Volumetric and Two-Dimensional Image Interpretation Show Different Cognitive Processes in Learners

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Rationale and Objectives: In current practice, radiologists interpret digital images, including a substantial amount of volumetric images. We hypothesized that interpretation of a stack of a volumetric data set demands different skills than interpretation of two-dimensional (2D) cross-sectional images. This study aimed to investigate and compare knowledge and skills used for interpretation of volumetric versus 2D images.

Materials and Methods: Twenty radiology clerks were asked to think out loud while reading four or five volumetric computed tomography (CT) images in stack mode and four or five 2D CT images. Cases were presented in a digital testing program allowing stack viewing of volumetric data sets and changing views and window settings. Thoughts verbalized by the participants were registered and coded by a framework of knowledge and skills concerning three components: perception, analysis, and synthesis. The components were subdivided into 16 discrete knowledge and skill elements. A within-subject analysis was performed to compare cognitive processes during volumetric image readings versus 2D cross-sectional image readings.

Results: Most utterances contained knowledge and skills concerning perception (46%). A smaller part involved synthesis (31%) and analysis (23%). More utterances regarded perception in volumetric image interpretation than in 2D image interpretation (Median 48% vs 35%; $z = -3.9$; $P < .001$). Synthesis was less prominent in volumetric than in 2D image interpretation (Median 28% vs 42%; $z = -3.9$; $P < .001$). No differences were found in analysis utterances.

Conclusions: Cognitive processes in volumetric and 2D cross-sectional image interpretation differ substantially. Volumetric image interpretation draws predominantly on perceptual processes, whereas 2D image interpretation is mainly characterized by synthesis. The results encourage the use of volumetric images for teaching and testing perceptual skills.

Key Words: Radiology; image interpretation; medical education; cognitive processes; verbal protocols.

INTRODUCTION

The daily practice of radiologists has changed since the introduction of cross-sectional imaging techniques (eg, computed tomography [CT] and magnetic resonance imaging) and digital viewing systems (1,2). Digital volumetric data sets have been introduced, which can be scrolled through in different planes and window settings. Volumetric image sets are increasingly used because this is advantageous for identification and analysis of radiologic abnormalities (3). We expect that the interpretation of stacks of volumetric data sets demands different skills than interpretation of two-dimensional (2D) images (1,4). For example, visual search patterns in stack mode viewing of CT images differ from tiled mode viewing (5). Drew et al. found that the pattern of errors made in volumetric CT image interpretation differs from error patterns in interpretation of 2D images, which were chest x-rays in this case, as decision errors are less common in CT image interpretation (6,7). In volumetric image interpretation, radiologists need to navigate through and manipulate images to identify and analyze lesions. Although the multidimensional information enables a radiologist to observe the image features in detail, this requires the processing of much more information which could make the radiologist's search more complex and time consuming (1).

As radiology practice has changed, and cognitive processes in image interpretation may have consequently altered, traditional 2D teaching methods may not align well with the

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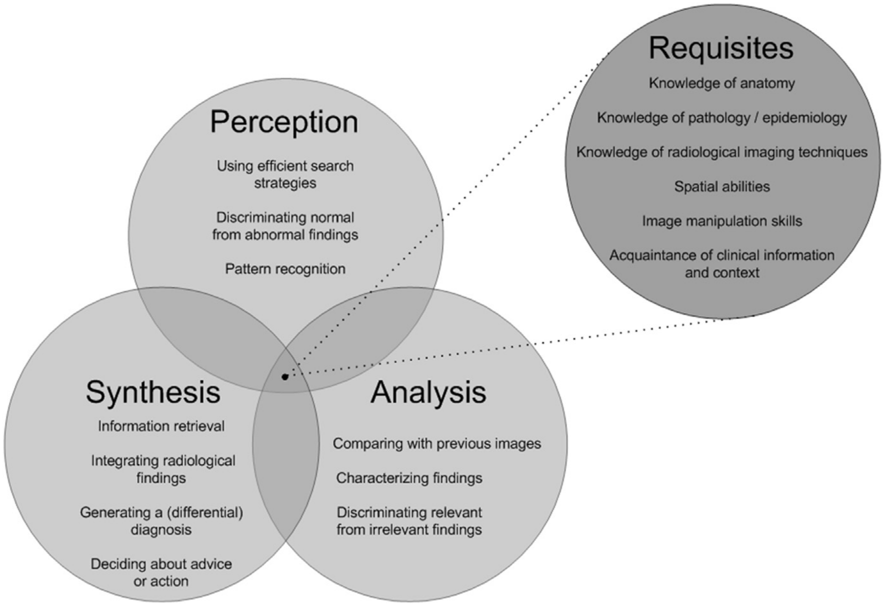

