid zone, the integrated saliency map can highlight the foreground and suppress the background. An overview of our proposed HCA is shown in Fig. 2.

Furthermore, the Hierarchical Cellular Automata is capable of optimizing other saliency detection methods. If a saliency map generated by one of the existing methods is used as the prior map and fed into HCA, it can be improved to the state-of-the-art precision level. Meanwhile, if multiple saliency maps generated by different existing methods are used as initial inputs, HCA can naturally fuse these saliency maps and achieve a result that outperforms each method.

In summary, the main contributions of our work include:

(1) We propose a novel Hierarchical Cellular Automata to adaptively detect salient objects of different scales based on hierarchical deep features. The model effectively improves all of the methods we have applied it to to state-of-the-art precision levels and is relatively insensitive to the original maps.
(2) Single-layer Cellular Automata serve as a propagation mechanism that exploits the intrinsic relevance of similar regions via interactions with neighbors.
(3) Cuboid Cellular Automata can integrate multiple saliency maps into a more favorable result under the Bayesian framework.

2 Related Work

2.1 Salient Object Detection

Methods of saliency detection can be divided into two categories: top-down (task-driven) methods and bottom-up (data-driven) methods. Approaches like (Alexe et al. 2010; Marchesotti et al. 2009; Ng et al. 2002; Yang and Yang 2012) are typical top-down visual attention methods that require supervised learning with manually labeled ground truth. To

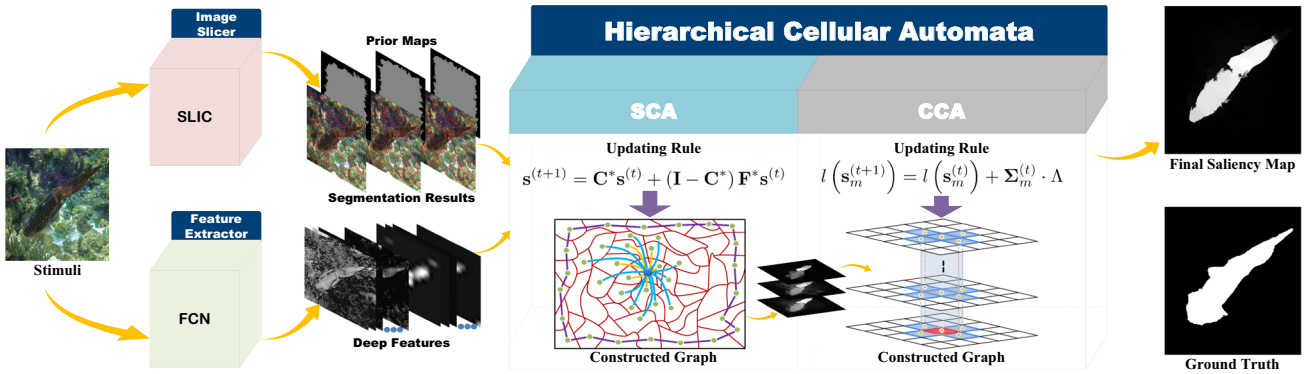


Fig. 2 The pipeline of our proposed Hierarchical Cellular Automata. First, the stimulus is segmented into multi-scale superpixels, and superpixels on the image boundary are selected as seeds for the propagation of the background (Sect. 3.1). Then FCN-32s (Long et al. 2015) is used as a feature extractor to obtain deep features (Sect. 3.2). The generated prior maps and deep features are both fed into the Single-Layer Cellular Automata (Sect. 3.3.1) to create multi-scale saliency maps. Finally, we integrate these saliency maps via the Cuboid Cellular Automata (Sect. 3.3.2) to obtain our ultimate result

better distinguish salient objects from the background, high-level category-specific information and supervised methods are incorporated to improve the accuracy of saliency maps. In contrast, bottom-up methods usually concentrate on low-level cues such as color, intensity, texture and orientation to construct saliency maps (Hou and Zhang 2007; Jiang et al. 2011; Klein and Frintrop 2011; Sun et al. 2012; Tong et al. 2015; Yan et al. 2013). Some global bottom-up approaches tend to build saliency maps by calculating the holistic statistics on uniqueness of each element over the whole image (Cheng et al. 2015; Perazzi et al. 2012; Bruce and Tsotsos 2005).

As saliency is defined as a particular part of an image that visually stands out compared to their neighboring regions or the rest of image, one of the most used principles, *contrast prior*, measures the saliency of a region according to the color contrast or geodesic distance against its surroundings (Cheng et al. 2013, 2015; Jiang et al. 2011; Jiang and Davis 2013; Klein and Frintrop 2011; Perazzi et al. 2012; Wang et al. 2011). Recently, the *boundary prior* has been introduced in several methods based on the assumption that regions along the image boundaries are more likely to be the background (Jiang et al. 2013b; Li et al. 2013; Wei et al. 2012; Yang et al. 2013; Borji et al. 2015; Shen and Wu 2012), although this takes advantage of photographer's bias and is less likely to be true for active robots. Considering the connectivity of regions in the background, Wei et al. (2012) define the saliency value for each region as the shortest-path distance towards the boundary. Yang et al. (2013) use manifold ranking to infer the saliency score of image regions according to their relevance to boundary superpixels. Furthermore, in (Jiang et al. 2013a), the contrast against the image border is used as a new regional feature vector to characterize the background.

However, one of the fundamental problems with all these conventional saliency detection methods is that the features used are not representative enough to capture the contrast between foreground and background, and this limits the precision of saliency detection. For one thing, low-level features cannot help salient objects stand out from a low-contrast background with similar visual appearance. Also, the extracted global features are weak in capturing semantic information and have much poorer generalization compared to the deep features used in this paper.

2.2 Deep Neural Networks

Deep convolutional neural networks have recently achieved a great success in various computer vision tasks, including image classification (Krizhevsky et al. 2012; Szegedy et al. 2015), object detection (Girshick et al. 2014; Hariharan et al. 2014; Szegedy et al. 2013) and semantic segmentation (Long et al. 2015; Pinheiro and Collobert 2014). With the rapid development of deep neural networks, researchers have begun to construct effective neural networks for saliency detection (Zhao et al. 2015; Li and Yu 2015; Zou and Komodakis 2015; Wang et al. 2015; Li et al. 2016; Kim and Pavlovic 2016). In (Zhao et al. 2015), Zhao *et al.* propose a unified multi-context deep neural network taking both global and local context into consideration. Li *et al.* (Li and Yu 2015) and Zou *et al.* (Zou and Komodakis 2015) explore high-quality visual features extracted from DNNs to improve the accuracy of saliency detection. DeepSaliency in (Li et al. 2016) is a multi-task deep neural network using a collaborative feature learning scheme between two correlated tasks, saliency detection and semantic segmentation, to learn better feature representation. One leading factor for the success of deep neural networks is the powerful expressibility and

strong capacity of deep architectures that facilitate learning high-level features with semantic information (Hariharan et al. 2015; Ma et al. 2015).

In (Donahue et al. 2014), Donahue *et al.* point out that features extracted from the activation of a deep convolutional network can be repurposed to many other generic tasks. Inspired by this idea, we use the hierarchical deep features extracted from fully convolutional networks (Long et al. 2015) to represent smaller image regions. The extracted deep features incorporate low-level features as well as high-level semantic information of the image and can be fed into our Hierarchical Cellular Automata to measure the similarity of different image patches.

2.3 Cellular Automata

Cellular Automata are a model of computation first proposed by Von Neumann (1951). They can be described as a temporally evolving system with simple construction but complex self-organizing behavior. A Cellular Automaton consists of a lattice of cells with discrete states, which evolve in discrete time steps according to specific rules. Each cell needs to make a decision on its next state in order to survive in the environment. How to make a better decision? The simpliest way is to hold the current state forever. However, it is not wise as there will be no improvements. Intuitively, we can see the nearest neighbors' states as a reference. If we are similar, then we should have similar states; otherwise, we should have different states. Therefore, at each time step, each cell intends to make a wise decision for its next state based on its current state as well as its neighbors'. Cellular Automata have been applied to simulate the evolution of many complicated dynamical systems (Batty 2007; Chopard and Droz 2005; Cowburn and Welland 2000; Almeida et al. 2003; Martins 2008; Pan et al. 2016).

Considering that salient objects are spatially coherent, we introduce Cellular Automata into this field as an unsupervised propagation mechanism. For saliency detection, we treat the saliency map as a dynamic system and the saliency values will be considered as the cell's states. The saliency value will evolve as time goes by in order to get a better saliency map, in other words, to make the dynamic system more stable. Because most salient objects in the images share similar feature representations as well as similar saliency values, we propose Single-layer Cellular Automata to exploit the intrinsic relationships of neighboring elements of the saliency map and eliminate gaps between similar regions. Furthermore, it can be observed that there is a high contrast between salient objects and its surrounding backgrounds in the feature space. Through interacting with neighbors, it is easy for the dynamic system to differentiate the foreground and background.

In addition, we propose a method to combine multiple saliency maps generated by different algorithms, or combine saliency maps at different scales through what we call Cuboid Cellular Automata (CCA). In CCA, states of the automaton are determined by a cuboid neighborhood corresponding to automata at the same location as well as their adjacent neighbors in different saliency maps. An illustration of the idea is in Fig. 3b. In this setting, the saliency maps are iteratively updated through interactions among neighbors in the cuboid zone. The state updates are determined through Bayesian evidence combination rules. Variants of this type of approach have been used before (Rahtu et al. 2010; Xie and Lu 2011; Xie et al. 2013; Li et al. 2013). Xie et al. (2013) use the low-level visual cues derived from a convex hull to compute the observation likelihood. Li et al. (2013) construct saliency maps through dense and sparse reconstruction and propose a Bayesian algorithm to combine them. Using Bayesian updates to combine saliency maps puts the algorithm for Cuboid Cellular Automata on a firm theoretical foundation.

3 Proposed Algorithm

In this paper, we propose an unsupervised Hierarchical Cellular Automata (HCA) for saliency detection, composed of two sub-units, a Single-layer Cellular Automata (SCA), and a Cuboid Cellular Automata (CCA), as described below. First, we construct prior maps of different scales with superpixels on the image boundary chosen as the background seeds. Then, hierarchical deep features are extracted from fully convolutional networks (Long et al. 2015) to measure the similarity of different superpixels. Next, we use SCA to iteratively update the prior maps at different scales based on the hierarchical deep features. Finally, a CCA is used to integrate the multi-scale saliency maps using Bayesian evidence combination. Figure 2 shows an overview of our proposed method.