Figure 1. Framework representing important knowledge and skills for radiological image interpretation. *Reprinted from van der Gijp et al. (13). With kind permission from Springer Science and Business Media.*

knowledge and skills required for current practice (8). To gain insight in image interpretation skills for educational purposes, it is useful to explore which cognitive processes occur in volumetric image interpretation and how these differ from 2D image interpretation.

Cognition is a generic term for processes that involve, for example, perceiving, recognizing, problem solving, judging, reasoning, and decision making (9). Cognitive processes in radiologic image interpretation encompass extracting image information and combining this with information acquired from patient history and external sources to understand and make inferences about the meaning of the image. The cognitive processes of interest in this article are the use of knowledge and skills for image interpretation.

So far, research has mainly focused on cognitive processes in interpretation of 2D images such as chest x-rays (10,11). Differences in cognitive processes of radiologists and radiology trainees in volumetric image interpretation are only recently researched. Morita et al. (12) focused on interaction between perceptual and conceptual processes. Perceptual processing pertains to retrieving visual information from a CT image, for example, density or shape of an abnormality. Conceptual processing refers to relating perceived image features to existing knowledge in the observer's memory, for instance, knowledge about radiologic appearances of diseases or normal anatomy. This study showed that the interaction between the two processes was more prominent and occurred at an earlier stage among radiologists than among radiology trainees (12).

In a previous study, we developed a framework representing knowledge and skills required for radiologic image interpretation based on an interview and survey study among experts (13). The framework has three main components: perception, analysis, and synthesis, and 16 subcomponents. Six requisite knowledge and skill items are related to more than one main component and are placed separately. The framework is presented in Figure 1. The framework proved to be convenient for coding cognitive processes during image interpretation, with a high interrater reliability (13). In the present study, the framework was used to characterize and compare cognitive processes used in volumetric and 2D image interpretation.

As current radiology practice largely involves volumetric image interpretation, the cognitive processes underlying volumetric image interpretation should be further explored to improve education in modern image interpretation. The aim of this study was to reveal cognitive processes during volumetric cross-sectional image interpretation and to compare these to cognitive processes used during 2D cross-sectional image interpretation. The research questions are as follows: 1) Which cognitive processes occur during volumetric image interpretation? and 2) Which cognitive processes during volumetric image interpretation differ from those in 2D image interpretation in radiology education? We hypothesized that perceptual processes are more important in volumetric image interpretation because searching for abnormalities could be more complex and time consuming than in 2D image interpretation.

MATERIALS AND METHODS

Study Design

A within-subjects design was used. Concurrent verbal protocols were used as a proxy of cognitive processes (14). Verbalizations of participants during volumetric and 2D radiologic image interpretation were compared. All participants gave written informed consent for the study.

Participants and Setting

The study focused on an intermediate-level study population because intermediates are likely to verbalize more than both novices and experts do, known as the "intermediate effect" (15). Twenty clerks of the radiology department of the University Medical Center Utrecht agreed to volunteer in the study. Participants were fourth- to sixth-year medical students with 75% women. In the Netherlands, medical school takes 6 years and includes clerkships. Their mean age was 24.7 years. All participants had completed an elective radiology clerkship (6–12 weeks) <2 weeks before the study. The objectives of the clerkship focused on acute or subacute pathology in four radiology subareas: neuroradiology, musculoskeletal radiology, abdominal radiology, and chest radiology.

Instrumentation

Image Cases. Participants were asked to solve an even number of volumetric CT image and 2D CT image cases; 15 participants received four of each and five participants received five of each. The volumetric CT images were read in stack mode. The 2D CT images consisted of one to four cross-sectional slices, selected from a volumetric data set. All cases involved prevalent acute or subacute diseases in four radiology subareas: neuroradiology (eg, brain infarction), musculoskeletal radiology (eg, vertebral fracture), abdominal radiology (eg, diverticulitis), and chest radiology (eg, pneumonia). The cases were introduced with clinical background information and corresponded with the teaching objectives of the clerkship. Two sets of volumetric and 2D images were used. All volumetric image cases in set A were presented as 2D image cases in set B and vice versa. Participants read eight or ten cases of set A or B, half of the cases being volumetric and half 2D. Each case was read only once by each participant. Cases were presented in random order.

Digital Assessment Environment. Cases were shown in VQuest (16), a digital assessment environment which allows scrolling through a stack of images and change view or window setting. VQuest was found to be user friendly, and image display was found to be a fair representation of clinical practice, especially when images were displayed in stack mode (8,17). In this study setting, it was not possible to retrieve images from the patient archive, and therefore, images could not be compared to previous patient studies.

Image Display. Both volumetric and 2D CT images were presented in gray scale. Volumetric images were displayed in stack mode. Participants had the opportunity to scroll back and forth through the stack of images at desired speed in axial, sagittal, and coronal view. Window setting could be adjusted in soft tissue, bone, lung, and brain setting. 2D image cases contained a selection of one to four slices of a volumetric data set, displayed in tiled mode. The selection of images showed the abnormalities needed to interpret the case. The window setting of each slice was fixed on the optimal setting for visualization of the abnormalities and could not be adjusted.

Coding Scheme. The coding scheme was based on the framework as shown in Figure 1, containing knowledge and skill elements related to image interpretation (13). All subcomponents of perception, analysis, and synthesis were labeled with a unique code. The framework also included six requisite knowledge and skill items, which were non–component specific. Requisite knowledge and skill items were all tagged with a code for perception, analysis, and synthesis.

Procedure

Image Reading. Prior to the think aloud investigation, participants received a standard instruction and did an exercise in thinking out loud (14). During the study, all participants were asked to think out loud while reading eight or ten digital radiologic CT cases. They were asked to report a diagnosis or differential diagnosis and to give an advice (eg, for follow-up imaging), if necessary. They were also asked to indicate if they felt the need for additional information to solve the case. However, additional information sources were not available in the room. A supervisor stayed in the room during the entire think aloud investigation, to encourage participants to keep thinking aloud. The supervisor was the same person during the entire data collection.

Coding Process. Two independent raters coded the verbalizations of 25% of all participants. Because interrater reliability was found to be satisfactory (mean Cohen κ = .76), one rater continued to code the remaining verbalizations. Utterances related to requisite knowledge and skills were all assigned to one of the three main components, perception, analysis, or synthesis, based on the content and context of the utterance. Although image manipulation was not allowed in 2D images, "image manipulation skills" could be coded during 2D image interpretation in case knowledge about image manipulation was expressed, for example, by stating how the image could be manipulated to support the interpretation process. Because participants could not retrieve images from the patient archive, the variable "comparing with previous images" could only be coded in case participants verbalized they would have liked to compare to previous patient images. As additional information sources, for example, books or the Internet, were not available during case reading, utterances related to the intention to search for additional information were coded as "information retrieval."

Data Analysis

Utterances that could not be related to image interpretation knowledge or skills were excluded from the analysis. The total number of utterances for each code was registered per