3.1 Background Priors

Recently, there have been various mathematical models proposed to generate a coarse saliency map to help locate potential salient objects in an image (Tong et al. 2015a; Zhu et al. 2014; Gong et al. 2015). Even though prior maps are effective in improving detection precision, they still have several drawbacks. For example, a poor prior map may greatly limit the accuracy of the final saliency map if it incorrectly estimates the location of the objects or classifies the foreground as the background. Also, the computational time to construct a prior map can be excessive. Therefore, in this paper, we build a quite simple and time-efficient prior map that only provides the propagation seeds for HCA, which is quite insensitive to the prior map and is able to refine this coarse prior map into an improved saliency map.

First, we use the efficient Simple Linear Iterative Clustering (SLIC) algorithm (Achanta et al. 2010) to segment the image into smaller superpixels in order to capture the essential structural information of the image. Let $s_i \in \mathbb{R}$ denote the saliency value of the superpixel i in the image. Based on the assumption that superpixels on the image boundary tend to have a higher probability of being the background, we assign a close-to-zero saliency value to the boundary superpixels. For others, we assign a uniform value as their initial saliency values,

$$s_i = \begin{cases} 0.001 & i \in \text{boundary} \\ 0.5 & i \notin \text{boundary}. \end{cases} \quad (1)$$

Considering the great variation in the scales of salient objects, we segment the image into superpixels at M different scales, which are displayed in Fig. 2 (*Prior Maps*).

3.2 Deep Features from FCN

As is well-known, the features in the last layers of CNNs encode semantic abstractions of objects, and are robust to appearance variations, while the early layers contain low-level image features, such as color, edge, and texture. Although high-level features can effectively discriminate the objects from various backgrounds, they cannot precisely capture the fine-grained low-level information due to their low spatial resolution. Therefore, a combination of these deep features is preferred compared to any individual feature map.

In this paper, we use the feature maps extracted from the fully-convolutional network (FCN-32s (Long et al. 2015)) to encode object appearance. The input image to FCN-32s is resized to 500×500, and a 100-pixel padding is added to the four boundaries. Due to subsampling and pooling operations in the CNN, the outputs of each convolutional layer in the FCN framework are not at the same resolution. Since we only care about the features corresponding to the original image, we need to (1) crop the feature maps to get rid of the padding; (2) resize each feature map to the input image size via the nearest neighbor interpolation. Then each feature map can be aggregated using a simple linear combination as:

$$g(\mathbf{r}_i, \mathbf{r}_j) = \sum_{l=1}^{L} \rho_l \cdot \|df_i^l - df_j^l\|_2, \quad (2)$$

where df_i^l denotes the deep features of superpixel i on the l-th layer and ρ_l is a weighting of the importance of the l-th feature map, which we set by cross-validation. The weights are constrained to sum to 1: $\sum_{l=1}^{L} \rho_l = 1$. Each superpixel is represented by the mean of the deep features of all contained pixels. The computed $g(\mathbf{r}_i, \mathbf{r}_j)$ is used to measure the similarity between superpixels.

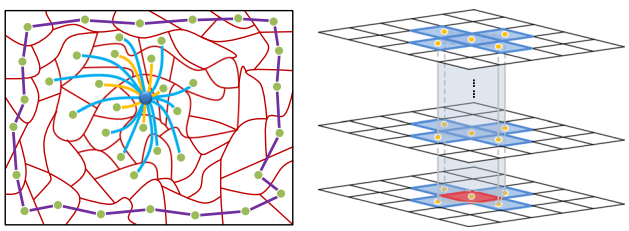
3.3 Hierarchical Cellular Automata

Hierarchical Cellular Automata (HCA) is a unified framework composed of single-layer propagation (Single-layer Cellular Automata) and multi-scale aggregation (Cuboid Cellular Automata). It can generate saliency maps at different scales and integrate them to get a fine-grained saliency map. We will discuss SCA and CCA respectively in Sects. 3.3.1 and 3.3.2.

3.3.1 Single-Layer Cellular Automata

In Single-layer Cellular Automata (SCA), each cell denotes a superpixel generated by the SLIC algorithm. SLIC takes the number of desired superpixels as a parameter, so by using different numbers of superpixels with SCA, we can obtain maps at different scales. In this section, we assume one scale, denoted m. We represent the number of superpixels in scale m as n_m, but we omit the subscript m in most notations in this section for clarity, *e.g.*, $\mathbf{F}$ for $\mathbf{F}_m$, $\mathbf{C}$ for $\mathbf{C}_m$ and $\mathbf{s}$ for $\mathbf{s}_m$. Different superpixel scales are treated independently.

We make three major modifications to the previous cellular automata models (Smith 1972; Von Neumann 1951) for saliency detection. First, the states of cells in most existing Cellular Automata models are discrete (Von Neumann et al. 1966; Wolfram 1983). However, in this paper, we use the saliency value of each superpixel as its state, which is continuous between 0 and 1. Second, we give a broader definition of the neighborhood that is similar to the concept of z-layer neighborhood (here $z = 2$) in graph theory. The z-layer neighborhood of a cell includes adjacent cells as well as those sharing common boundaries with its adjacent cells. Also, we assume that superpixels on the image boundaries are all connected to each other because all of them serve as background seeds. The connections between the neighbors are clearly illustrated in Fig. 3a. Finally, instead of uniform



(a) **(b)**

Fig. 3 The constructed graph models used in our algorithm. **a** Is used in SCA, the orange lines and the blue lines represent the connections between the blue center cell and its 2-layer neighbors. The purple lines indicate that superpixels on the image boundaries are all connected to each other; **b** is used in CCA, a cell (e.g. the red pixel in the bottom layer) is connected to the pixels with the same coordinates in other layers as well as their four adjacent neighbors (e.g. cells in blue color). All these pixels construct a cuboid interaction zone (Color figure online)

influence of the neighbors , the influence is based on the similarity between the neighbor to the cell in feature space, as explained next.

Impact Factor Matrix Intuitively, neighbors with more similar features have a greater influence on the cell's next state. The similarity of any pair of superpixels is measured by a predefined distance in feature space. For the m-th saliency map, which has n_m superpixels in total, we construct an impact factor matrix $\mathbf{F} \in \mathbb{R}^{n_m \times n_m}$. Each element f_{ij} in $\mathbf{F}$ defines the impact factor of superpixel i to j as:

$$f_{ij} = \begin{cases} \exp(\frac{-g(\mathbf{r}_i, \mathbf{r}_j)}{\sigma_f^2}) & j \in \mathrm{NB}(i) \\ 0 & j = i \text{ or otherwise,} \end{cases} \tag{3}$$

where $g(\mathbf{r}_i, \mathbf{r}_j)$ is a function that computes the distance between the superpixel i and j in feature space with $\mathbf{r}_i$ as the feature descriptor of superpixel i. In this paper, we use the weighted distance of hierarchical deep features computed by Eq. (2) to measure the similarity between neighbors. σ_f is a parameter that controls the strength of similarity and $\mathrm{NB}(i)$ is the set of the neighbors of the cell i. In order to normalize the impact factors, a degree matrix $\mathbf{D} = diag\{d_1, d_2, \ldots, d_{n_m}\}$ is constructed, where $d_i = \sum_j f_{ij}$. Finally, a row-normalized impact factor matrix can be calculated as $\mathbf{F}^* = \mathbf{D}^{-1} \cdot \mathbf{F}$.

Coherence Matrix Given that each cell's next state is determined by its current state as well as its neighbors, we need to balance the importance of these two factors. On the one hand, if a superpixel is quite different from all its neighbors in the feature space, its next state will be primarily based on itself. On the other hand, if a cell is similar to its neighbors, it should be assimilated by the local environment. To this end, we build a coherence matrix $\mathbf{C} = diag\{c_1, c_2, \ldots, c_{n_m}\}$ to promote the evolution among all cells. Each cell's coherence towards its current state is initially computed as: $c_i = \frac{1}{\max(f_{ij})}$, so it is inversely proportional to its maximum similarity to its neighbors. As c_i represents the coherence of the current state, we normalize it to be in a range $c_i \in [\, b\, , a + b\,]$, where $[\, b\, , a + b\,] \subseteq [\, 0, 1\,]$, via:

$$c_i^* = a \cdot \frac{c_i - \min\left(c_j\right)}{\max\left(c_j\right) - \min\left(c_j\right)} + b, \tag{4}$$

where the min and max are computed over $j = 1, 2, \ldots, n_m$. Based on preliminary experiments, we empirically set the parameters a and b in Eq. (4) to be 0.9 and 0. The final, normalized coherence matrix is then: $\mathbf{C}^* = diag\{c_1^*, c_2^*, \ldots, c_{n_m}^*\}$.

Synchronous Update Rule In the existing Cellular Automata models, all cells will simultaneously update their states according to the update rule, which is a key point in Cellular Automata, as it controls whether the ultimate evolving state is chaotic or stable (Wolfram 1983). Here, we define the synchronous update rule based on the impact factor matrix $\mathbf{F}^* \in \mathbb{R}^{n_m \times n_m}$ and coherence matrix $\mathbf{C}^* \in \mathbb{R}^{n_m \times n_m}$:

$$\mathbf{s}^{(t+1)} = \mathbf{C}^* \mathbf{s}^{(t)} + \left(\mathbf{I} - \mathbf{C}^*\right) \mathbf{F}^* \mathbf{s}^{(t)}, \tag{5}$$

where $\mathbf{I}$ is the identity matrix of dimension $n_m \times n_m$ and $\mathbf{s}^{(t)} \in \mathbb{R}^{n_m}$ denotes the saliency map at time t. When $t = 0$, $\mathbf{s}^{(0)}$ is the prior map generated by the method introduced in Sect. 3.1. After T_S time steps (a time step is defined as one update of all cells), the saliency map can be represented as $\mathbf{s}^{(T_S)}$. It should be noted that the update rule is invariant over time; only the cells' states $\mathbf{s}^{(t)}$ change over iterations.

Our synchronous update rule is based on the generalized intrinsic characteristics of most images. First, superpixels belonging to the foreground usually share similar feature representations. By exploiting the correlation between neighbors, the SCA can enhance saliency consistency among similar regions and develop a steady local environment. Second, it can be observed that there is a high contrast between the object and its surrounding background in feature space. Therefore, a clear boundary will naturally emerge between the object and the background, as the cell's saliency value is greatly influenced by its similar neighbors. With boundary-based prior maps, salient objects can be naturally highlighted after the evolution of the system due to the connectivity and compactness of the object, as exemplified in Fig. 4. Specifically, even though part of the salient object is incorrectly selected as the background seed, the SCA can adaptively increase their saliency values under the influence of the local environment. The last three columns in Fig. 4 show that when the object touches the image boundary, the results achieved by the SCA are still satisfying.