TABLE 1. Examples of Verbalizations of Knowledge and Skill Items

Framework Components	Code Items	Examples
Requisites*	Knowledge of anatomy	"*This is the posterior edge of the maxillary sinus.*" (perception, subdural hematoma and maxillary sinus fracture)
	Knowledge of pathology/epidemiology	"The filling defect seems to be situated in the middle of the vessel. *Of course, this is a sign of* an acute pulmonary embolism." (synthesis, pulmonary embolism with lung infarction)
	Knowledge of radiologic imaging techniques	"Let's see if there is contrast leakage present. *I am not sure if a contrast agent is used. I think there is.*" (analysis, spleen laceration)
	Spatial abilities†	—
	Image manipulation skills (navigating through, changing views or contrast)	"*I always count vertebral bodies in the sagittal view.*" (perception, Jefferson fracture)
	Acquaintance of clinical information and context	"I see a large hypodense area in the right hemisphere. *This corresponds to the hemiparesis at the left.*" (analysis, brain infarction)
Perception	Using efficient search strategies	"I *try to divide the head in three parts. First, I examine the upper part, than the middle part and finally the lower part.*" (subarachnoid hemorrhage)
	Discriminating normal from abnormal findings	"*I see abnormalities* in the lung. The heart *looks normal.*" (pulmonary contusion)
	Pattern recognition	"Then we *directly see what this is:* a scapular fracture." (scapular fracture)
Analysis	Comparing with previous images	"A lesion in the left adrenal gland, probably an incidentaloma, though I can't exclude malignancy. Besides, *I don't have anything to compare with.*" (diverticulitis)
	Characterizing findings	"There is an *increased density especially at the right side.*" (subarachnoid hemorrhage)
	Discriminating relevant from irrelevant findings	"This is probably a renal cyst. *I don't think this is causing any problems.*" (aneurysm of the abdominal aorta)
Synthesis	Information retrieval	"Fracture of (…) *I would have to look up* which bone has been broken." (subdural hematoma and maxillary sinus fracture)
	Integrating radiologic findings	"*I see air in the brain which is probably coming from the maxillary sinus which is fractured (…) This means there is a connection between the maxillary sinus and the brain which causes intracranial air.*" (subdural hematoma and maxillary sinus fracture)
	Generating a (differential) diagnosis	"I believe this is *an aortic dissection*. Where does it start, before or behind the vessels? No behind, *so it is type B.*" (aortic dissection)
	Deciding about advice or action	"Cerebral herniation…if I was a radiology resident, *I would have warned them that they should pay attention to that.*" (epidural hematoma)

*Knowledge and skill items of the category "requisites" could relate to perception, analysis, or synthesis.
†The variable "spatial abilities" was not identified.

participant per case. For each participant, the number and percentage of utterances per code and per main component was calculated for volumetric and 2D image cases. Wilcoxon signed-rank tests were conducted to compare the codes of the main components in volumetric readings and 2D readings. If main components were significantly different, codes of subcomponents in volumetric and 2D readings were compared using Wilcoxon signed-rank tests with a Bonferroni correction.

Institutional Review Board Approval

The study was approved by the Ethical Review Board of the Netherlands Association for Medical Education.

TABLE 2. Distribution of Utterances Among Volumetric and 2D Image Interpretation

	Volumetric	2D
N participants	20	20
Total number of utterances	5429	2563
Range among cases	11–253	7–60
Range among participants (average per case)	19–168	14–54
Mean completion time per case (s)	390	181

2D, two dimensional.

RESULTS

Except for spatial abilities, all knowledge and skill items were found to be verbalized by participants. Examples of utterances of each item are presented in Table 1.

Fourteen percent of all utterances could not be related to image interpretation knowledge and skills and were excluded from the analysis. The total number of the remaining coded utterances was slightly more than twice as high in volumetric image cases compared to 2D image cases. This ratio was comparable in all four radiology subareas. Completion time was also more than twice as high in volumetric image cases. A wide range in number of utterances was found among cases and among participants. Distribution of the number of utterances among volumetric and 2D image cases is given in Table 2.

Most utterances were categorized as perception (46%), followed by synthesis (31%), and analysis (23%). In volumetric image interpretation, most utterances represented perception (Median, 47.9%) in contrast to 2D image interpretation (Median, 34.6%). The percentage of perceptual utterances was significantly higher in volumetric images than in 2D images ($z = -3.9$; $P < .001$; $r = .61$). The percentage of utterances related to synthesis was significantly larger in 2D images than in volumetric images ($z = -3.9$; $P < .001$; $r = .61$). The percentage of analysis was almost equal in both groups. Results of Wilcoxon signed-rank tests are presented in Table 3.