Fig. 4 Saliency maps generated by SCA ($n_m = 200$). The first three columns show that salient objects can be precisely detected when the saliency appears in the center of the image. The last three columns indicate that SCA can still have good performance even when salient objects touch the image boundary

3.3.2 Cuboid Cellular Automata

To better capture the salient objects of different scales, we propose a novel method named Cuboid Cellular Automata (CCA) to incorporate M different saliency maps generated

by SCA under M scales, each of which serves as a layer of the Cuboid Cellular Automata. In CCA, each cell corresponds to a pixel, and the saliency values of all pixels constitute the set of cells' states. The number of all pixels in an image is denoted as H. Unlike the definition of a neighborhood in Multi-layer Cellular Automata in (Qin et al. 2015), where each pixel will only be influenced by the pixels with the same coordination on other saliency maps, in CCA, we enlarge the neighborhood into a cuboid zone. Here pixels with the same coordinates in different saliency maps as well as their 4-connected pixels are all regarded as neighbors. That is, for any cell in a saliency map, it should have $5M-1$ neighbors, constructing a cuboid interaction zone. The hierarchical graph is presented in Fig. 3b to illustrate the connections between neighbors. The idea that we want to enlarge the influential zone is inspired by the success of SCA, which indicates that the neighboring pixels will have a good impact on the evolution of the saliency map.

In Cuboid Cellular Automata, the saliency value of pixel i in the m-th saliency map at time t is its probability of being the foreground F, represented as $s_{m,i}^{(t)} = P(i \in_m^{(t)} F)$, while $1-s_{m,i}^{(t)}$ is its probability of being the background B, denoted as $1-s_{m,i}^{(t)} = P(i \in_m^{(t)} B)$. We binarize each map with an adaptive threshold using Otsu's method (Otsu 1975), which is computed from the initial saliency map and does not change over time. The threshold of the m-th saliency map is denoted by γ_m. If pixel i in the m-th binary map is classified as foreground at time t ($s_{m,i}^{(t)} \geq \gamma_m$), then it will be denoted as $\eta_{m,i}^{(t)} = +1$. Correspondingly, $\eta_{m,i}^{(t)} = -1$ means that pixel i is binarized as background ($s_{m,i}^{(t)} < \gamma_m$).

If pixel i belongs to the foreground, the probability that one of its neighboring pixels j in the m-th binary map is classified as foreground at time t is denoted as $P(\eta_{m,j}^{(t)} = +1 | i \in_m^{(t)} F)$. In the same way, the probability $P(\eta_{m,j}^{(t)} = -1 | i \in_m^{(t)} B)$ represents that the pixel j is binarized as B conditioned on that pixel i belongs to the background at time t. We make the simplifying assumption that $P(\eta_{m,j}^{(t)} = +1 | i \in_m^{(t)} F)$ is the same for all the pixels in any saliency map and it does not change over time. Additionally, it is reasonable to assume that $P(\eta_{m,j}^{(t)} = +1 | i \in_m^{(t)} F) = P(\eta_{m,j}^{(t)} = -1 | i \in_m^{(t)} B)$ if we simply consider to be the foreground and to be the background as two choices with the same probability. Then we can use a constant λ to denote these two probablities:

$$P(\eta_{m,j}^{(t)} = +1 | i \in_m^{(t)} F) = P(\eta_{m,j}^{(t)} = -1 | i \in_m^{(t)} B) = \lambda. \tag{6}$$

Then the posterior probability $P(i \in_m^{(t)} F | \eta_{m,j}^{(t)} = +1)$ can be calculated as follows:

$$\begin{aligned} & P\left(i \in_m^{(t)} F \,\middle|\, \eta_{m,j}^{(t)} = +1\right) \\ \propto\ & P\left(i \in_m^{(t)} F\right) P\left(\eta_{m,j}^{(t)} = +1 \,\middle|\, i \in_m^{(t)} F\right) \\ =\ & s_{m,i}^{(t)} \cdot \lambda \end{aligned} \tag{7}$$

In order to get rid of the normalizing constant in Eq. (7), we define the prior ratio $\Omega(i \in_m^{(t)} F)$ as:

$$\Omega\left(i \in_m^{(t)} F\right) = \frac{P\left(i \in_m^{(t)} F\right)}{P\left(i \in_m^{(t)} B\right)} = \frac{s_{m,i}^{(t)}}{1-s_{m,i}^{(t)}}. \tag{8}$$

Combining Eq. (7) and Eq. (8), the posterior ratio $\Omega(i \in_m^{(t)} F \mid \eta_{m,j}^{(t)} = +1)$ turns into:

$$\begin{aligned} \Omega\left(i \in_m^{(t)} F \,\middle|\, \eta_{m,j}^{(t)} = +1\right) &= \frac{P\left(i \in_m^{(t)} F \,\middle|\, \eta_{m,j}^{(t)} = +1\right)}{P\left(i \in_m^{(t)} B \,\middle|\, \eta_{m,j}^{(t)} = +1\right)} \\ &= \frac{s_{m,i}^{(t)}}{1-s_{m,i}^{(t)}} \cdot \frac{\lambda}{1-\lambda}. \end{aligned} \tag{9}$$

As the posterior probability $P(i \in_m^{(t)} F | \eta_{m,j}^{(t)} = +1)$ represents the probability of pixel i of being the foreground F conditioned on that its neighboring pixel j in the m-th saliency map is binarized as foreground at time t, $P(i \in_m^{(t)} F | \eta_{m,j}^{(t)} = +1)$ can also be used to represent the probability of pixel i of being the foreground F at time $t+1$. Then,

$$s_{m,i}^{(t+1)} = P(i \in_m^{(t)} F | \eta_{m,j}^{(t)} = +1). \tag{10}$$

According to Eq. (9) and Eq. (10), we can get:

$$\begin{aligned} \frac{s_{m,i}^{(t+1)}}{1-s_{m,i}^{(t+1)}} &= \frac{P(i \in_m^{(t)} F | \eta_{m,j}^{(t)} = +1)}{1-P(i \in_m^{(t)} F | \eta_{m,j}^{(t)} = +1)} \\ &= \frac{P(i \in_m^{(t)} F | \eta_{m,j}^{(t)} = +1)}{P(i \in_m^{(t)} B | \eta_{m,j}^{(t)} = +1)} \\ &= \frac{s_{m,i}^{(t)}}{1-s_{m,i}^{(t)}} \cdot \frac{\lambda}{1-\lambda}. \end{aligned} \tag{11}$$

It is much easier to deal with the logarithm of this quantity because the changes in logodds will be additive. So Eq. (11) turns into:

$$l\left(s_{m,i}^{(t+1)}\right) = l\left(s_{m,i}^{(t)}\right) + \Lambda, \tag{12}$$

where $l\left(s_{m,i}^{(t+1)}\right) = \ln\left(\frac{s_{m,i}^{(t+1)}}{1-s_{m,i}^{(t+1)}}\right)$ and $\Lambda = \ln(\frac{\lambda}{1-\lambda})$ is a constant. The intuitive explanation for Eq. (12) is that: if

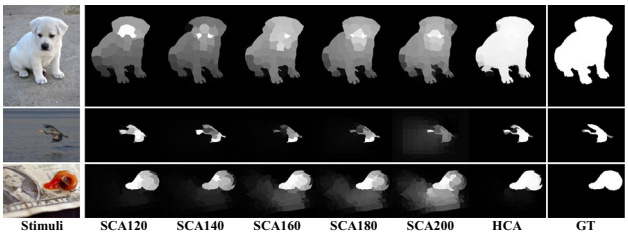


Fig. 5 Visual comparison of saliency maps generated by SCA at different scales ($n_1 = 120$, $n_2 = 140$, $n_3 = 160$, $n_4 = 180$ and $n_5 = 200$) and HCA

a pixel observes that one of its neighbors is binarized as foreground, it ought to increase its saliency value; otherwise, it should decrease its saliency value. Therefore, Eq. (12) can be turned into:

$$l\left(s_{m,i}^{(t+1)}\right) = l\left(s_{m,i}^{(t)}\right) + \text{sign}(s_{j,k}^{(t)} - \gamma_k) \cdot \Lambda, \tag{13}$$

where $s_{j,k}^{(t)}$ is the saliency value of the pixel i's j-th neighbor in the k-th saliency map at time t and Λ must be greater than 0. In this paper, we empirically set $\Lambda = 0.04$.

As each pixel has $5M - 1$ neighbors in total, the pixel will decide its action (increase or decrease it saliency value) based on all its neighbors' current states. Assuming the contribution of each neighbor is conditionally independent, we derive the synchronous update rule from Eq. (13) as:

$$l\left(\mathbf{s}_m^{(t+1)}\right) = l\left(\mathbf{s}_m^{(t)}\right) + \mathbf{\Sigma}_m^{(t)} \cdot \Lambda, \tag{14}$$

where $\mathbf{s}_m^{(t)} \in \mathbb{R}^H$ is the m-th saliency map at time t and H is the number of pixels in the image. $\mathbf{\Sigma}_m^{(t)} \in \mathbb{R}^H$ can be computed by:

$$\mathbf{\Sigma}_m^{(t)} = \sum_{j=1}^{5} \sum_{k=1}^{M} \delta(k = m, j > 1) \cdot \text{sign}\left(\mathbf{s}_{j,k}^{(t)} - \gamma_k \cdot \mathbf{1}\right), \tag{15}$$

where M is the number of different saliency maps, $\mathbf{s}_{j,k}^{(t)} \in \mathbb{R}^H$ is a vector containing the saliency values of the j-th neighbor for all the pixels in the m-th saliency map at time t and $\mathbf{1} = [1, 1, \ldots, 1]^\top \in \mathbb{R}^H$. We use $\delta(k = m, j > 1)$ to represent the occasion that the cell only has 4 neighbors instead of 5 in the m-th saliency map when it is in the m-th saliency map. After T_C iterations, the final integrated saliency map $\mathbf{s}^{(T_C)}$ is calculated by

$$\mathbf{s}^{(T_C)} = \frac{1}{M} \sum_{m=1}^{M} \mathbf{s}_m^{(T_C)}. \tag{16}$$

In this paper, we use CCA to integrate saliency maps generated by SCA at $M = 5$ scales. The five scales are respectively, $n_1 = 120$, $n_2 = 140$, $n_3 = 160$, $n_4 = 180$ and $n_5 = 200$. This combination is denoted as HCA, and the visual saliency maps generated by HCA can be seen in Fig. 5. Here we use the notation SCAn to denote SCA applied with n superpixels. We can see that the detected objects in the integrated saliency maps are uniformly highlighted and much closer to the ground truth.

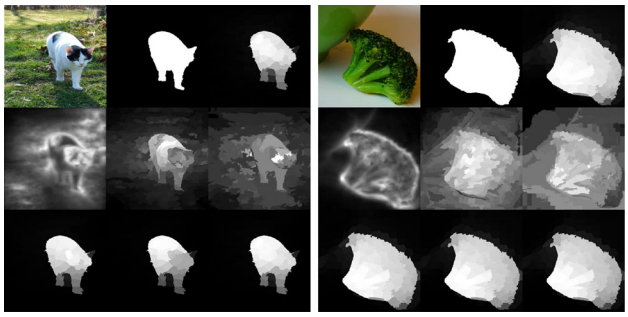


Fig. 6 Comparison of saliency maps generated by different methods and their optimized results via Single-layer Cellular Automata. The first row is respectively input images, ground truth and saliency maps generated by our proposed SCA with 200 superpixels. The second row displays original saliency maps generated by three traditional methods (from left to right: CAS (Goferman et al. 2010), LR (Shen and Wu 2012), RC (Cheng et al. 2015)). The third row is their corresponding optimized results by SCA with 200 superpixels

3.4 Consistent Optimization

3.4.1 Single-Layer Propagation

Due to the connectivity and compactness of the object, the salient part of an image will naturally emerge with the Single-layer Cellular Automaton, which serves as a propagation mechanism. Therefore, we use the saliency maps generated by several well-known methods as the prior maps and refresh them according to the synchronous update rule. The saliency maps achieved by CAS (Goferman et al. 2010), LR (Shen and Wu 2012) and RC (Cheng et al. 2015) are taken as $\mathbf{s}^{(0)}$ in Eq. (5). The optimized results via SCA are shown in Fig. 6. We can see that the foreground is uniformly highlighted and a clear object contour naturally emerges with the automatic single-layer propagation mechanism. Even though the original saliency maps are not particularly good, all of them are significantly improved to a similar accuracy level after evolution. That means our method is independent of prior maps and can make a consistent and efficient optimization towards state-of-the-art methods.

3.4.2 Pixel-Wise Integration

A variety of methods have been developed for visual saliency detection, and each of them has its advantages and limitations. As shown in Fig. 7, the performance of a saliency

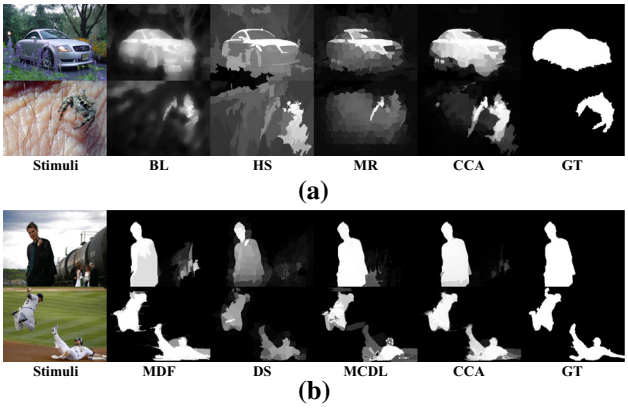


Fig. 7 Effects of pixel-wise saliency aggregation with Cuboid Cellular Automata. We integrate saliency maps generated by three conventional algorithms: BL (Tong et al. 2015a), HS (Yan et al. 2013) and MR (Yang et al. 2013) in (**a**) and incorporate saliency maps generated by three deep learning methods: MDF (Li and Yu 2015), DS (Li et al. 2016), MCDL (Zhao et al. 2015) in (**b**). The integrated result is denoted as CCA. **a** Saliency aggregation of three conventional methods. **b** Saliency aggregation of three deep learning methods

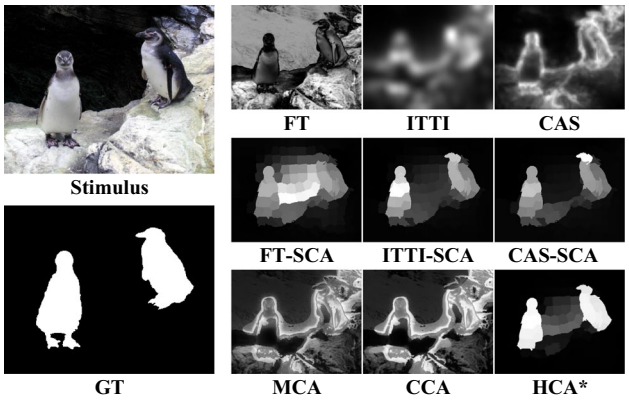


Fig. 8 Effects of holistic optimization by Hierarchical Cellular Automata. We use MCA (Qin et al. 2015), CCA and HCA to integrate saliency maps generated by three classic methods: FT (Achanta et al. 2009), ITTI (Itti et al. 1998) and CAS (Goferman et al. 2010). Their respective saliency maps optimized by SCA with 200 superpixels are shown in the second row. Note that HCA* uses as input the saliency maps processed by SCA (the second row) and applies CCA to them, while the MCA and CCA models are applied directly to the first row

detection method varies with individual images. Each method can work well for some images or some parts of the images but none of them can perfectly handle all the images. Furthermore, different methods may complement each other. To take advantage of the superiority of each saliency map, we use Cuboid Cellular Automata to aggregate two groups of saliency maps, which are generated by three conventional algorithms: BL (Tong et al. 2015a), HS (Yan et al. 2013) and MR (Yang et al. 2013) and three deep learning methods: MDF (Li and Yu 2015) and DS (Li et al. 2016) and MCDL (Zhao et al. 2015). Each of them serves as a layer of Cellular Automata $\mathbf{s}_m^{(0)}$ in Eq. (14). Figure 7 shows that our proposed pixel-wise aggregation method, Cuboid Cellular Automata, can appropriately integrate multiple saliency maps and outperforms each one. The saliency objects on the aggregated saliency map are consistently highlighted and much closer to the ground truth.

3.4.3 SCA + CCA = HCA

Here we show that when CCA is applied to some (poor) prior maps, it does not perform as well as when the prior map is post-processed by SCA. This motivates their combination into HCA. As is shown in Fig. 8, when the candidate saliency maps are not well constructed, both CCA and MCA (Qin et al. 2015) fail to detect the salient object. Unlike CCA and MCA, HCA overcomes this limitation through incorporating single-layer propagation (SCA) together with pixel-wise integration (CCA) into a unified framework. The salient objects can be intelligently detected by HCA regardless of the original performance of the candidate methods. When we use HCA to integrate existing methods, the optimized results will be denoted as HCA*.

4 Experiments

In order to demonstrate the effectiveness of our proposed algorithms, we compare the results on four challenging datasets: ECSSD (Yan et al. 2013), MSRA5000 (Liu et al. 2011), PASCAL-S (Li et al. 2014b) and HKU-IS (Li and Yu 2015). The Extended Complex Scene Saliency Dataset (ECSSD) contains 1000 images with multiple objects of different sizes. Some of the images come from the challenging Berkeley-300 dataset. MSRA- 5000 contains more comprehensive images with complex background. The PASCAL-S dataset derives from the validation set of PASCAL VOC2010 (Everingham et al. 2010) segmentation challenge and contains 850 natural images. The last dataset, HKU-IS, contains 4447 challenging images and their pixel-wise saliency annotation. In this paper, we use ECSSD as the validation dataset to help choose the feature maps in FCN (Long et al. 2015).

We compare our algorithm with 20 classic or state-of-the-art methods including ITTI (Itti et al. 1998), FT (Achanta et al. 2009), CAS (Goferman et al. 2010), LR (Shen and Wu 2012), XL13 (Xie et al. 2013), DSR(Li et al. 2013), HS (Yan et al. 2013), UFO (Jiang et al. 2013c), MR (Yang et al. 2013), DRFI (Jiang et al. 2013b), wCO (Zhu et al. 2014), RC (Cheng et al. 2015), HDCT (Kim et al. 2014), BL (Tong et al. 2015a), BSCA (Qin et al. 2015), LEGS (Wang et al. 2015), MCDL (Zhao et al. 2015), MDF (Li and Yu 2015), DS (Li et al. 2016), SSD-HS (Kim and Pavlovic 2016), where

the last 5 methods are deep learning-based methods. The results of different methods are either provided by authors or achieved by running available code or binaries. The code of HCA will be publicly available at our project site and github.

4.1 Parameter Setup

For the Single-layer Cellular Automaton, we set the number of iterations $T_S = 20$. For the Cuboid Cellular Automata, we set the number of iterations $T_C = 3$. We determined empirically that SCA and CCA converge by 20 and 3 iterations, respectively. We choose $M = 5$ and run SCA with $n_1 = 120, n_2 = 140, n_3 = 160, n_4 = 180$ and $n_5 = 200$ superpixels to generate multi-scale saliency maps for CCA.

4.2 Evaluation Metrics

We evaluate all methods by standard Precision-Recall (PR) curves via binarizing the saliency map with a threshold sliding from 0 to 255 and then comparing the binary maps with the ground truth. Specifically,

$$\text{precision} = \frac{|SF \cap GF|}{|SF|}, \text{recall} = \frac{|SF \cap GF|}{|GF|}, \tag{17}$$

where SF is the set of the pixels segmented as the foreground, GF denotes the set of the pixels belonging to the foreground in the ground truth, and $|\cdot|$ refers to the number of elements in a set. In many cases, high precision and recall are both required. These are combined in the F-measure to obtain a single figure of merit, parameterized by β:

$$F_\beta = \frac{\left(1+\beta^2\right) \cdot \text{precision} \cdot \text{recall}}{\beta^2 \cdot \text{precision} + \text{recall}} \tag{18}$$

where β^2 is set to 0.3 as suggested in (Achanta et al. 2009) to emphasize the precision. To complement these two measures, we also use mean absolute error (MAE) to quantitatively measure the average difference between the saliency map $\mathbf{s} \in \mathbb{R}^H$ and the ground truth $\mathbf{g} \in \mathbb{R}^H$ in pixel level:

$$\text{MAE} = \frac{1}{H}\sum_{i=1}^{H} |s_i - g_i|. \tag{19}$$

MAE indicates how similar a saliency map is compared to the ground truth, and is of great importance for different applications, such as image segmentation and cropping (Perazzi et al. 2012). In addition, we also compute the Area Under ROC Curve (AUC) to better compare the performance of different methods.

4.3 Validation of the Proposed Algorithm

4.3.1 Feature Analysis

In order to construct the Impact Factor matrix, we need to choose the features that will enter into Eq.(2). Here we analyze the efficacy of the features in different layers of a deep network in order to choose these feature layers. In deep neural networks, earlier convolutional layers capture fine-grained low-level information, e.g., colors, edges and texture, while later layers capture high-level semantic features. In order to select the best feature layers in the FCN (Long et al. 2015), we use ECSSD as a validation dataset to measure the performance of deep features extracted from different layers. The function $g(\mathbf{r}_i, \mathbf{r}_j)$ in Eq. (3) can be computed as

$$g(\mathbf{r}_i, \mathbf{r}_j) = \left\| df_i^l - df_j^l \right\|_2, \tag{20}$$

where df_i^l denotes the deep features of superpixel i on the l-th layer. The outputs of convolutional layers, relu layers and pooling layers are all regarded as a feature map. Therefore, we consider in total 31 layers of fully convolutional networks. We do not take the last two convolutional layers into consideration as their spatial resolutions are too low.