In volumetric image interpretation, "knowledge of anatomy" was verbalized most (29.0% of the utterances), followed by "discriminating normal from abnormal findings" (19.8%). "Comparing with previous images" and "discriminating relevant from irrelevant findings" were coded the least, with one and five coded utterances, respectively. "Characterizing findings" was most verbalized within analysis, and "generating a differential diagnosis" was most verbalized within synthesis. Figures 2 and 3 show the distributions of knowledge and skills in volumetric image interpretation and 2D image interpretation, respectively. The horizontal scales of Figures 2 and 3 are not equal.

The perception subcomponents "knowledge of anatomy," "using efficient search strategies," and "image manipulation skills" represented a larger part of utterances in volumetric image interpretation than in 2D image interpretation ($z = -3.1$, $P < .005$, $r = .49$; $z = -3.6$, $P < .001$, $r = .57$; and $z = -3.9$, $P < .001$, $r = .62$, respectively). The synthesis component "generating a differential diagnosis" represented a larger part of 2D image interpretation than volumetric image interpretation ($z = -3.2$; $P < .001$; $r = .51$).

DISCUSSION

Cognitive processes in volumetric image interpretation were found to differ from 2D cross-sectional image interpretation. Volumetric image interpretation involves more cognitive processes than 2D image interpretation, but completion time differed with the same factor. Perception is more prominent in volumetric image interpretation than in 2D image interpretation. Cognitive processes related to synthesis have a bigger share in 2D image interpretation (although in absolute numbers, synthesis is also more prevalent in volumetric image interpretation). A framework of knowledge and skills in radiologic image interpretation was used to subcategorize these cognitive processes on a knowledge and skill level (13). In the category perception, "knowledge of anatomy," "the use of efficient search strategies," and "image manipulation skills" were more prominent in volumetric than in 2D image interpretation. In the category synthesis, "generating a differential diagnosis" was less prominent in volumetric than in 2D image interpretation.

The prominence of perception in volumetric image interpretation could be due to a more complex and time-consuming search for abnormalities in volumetric image interpretation, which is supported by our results showing more verbalizations of using efficient search strategies and image manipulation skills in volumetric image interpretation. Knowledge of anatomy was also more frequently used in volumetric image interpretation, which is probably due to a larger amount of anatomic information that has to be processed. In absolute numbers, synthesis is found more in volumetric image interpretation but less than expected based on completion time differences. This could be caused by a relatively less complex and time-consuming search, which leaves time and mental effort for a more thorough synthesis process.

Based on the number of verbalized cognitive processes and the completion time, mental effort seems higher in volumetric image interpretation than in 2D image interpretation. This aligns to previous research showing a positive relation between "multiplanar image information" and self-reported mental effort of medical students performing a radiologic image interpretation task (18).

We did not find other studies reporting differences in cognitive processes in volumetric versus 2D image interpretation in the context of radiology education. Previously reported differences in visual search patterns and error patterns (5–7) only suggest a difference in cognitive processes, although the actual cognitive processes during image interpretation, in terms of the thinking process of the image interpreter, was not investigated. Most verbal protocol studies investigating cognitive processes in radiologic image interpretation research are related to differences in expertise levels. For example,

TABLE 3. Differences in Image Interpretation Components in 2D and Volumetric Image Interpretation

	Volumetric		2D			
Component	Total	Median (%)	Total	Median (%)	*P* Value*	Effect Size (r)
Perception	2751	47.9	945	34.6	<.001	.61
Analysis	1245	23.4	555	21.7	.31	.16
Synthesis	1433	27.8	1063	41.5	<.001	.61

2D, two dimensional.
*Wilcoxon signed-rank test.