We use the F-measure (the higher, the better) and mean absolute error (MAE) (the lower, the better) to evaluate the performance of different layers on the ECSSD dataset. The results are shown in Fig. 10a and b. The F-measure score is obtained by thresholding the saliency maps at twice the mean saliency value. We use this convention for all of the subsequent F-measure results. The x-index in Fig. 10a and b refers to convolutional, ReLu, and pooling layers as implemented in the FCN. We can see that deep features extracted from the pooling layer in `Conv1` and `Conv5` can achieve the best two F-measure scores, and also perform well on MAE. The saliency maps in Fig. 9 correspond to the bars in Fig. 10. Here it is visually apparent that salient objects are better detected with the final pooling layers of `Conv1` and `Conv5` . Therefore, in this paper, we combine the feature maps from `pool1` and `pool5` with a simple linear combination. Equation (2) then turns into:

$$\begin{aligned} g(\mathbf{r}_i, \mathbf{r}_j) = \rho_1 \cdot \left\| df_i^5 - df_j^5 \right\|_2 \\ +(1-\rho_1) \cdot \left\| df_i^{31} - df_j^{31} \right\|_2, \end{aligned} \tag{21}$$

where ρ_1 balance the weight of `pool1` and `pool5`.

4.3.2 Parameter Learning

We learn the parameters in our HCA via a grid search with the ECSSD dataset as the validation set, *e.g.*, ρ_1 in Eq. (21), σ_f in

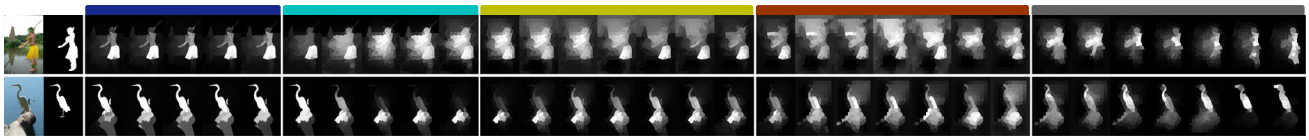


Fig. 9 Visual comparison of saliency maps with different layers of deep features. The left two columns are the input images and their ground truth. Other columns present the saliency maps with different layers of deep features. The color bars on the top stand for different convolutional layers (see Fig. 10a, b)

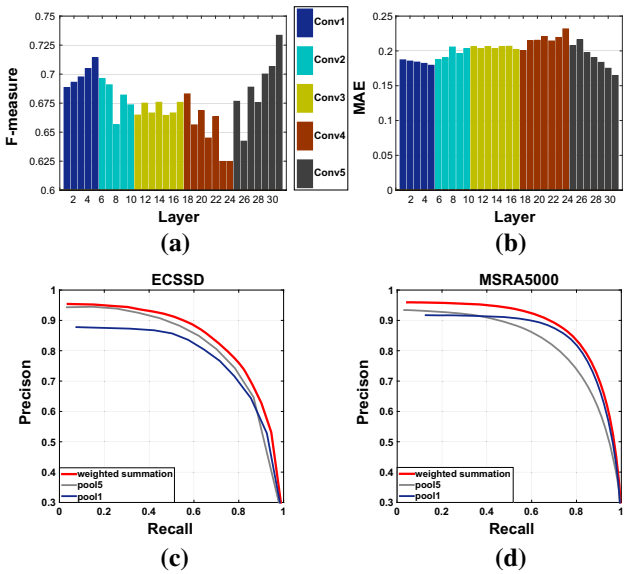


Fig. 10 **a** The F-measure score for each layer in FCN-32s on ECSSD; **b** the MAE score for each layer in FCN-32s on ECSSD; **c** and **d** Precision-Recall curves of SCA using deep features extracted from `pool1` and `pool5` as well as a weighted summation of these two layers of deep features. **a** F-measure bars, **b** MAE bars, **c** and **d** Precision-Recall curves comparison

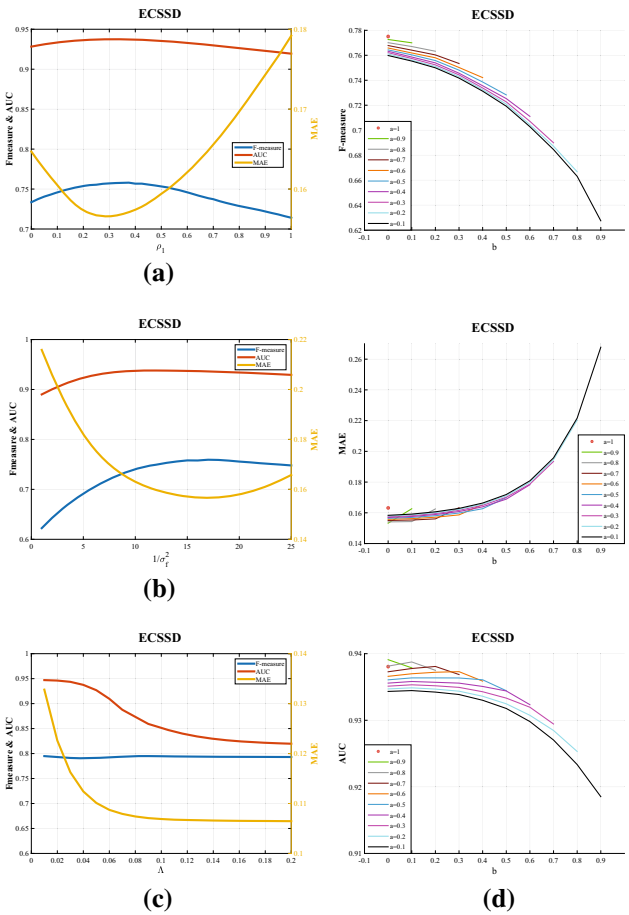


Fig. 11 Experiments for the parameter learning on the ECSSD dataset. The F-measure, AUC and MAE scores of SCA200 are used for parameter selection. **a** ρ_1 in SCA200. **b** σ_f in SCA200. **c** Λ in CCA. **d** a and b in SCA200

Eq. (3), a and b in Eq. (4) and Λ in Eq. (12). The F-measure, AUC and MAE scores of SCA200 are used for parameter selection. We vary ρ_1 from 0 to 1 and plot the performance versus ρ_1 in Fig. 11a. We can see that when $\rho_1 = 0.325$, the F-measure and AUC achieve the highest scores (higher is better) and MAE achieves the lowest value (lower is better). Therefore, we empirically set $\rho_1 = 0.325$ and apply it to all other datasets.

For the parameter σ_f, we test the performance of SCA200 when $\frac{1}{\sigma_f^2}$ varies from 1 to 25. The plots of F-measure, AUC and MAE are shown in Fig. 11b. It can be seen that the best performance is achieved when $\frac{1}{\sigma_f^2} = 17$. Therefore, we use $\frac{1}{\sigma_f^2} = 17$ in all other experiments.

In our paper, we use the two hyperparameters a and b to control $c_i^* \in [b, a+b]$, where $[b, a+b] \subseteq [0, 1]$. In Fig. 11d, we compare the performance of different combinations of a and b. First, we choose a from 0.1 to 1, taking an interval of 0.1. Correspondingly, the parameter b is also chosen from 0.1 to 1 with an interval of 0.1, constrained by $a + b \leq 1$. We can see from Fig. 11d that when $a = 0.9$ and $b = 0$, the MAE value is the smallest, AUC and F-measure scores are the highest. All the three evaluation metrics have the best scores when $c_i^* \in [0.0.9]$. Therefore, we use the this combination: $a = 0.9, b = 0$ for all the experiments in our paper.

After fixing all the hyperparameters discussed above ($\rho_1 = 0.325$, $1/\sigma_f^2 = 17$, $a = 0.9$ and $b = 0$), we conduct a grid search when the parameter Λ in CCA varies from 0 to 0.2. The plots of F-measure, AUC and MAE scores of CCA versus the parameter Λ are shown in Fig. 11c. It is easy to see that as Λ becomes larger, the MAE value becomes

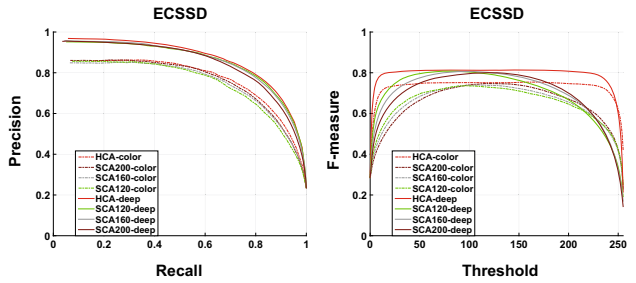


Fig. 12 Comparison between BSCA (Qin et al. 2015) that uses color featuers and our SCA using deep features (Color figure online)

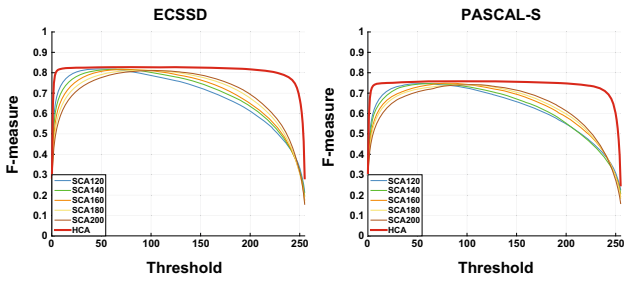


Fig. 13 F-measure/Threshold curves of saliency maps generated by SCA at different scales ($n_1 = 120$, $n_2 = 140$, $n_3 = 160$, $n_4 = 180$ and $n_5 = 200$ respectively), and the integrated results by HCA on ECSSD and PASCAL-S

smaller (better). However, the AUC score also decreases a bit. This is because that when Λ is large, the saliency map integrated by CCA will be much closer to a binary map. Then the MAE value will become smaller and AUC score will become poorer. The F-measure score is not very sensitive to the parameter Λ. To balance the performance of MAE and AUC score, we choose $\Lambda = 0.04$ as our final setting.

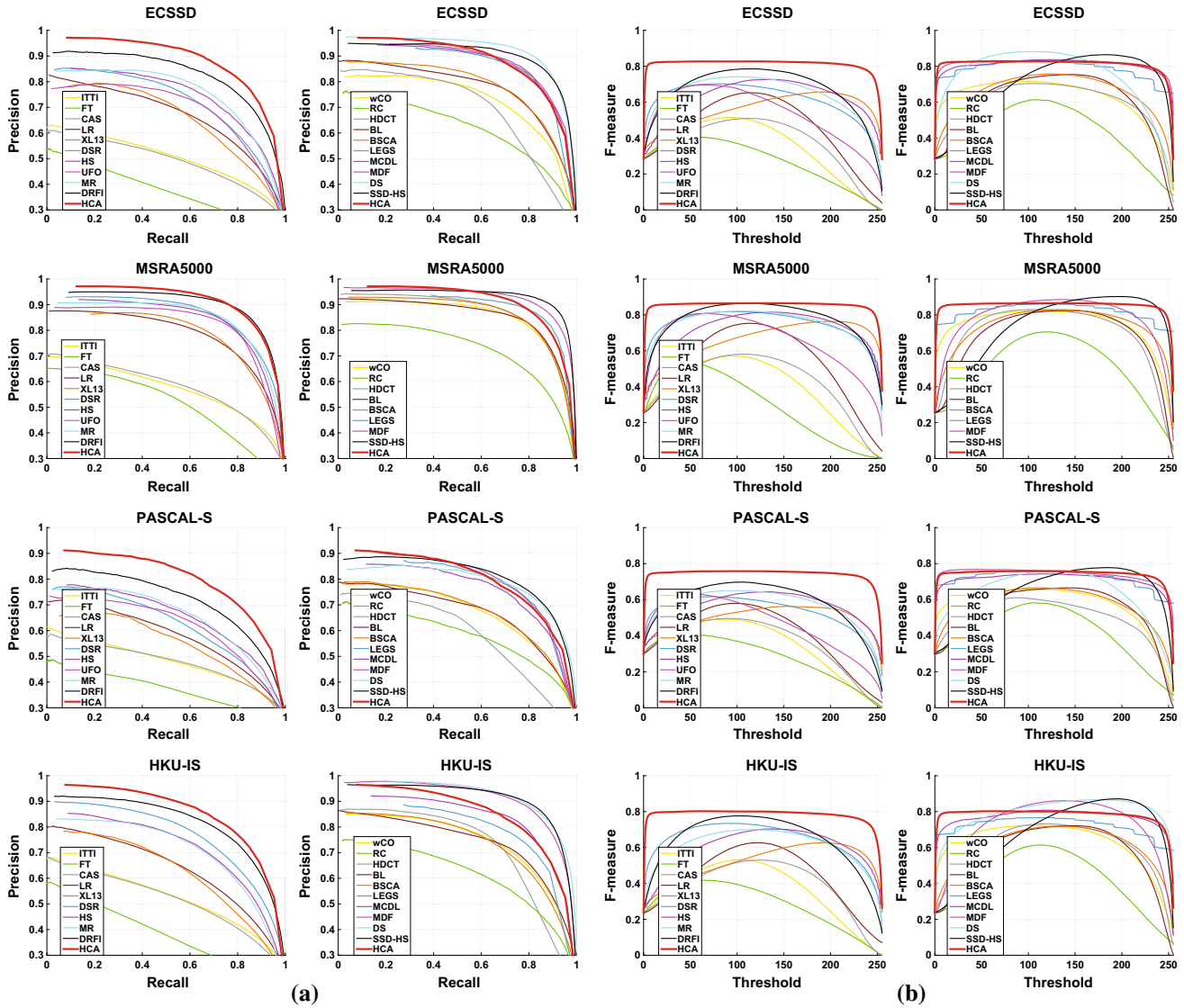


Fig. 14 PR curves, FT curves and MAE scores of different methods compared with our algorithm (HCA). From top to bottom: ECSSD, MSRA5000, PASCAL-S and HKU-IS are tested. **a** PR curves. **b** FT curves

Table 1 Comparison of AUC, F-measure and MAE scores of 20 state-of-the-art methods as well as our proposed HCA on all four benchmarks

Method	ECSSD			HKU-IS			MSRA5000			PASCALS		
	AUC	F-measure	MAE	AUC	F-measure	MAE	AUC	F-measure	MAE	AUC	F-measure	MAE
ITTI	0.794	0.428	0.290	0.840	0.465	0.255	0.853	0.515	0.249	0.781	0.394	0.297
FT	0.635	0.353	0.291	0.667	0.376	0.253	0.746	0.498	0.230	0.610	0.327	0.316
CAS	0.784	0.430	0.309	0.831	0.464	0.272	0.856	0.537	0.250	0.780	0.404	0.301
LR	0.864	0.563	0.274	0.866	0.555	0.257	0.924	0.694	0.221	0.814	0.479	0.287
XL13	0.854	0.568	0.259	0.853	0.552	0.254	0.925	0.704	0.184	0.800	0.469	0.285
DSR	0.889	0.662	0.178	0.923	0.677	0.142	0.957	0.784	0.117	0.841	0.557	0.215
HS	0.885	0.635	0.227	0.879	0.636	0.215	0.930	0.767	0.162	0.838	0.531	0.264
UFO	0.872	0.644	0.203	–	–	–	0.928	0.774	0.147	0.822	0.553	0.232
MR	0.891	0.691	0.186	0.867	0.655	0.188	0.939	0.801	0.128	0.835	0.586	0.232
DRFI	0.945	0.733	0.164	0.949	0.722	0.145	***0.970***	0.831	0.106	0.901	0.618	0.207
wCO	0.896	0.677	0.171	0.908	0.677	0.142	0.947	0.794	0.111	0.865	0.600	0.202
RC	0.836	0.456	0.300	0.854	0.501	0.272	0.896	0.575	0.263	0.815	0.404	0.313
HDCT	0.868	0.645	0.197	0.890	0.658	0.167	0.960	0.797	0.142	0.812	0.536	0.232
BL	0.916	0.684	0.216	0.916	0.660	0.207	0.955	0.784	0.169	0.870	0.574	0.249
BSCA	0.922	0.705	0.182	0.910	0.654	0.175	0.953	0.793	0.132	0.872	0.601	0.223
LEGS	0.925	0.785	0.118	0.905	0.723	0.119	0.954	***0.834***	*0.083*	0.892	***0.704***	0.155
MCDL	***0.953***	***0.796***	**0.101**	0.949	0.757	*0.092*	–	–	–	***0.913***	0.691	**0.145**
MDF	0.947	*0.807*	*0.105*	***0.969***	*0.784*	0.129	*0.980*	**0.850**	***0.104***	0.904	**0.709**	*0.146*
DS	**0.977**	**0.826**	0.122	**0.981**	**0.790**	**0.079**	–	–	–	**0.943**	0.659	0.176
SSD-HS	*0.972*	0.707	0.192	*0.976*	0.740	0.177	**0.984**	0.816	0.160	*0.942*	0.589	0.219
HCA	0.938	0.791	***0.112***	0.933	***0.765***	***0.104***	0.957	*0.841*	**0.079**	0.907	*0.708*	***0.152***

We mark the first, second, third results in bold, italic, bolditalic respectively. Deep methods are annotated with underlines

4.3.3 Component Effectiveness

To test the effectiveness of the integrated deep features, we show the Precision-Recall curves of Single-layer Cellular Automata with each layer of deep features as well as the integrated deep features on two datasets. The Precision-Recall curves in Fig. 10c and d demonstrate that hierarchical deep features outperform single-layer features, as they contain both category-level semantics and fine-grained details.

In addition, we compare the performance between our SCA and the BSCA in (Qin et al. 2015) to see the superiority of deep features over low-level color features. The PR curves and F-measure/Threshold curves are displayed in Fig. 12. Here we compare the two SCAs at different scales and the performance of HCA on the ECSSD dataset. It is notable to see that the deep features improve the performance with a large margin compared to using color features.

In order to demonstrate the effectiveness of our proposed HCA, we test the performance of each component in HCA on the standard ECSSD and PASCAL-S datasets. We generate saliency maps at five scales: $n_1 = 120, n_2 = 140, n_3 = 160, n_4 = 180, n_5 = 200$ and use CCA to integrate them. FT curves in Fig. 13 indicate that the results of the Single-layer Cellular Automata are already quite satisfying. In addition, CCA can improve the overall performance of SCA with a wider range of high F-measure scores than SCA alone. Similar results are also achieved on other datasets but are not presented here to be succinct.

4.3.4 Performance Comparison

We display the Precision-Recall curves and F-measure/-Threshold curves of 20 state-of-art methods as well as our proposed HCA in Fig. 14 and the AUC, F-measure and MAE scores in Table 1. As is shown in Fig. 14 and Table 1, our proposed Hierarchical Cellular Automata performs favorably against state-of-the-art conventional algorithms with higher precision and recall values on four challenging datasets. HCA is competitive with deep learning based approaches. The fairly low MAE value indicates that our saliency maps are very close to the ground truth. As MCDL (Zhao et al. 2015) and DS (Li et al. 2016) trained the network on the MSRA dataset, we do not report their results on this dataset in Fig. 14 and Table. 1. In addition, LEGS (Wang et al. 2015) used part of the images in the MSRA and PASCAL-S datasets as the training set. As a result, we only test LEGS with the test