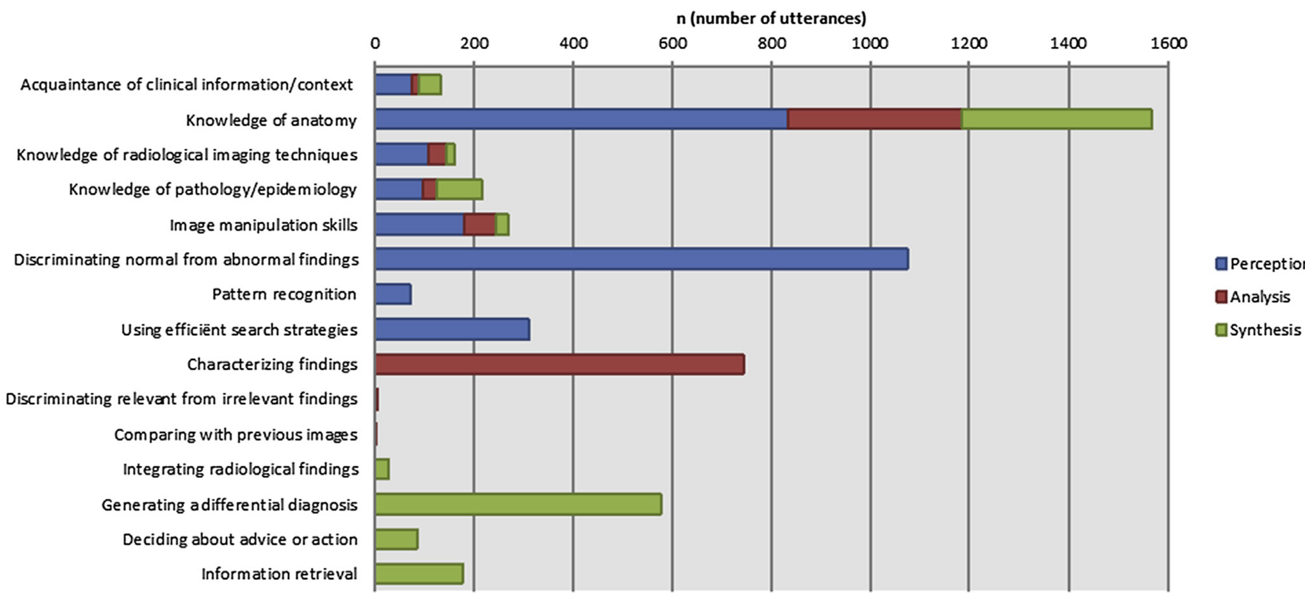

Figure 2. Distribution of knowledge and skill items used in volumetric image interpretation.

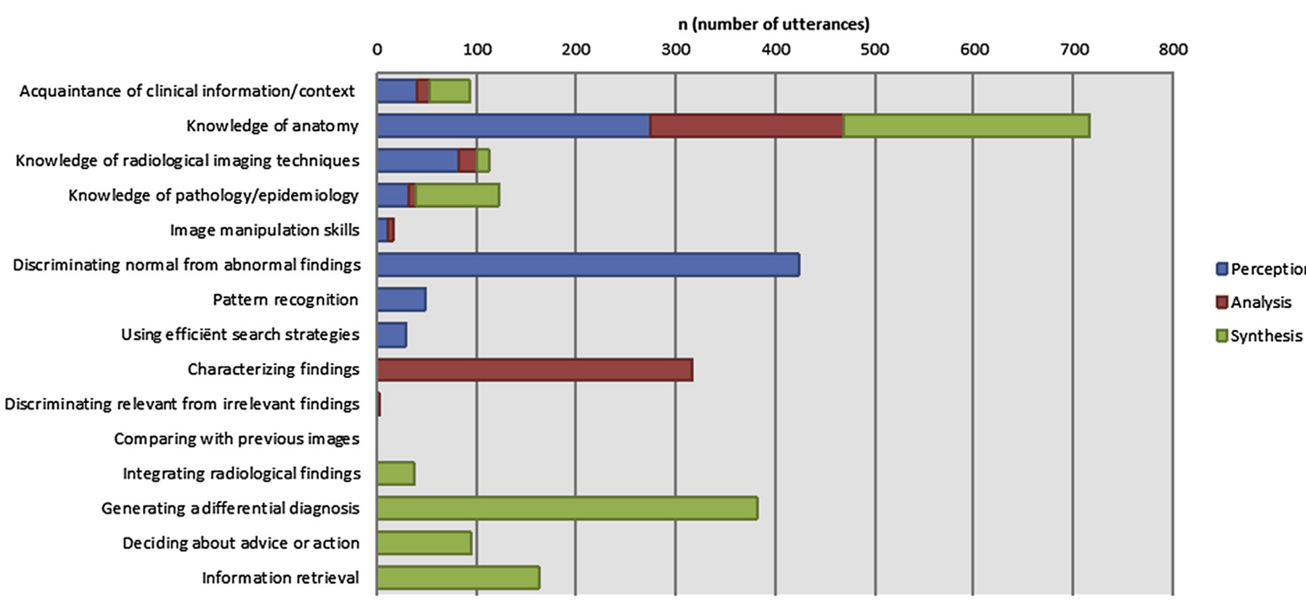

Figure 3. Distribution of knowledge and skill items used in two-dimensional image interpretation.

studies in x-ray image interpretation show that experts report more different and connecting findings than novices and generate longer chains of reasoning (10,11). Besides, experts appear to ignore irrelevant data but take immediate account of relevant data (10,11). Lesgold et al. studied the cognitive processes of experts and concluded they "see things differently," "build mental representations of patient anatomy," and "exhibit flexibility." These studies describe important differences in verbalizations between expert levels but do not translate these into knowledge and skills needed for the task. In our study, verbal protocols during image interpretation were analyzed on a level of knowledge and skills, to make the results useful for educational purposes. One other study, conducted in CT image interpretation reported a detailed analysis of verbal protocols in numerous subcategories (19). The authors reported the content of the information verbalized by the participants but did not translate the information into knowledge and skills. For example, it was registered how many times words like "density," "shape," and "size" of the lesion were mentioned, which we translated into the skill, "characterizing findings."

Our results regarding examination time, being longer in volumetric image interpretation than in 2D image interpretation, are contradictory to the results of Ellis et al. (5) who found longer examination times in tiled reading versus stack reading. This difference can be explained by the difference in number of 2D images presented to participants. Tiled reading includes multiple images presented next to each other, whereas in our study, only a few 2D CT slices were presented, as this is more common in radiology education, and we tried to find differences in 2D and volumetric image interpretation relevant for education.

Our study has some limitations. Verbal protocols are used as a proxy of cognitive processes. Utterances of participants are used to capture knowledge and skills that might underlie those utterances (20). Relying on verbal protocols could possibly underestimate the amount of cognitive processes and could blur the distribution. Cognitive processes can be unconscious and therefore might not be verbalized. For example, "discriminating relevant from irrelevant findings" is a process that probably frequently occurs during image interpretation as not all findings are being reported, although the decision to report a finding because it is judged relevant (or not to report a finding because it is judged irrelevant) is barely verbalized. This potential bias increases with growing automaticity of the processes and is therefore more prominent in experts (14). To minimize discrepancies between the cognitive processes actually used during the performance and the cognitive processes reported, we collected concurrent instead of retrospective verbal reports (14). Thinking aloud is expected to have little effect on perceptual performance in radiology image interpretation, except for prolonging the task (21). Some cognitive processes may have been underestimated or overestimated due to the experimental conditions. Because previous patient studies were not available, the variable "comparing with previous images" could only be coded when participants made explicit that they wanted to compare. As a consequence, "comparing with previous images" was hardly verbalized in this study. One skill that may have been overestimated is "information retrieval." Because information sources were not available in the study setting, participants were asked whether they needed additional information to solve the case. This could have encouraged participants to verbalize thoughts about the intention to search for additional information, which was coded as "information retrieval." We do not suppose that these underestimations or overestimations influenced our results concerning the comparison of 2D and three dimensional image interpretation because we used a within-subject design.

The study population consisted of radiology clerks, that is, fourth- to sixth-year medical students. The distribution of cognitive processes could be different in novices and experts. It is not sure if the differences in cognitive processes between volumetric and 2D image interpretation will persist in radiology experts because experts have proven to be more proficient searchers as shown in numerous eye-tracking studies (22–26), and perceptual processes might be less prominent in volumetric image interpretation. Characterizing differences in cognitive processes in volumetric and 2D image interpretation of novices and experts could be subject for further investigation. A suggestion for further research would be to validate our results in other expertise levels.

Our results encourage the use of volumetric images in radiology education because its interpretation requires different and more extensive knowledge and skills than 2D image interpretation. Especially for teaching and testing perceptual skills, volumetric images are recommended.

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