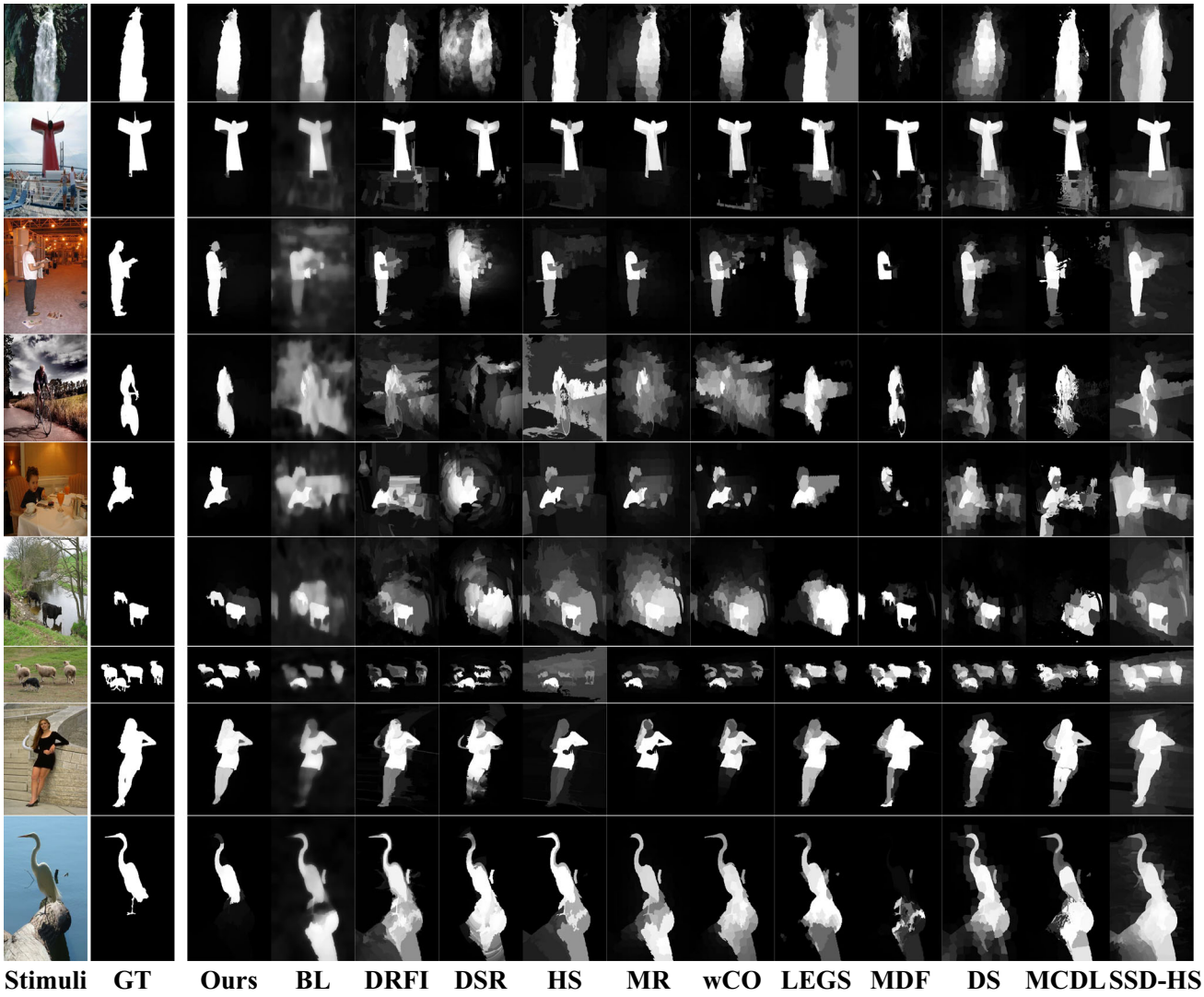


Fig. 15 Visual comparison of saliency maps of different methods. GT: Ground Truth, Ours: Saliency maps generated by Hierarchical Cellular Automata (HCA)

images on these two datasets. Saliency maps are shown in Fig. 15 for visual comparison of our method with other models.

4.4 Optimization of State-of-the-Art Methods

In the previous sections, we showed qualitatively that our model creates better saliency maps by improving initial saliency maps with SCA, or by combining the results of multiple algorithms with CCA, or by applying SCA and CCA. Here we compare our methods to other methods quantitatively. When the initial maps are imperfect, we apply SCA to improve them and then apply CCA. When the initial maps are already very good, we show that we can combine state-of-the-art methods to perform even better by simply using CCA.

4.4.1 Consistent Improvement

In Sect. 3.4.1, we concluded that results generated by different methods can be effectively optimized via Single-layer Cellular Automata. Figure 16 shows the precision-recall curves and mean absolute error bars of various saliency methods and their optimized results on four datasets. These results demonstrate that SCA can greatly improve existing results to a similar precision level. Even though the original saliency maps are not well constructed, the optimized results are comparable to the state-of-the-art methods. It should be noted that SCA can even optimize deep learning-based methods to a better precision level, e.g., MCDL (Zhao et al. 2015), MDF (Li and Yu 2015), LEGS (Wang et al. 2015), SSD-HS (Kim and Pavlovic 2016). In addition, for one existing method, we can use SCA to optimize it at different scales

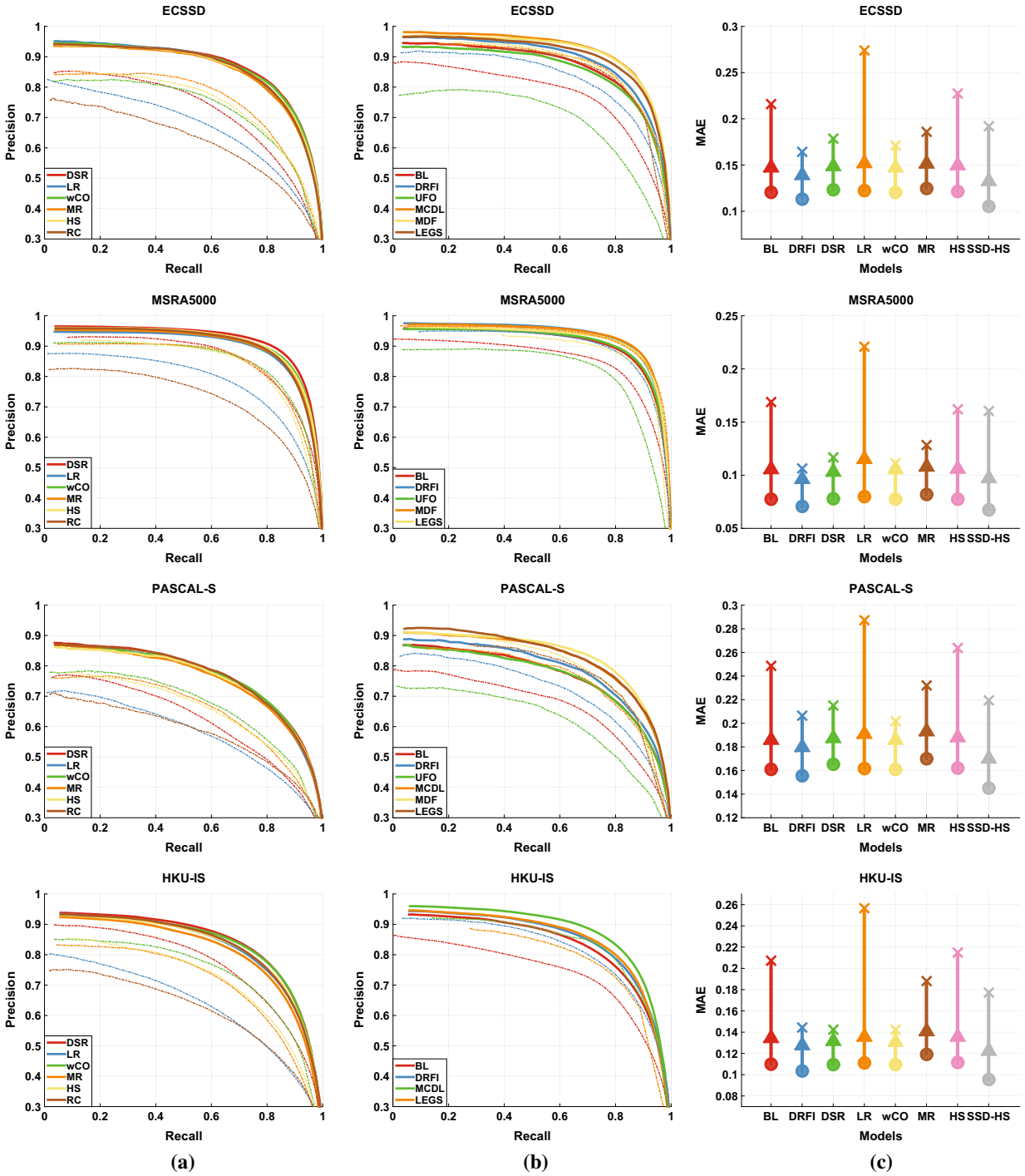


Fig. 16 Consistent improvement of our proposed SCA and HCA on four datasets. (**a**) and (**b**): PR curves of different methods (dashed line) and their optimized version via SCA200 (solid line). The right column shows that SCA200 (triangle), improves the MAEs of the original methods (multiplication symbol) and that HCA* (circle), here applied to SCA120, SCA160, and SCA200, further improves the results. **a** PR curves for unsupervised models. **b** PR curves for supervised models. **c** MAE scores

and then use CCA to integrate the multi-scale saliency maps. The ultimate optimized result is denoted as HCA*. The lowest MAEs of saliency maps optimized by HCA in Fig. 16c show that HCA's use of CCA improves performance over SCA alone.

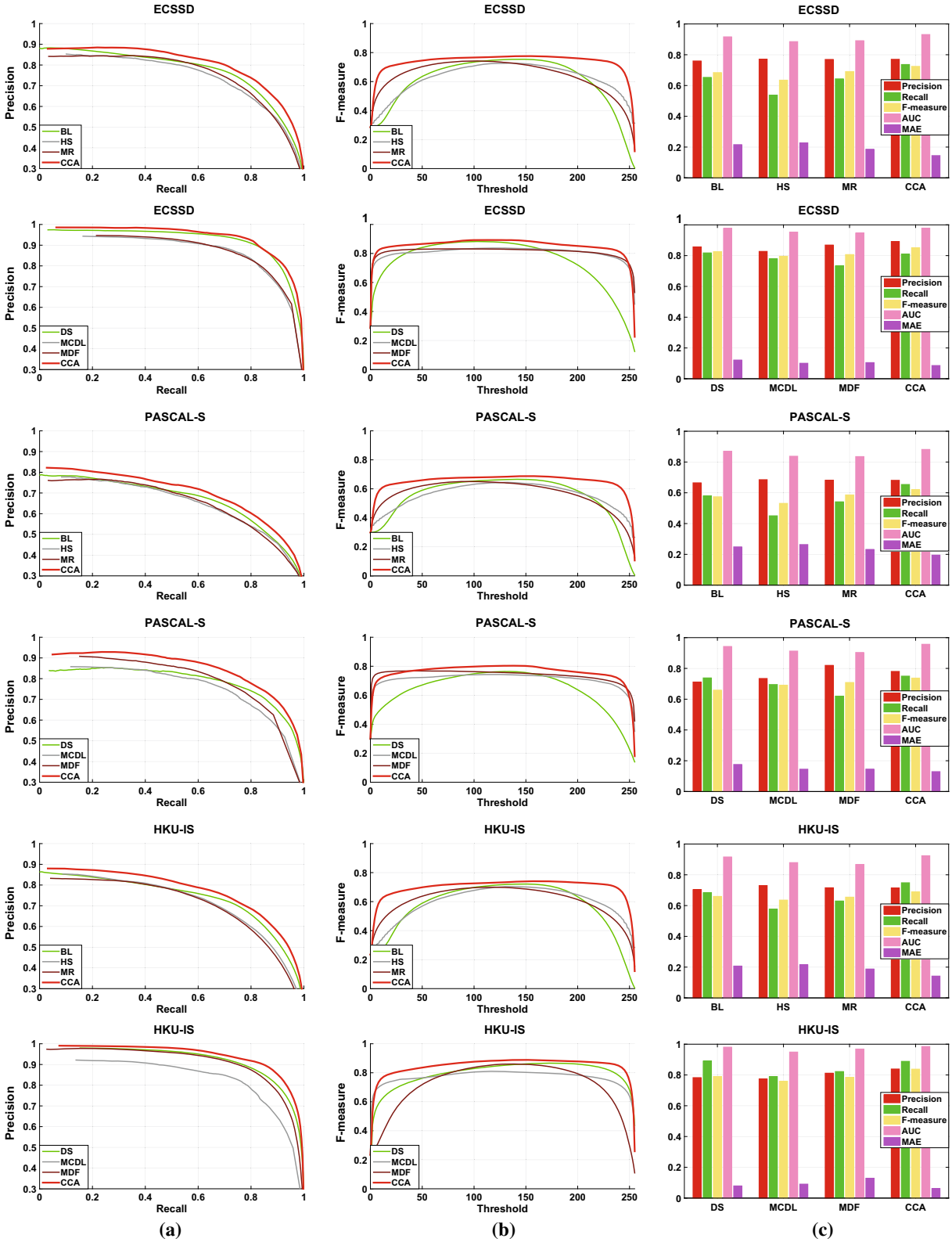


Fig. 17 Effects of pixel-wise aggregation via Cuboid Cellular Automata on ECSSD, PASCAL-S and HKU-IS dataset. For each dataset, the first row compares three conventional methods BL (Tong et al. 2015a), HS (Yan et al. 2013), MR (Yang et al. 2013) and their integrated results via Cuboid Cellular Automata, denoted as CCA. The second row compares three deep learning models, e.g. DS (Li et al. 2016), MCDL (Zhao et al. 2015), MDF ((Li and Yu 2015)) and their integrated results. The precision, recall and F-measure scores in the right column are obtained by thresholding the saliency maps at twice the mean saliency value. **a** PR curves. **b** FT curves. **c** Score bars

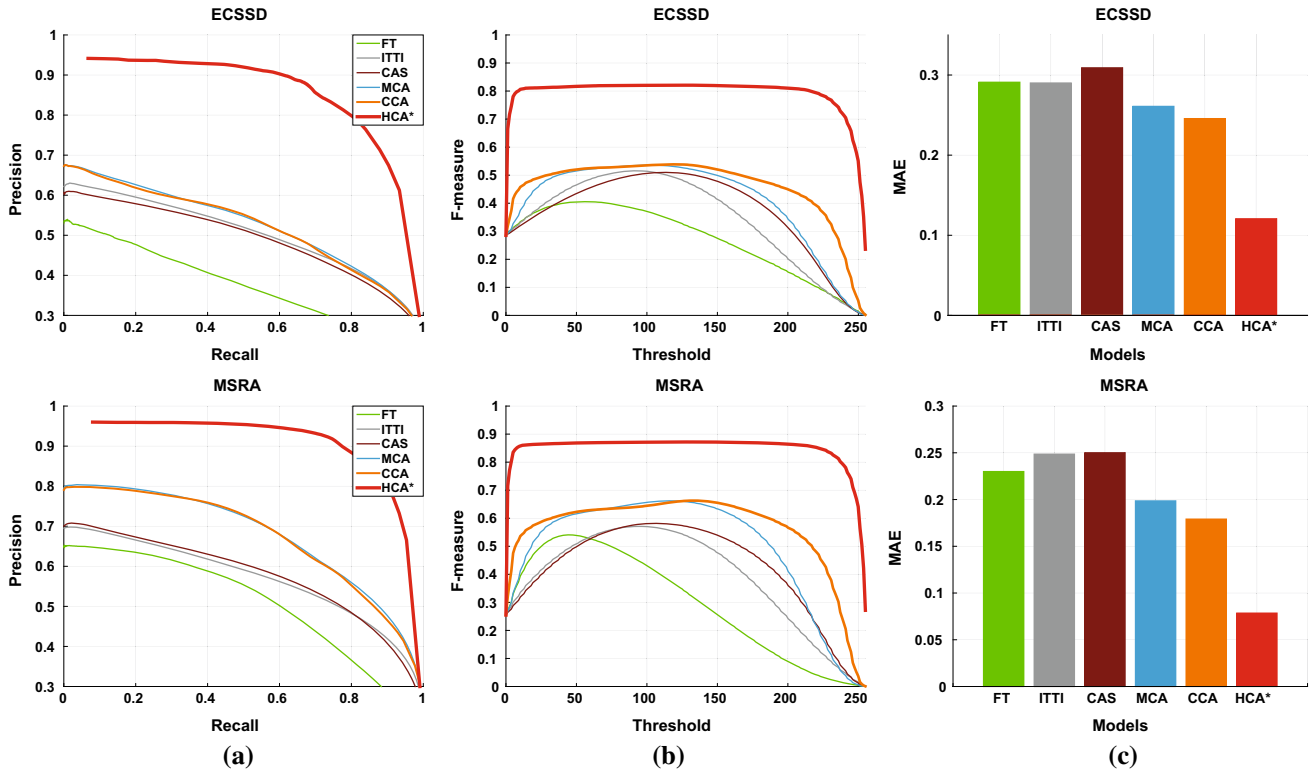


Fig. 18 Comparison between three different integration methods MCA (Qin et al. 2015), CCA and HCA when integrating FT (Achanta et al. 2009), ITTI (Itti et al. 1998) and CAS (Goferman et al. 2010) on ECSSD and MSRA datasets. **a** PR curves. **b** FT curves. **c** MAE scores

4.4.2 Effective Integration

In Sect. 3.4.2, we used Cuboid Cellular Automata as a pixel-wise aggregation method to integrate two groups of state-of-the-art methods. One group includes three of the latest conventional methods while the other contains three deep learning-based methods. We test the various methods on the ECSSD, PASCAL-S and HKU-IS datasets, and the integrated result is denoted as CCA. PR curves in Fig. 17a strongly prove the effectiveness of CCA that outperforms all the individual methods. FT curves of CCA in Fig. 17b are fixed at high values that are insensitive to the selective thresholds. In addition, we binarize the saliency map with two times mean saliency value. From Fig. 17c we can see that the integrated result has higher precision, recall and F-measure scores compared to each method that is integrated. Also, the mean absolute errors of CCA are always the lowest as displays. The fairly low mean absolute errors indicate that the integrated results are quite similar to the ground truth.

Although Cuboid Cellular Automata has exhibited great strength in integrating multiple saliency maps, it has a major drawback that the integrated result highly relies on the precision of candidate saliency detection methods as MCA in (Qin et al. 2015). If saliency maps fed into Cuboid Cellular Automata are not well constructed, Cuboid Cellular Automata cannot naturally detect the salient objects via ineractions between these candidate saliency maps. HCA, however, can easily address this problem as it incorporates single-layer propagation and multi-scale integration into a unified framework. Unlike MCA and CCA, HCA can achieve better integrated saliency map regardless of their original detection performance. PR curves, FT curves and MAE scores in Fig. 18 show that (1) CCA has a better performance than MCA as it considers the influence of adjacent cells at different scales. (2) HCA can greatly improve the aggregation results compared to MCA and CCA because it is independent to the initial saliency maps. Similar results are also achieved on other datasets but are not presented here to be succinct.

4.5 Run Time

The run time is to process one image in MSRA5000 dataset via Matlab R2014b-64bit with a PC equipped with an i7-4790k 3.60 GHz CPU and 32GB RAM. Table 2 displays the average run time of each component in our algorithm except for the time for extracting deep features. We can see that Single-layer Cellular Automata and Cuboid Cellular Automata are very fast to process one image, on average 0.1196 s. And the holistic HCA takes only 0.3582 s to process one image without superpixel segmentation and 0.6324 s with SLIC.

Table 2 Run time of each component of HCA

Method	SCA120	SCA140	SCA160	SCA180	SCA200	CCA	HCA
w/ SLIC(s)	.0848	.0929	.0997	.1140	.1214	–	.6324
wo/ SLIC(s)	.0310	.0371	.0444	.0585	.0676	.1196	.3582

Table 3 Comparison of run time

Model	Year	Code	Time(s)	Model	Year	Code	Time(s)	Model	Year	Code	Time (s)
HCA		Matlab	1.7168	HDCT	2014	Matlab	5.1248	MR	2013	Matlab	0.4542
MCDL	2015	Python	2.2521	wCO	2014	Matlab	0.1484	XL13	2013	Matlab	65.5491
LEGS	2015	Matlab + C	1.9050	DRFI	2013	Matlab	8.0104	LR	2012	Matlab	10.0259
MDF	2015	Matlab	25.7328	DSR	2013	Matlab	3.4796	RC	2011	C	0.1360
BL	2015	Matlab	21.5161	HS	2013	EXE	0.3821	CA	2010	Matlab + C	44.3270

Deep methods are annotated with underlines

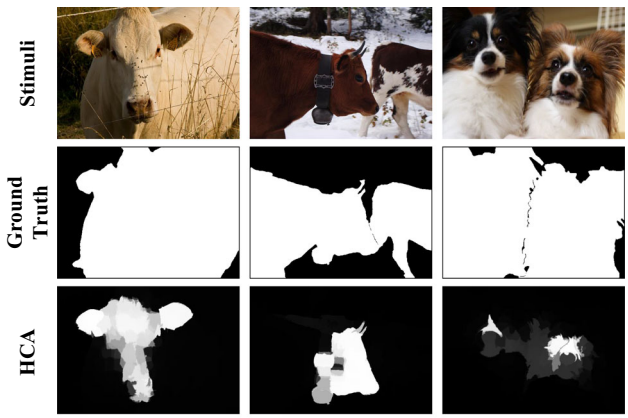


Fig. 19 Failure cases of our proposed HCA

We also compare the run time of our method with other state-of-the-art methods in Table 3. Here we compute the run time including superpixel segmentation and feature extraction for all models. It can be observed that our algorithm has the least run time compared to other deep learning based methods and is the top 5 fastest method among all the methods.

4.6 Failcure Cases

We further qualitatively analyze some failure cases with our proposed HCA and present the saliency maps in Fig. 19. We can see that when a large amount of objects are touching the image boundary, our HCA fails to detect the whole objects. This is because we directly use the image boundary as the background seeds in our algorithm. We hypothesize that well-selected background seeds may alleviate the problem to a great extent. How to efficiently and effectively select the background seeds is left as a future work.

5 Conclusion

In this paper, we propose an unsupervised Hierarchical Cellular Automata, a temporally evolving system for saliency detection. With superpixels on the image boundary chosen as the background seeds, Single-layer Cellular Automata is designed to exploit the intrinsic connectivity of saliency objects through interactions with neighbors. Low-level image features and high-level semantic information are both extracted from deep neural networks and incorporated into SCA to measure the similarity between neighbors. The saliency maps will be iteratively updated according to well-defined update rules, and salient objects will naturally emerge under the influence of neighbors. This context-based propagation mechanism can improve the saliency maps generated by existing methods to a similar performance level with higher accuracy. In addition, Cuboid Cellular Automata is proposed to aggregate multiple saliency maps generated by SCA under different scales based on Bayesian framework. Meanwhile, Cuboid Cellular Automata and Hierarchical Cellular Automata can act as a saliency aggregation method to incorporate saliency maps generated by multiple state-of-art methods into a more discriminative saliency map with higher precision and recall. Experimental results demonstrate the superior performance of our algorithms compared to other existing methods.

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