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Research on the Optimization of Specialized Training Load during the Sensitive Period of Physical Development for Adolescent Swimmers

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Abstract: *The adolescent stage is a critical period for the physical fitness development of swimmers, and scientific training during the sensitive period of physical fitness development directly determines the quality of reserve talent cultivation. This article takes 10-18-year-old adolescent swimmers as the research object, and adopts literature research method, questionnaire survey method, experimental method, mathematical statistics method, and expert interview method to systematically explore the characteristics of the sensitive period of physical development and the current situation of specialized training load. It constructs an optimized model of specialized training load suitable for the sensitive period and conducts empirical testing. Research has shown that adolescent swimmers experience a period of coordination and flexibility sensitivity between the ages of 10-12, a period of speed and explosiveness sensitivity between the ages of 13-15, and a period of endurance and strength endurance consolidation between the ages of 16-18; The current specialized training load has problems such as insufficient quantification, lack of individualization, and weak correlation between specialties; The four-dimensional optimization model of "age adaptation - specific guidance - individual differences - safe and controllable" and the age segmented sub model constructed have been empirically verified to significantly improve athletes' physical fitness, specific sports performance, and reduce the incidence of sports injuries. The research results provide theoretical support and practical reference for the physical training of adolescent swimmers during their sensitive period.*

Keywords: *teenage swimming; physical development; sensitive period; specialized training load; optimization mode*

1. Introduction

With the acceleration of professionalization and scientification in competitive sports, the strategic significance of cultivating young reserve talents has become increasingly prominent. Swimming, as a sport that combines competitiveness and fitness, continues to increase in popularity in China. As of 2023, there are over 300000 registered young swimmers nationwide, and the average annual number of youth swimming events at or above the provincial level has exceeded 200. However, there are prominent problems in current youth swimming training, such as "emphasis on technique over physical fitness" and "homogenization of load and neglect of developmental patterns", which have led to some athletes missing the critical period of physical development or causing sports injuries due to improper load, restricting the release of competitive potential.

The sensitive period of physical development is the "window of rapid improvement" for physical fitness (strength, speed, endurance, etc.) that is generated by the rapid development of the nervous, muscular, cardiovascular, and other systems in the physiological development of adolescents. Research in exercise physiology has confirmed that applying scientific training load during sensitive periods can improve physical fitness efficiency by 2-3 times compared to non-sensitive periods. Swimming requires significant specialized physical abilities such as stroke strength, turning speed, and long-distance endurance, and there are clear sensitive period characteristics in the development of these qualities. Therefore, optimizing the specialized training load based on the sensitive period has become a key path to solving the current training pain points[1].

This study has both theoretical and practical value: at the theoretical level, it systematically sorts out the physiological mechanisms and specific needs of the sensitive period, constructs a framework for adapting the sensitive period and specific training load, enriches the application of sports training and

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sports physiology in the field of adolescent swimming, fills the gap in the linkage research of "sensitive period specific load quantitative indicators", and provides reference for similar projects such as synchronized swimming and open water swimming; At the practical level, feasible optimization models and strategies are proposed to address issues such as unscientific load design and lack of monitoring, in order to assist coaches in accurately controlling the training pace, reducing the risk of injury, and improving the reserve talent training system.

The research adopts a multi method fusion design: literature research method searches CNKI, Web of Science and other databases, and sorts out more than 320 Chinese and English literature; The questionnaire survey method distributed questionnaires to 16 youth swimming teams in 8 provinces, and 386 valid questionnaires were collected (with an effective response rate of 89.7%); Conduct 45-60 minute in-depth interviews with 12 domain experts using expert interview method; The experimental method involved 40 athletes from a professional team in Hebei Province, who were divided into an experimental group (optimized load) and a control group (traditional load) for a 10 month intervention; The mathematical statistics method used SPSS 26.0 software to analyze the data through descriptive statistics, independent sample t-test, and other methods (α=0.05).

2. Characteristics of the sensitive period of physical development and the current situation of specialized training load for adolescent swimmers

2.1 Analysis of the sensitive period characteristics of physical development in adolescent swimmers

Based on literature research and expert interviews, combined with the physiological development laws of adolescents, this study divides adolescent swimmers aged 10-18 into three stages. The characteristics of the sensitive period of core physical fitness in each stage are shown in Table 1.

Table 1. Distribution of sensitive periods for physical development of adolescent swimmers

Age stage	Core sensitive period type	Fundamentals of physiological development	Key points of specialized physical fitness development
10-12	Coordination, flexibility, and sensitivity period of basic strength	Rapid development of the nervous system, good flexibility of bones, and gradual increase in muscle mass	Water coordination ability (swimming turning breathing coordination), joint flexibility, basic swimming strength
13-15	Sensitivity period for speed, explosive power, and specialized forces	Adolescence development, rapid increase in muscle mass, and enhancement of anaerobic metabolic capacity	Turning speed, paddling explosiveness, short distance sprinting ability
16-18	Sensitivity period for endurance, strength endurance, and physical fitness integration	Mature cardiovascular system, stable aerobic metabolism, and consolidated muscle strength	Long range endurance, high-intensity intermittent tolerance, specialized physical fitness and technology integration

The water environment and technical characteristics of swimming pose clear specific requirements for the physical fitness of young athletes, and the development of each core physical fitness is highly correlated with the sensitive period of physical development in specific age groups. In terms of coordination quality, precise coordination of swimming, turning, and breathing movements needs to be achieved. The systematic training during the sensitive period of coordination between 10-12 years old directly determines the formation of standardized technical movements, which is the basis for subsequent optimization of specialized skills; In terms of flexibility, the flexibility of the shoulder, hip, and ankle joints directly affects the stroke range and turning flexibility. The sensitive period of flexibility between 10-12 years old is a key period for improving joint range of motion, and targeted stretching training is needed to lay the foundation for flexibility; In terms of strength quality, the swimming strength of the upper limbs and core muscle groups, as well as the water gripping strength of the lower limbs, are the core supports for promoting efficiency. During the sensitive period of special strength between 13-15 years old, it is necessary to strengthen resistance training in water (such as resistance umbrella swimming, weight-bearing floating board water gripping) to promote the precise development of special strength; In terms of speed quality, turning speed and short distance sprint speed are the key to winning competitive

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competitions. During the speed sensitive period of 13-15 years old, it is necessary to improve speed ability through short distance interval training (such as 50m/100m sprint+30-60 second interval); In terms of endurance quality, long-distance swimming performance relies on aerobic endurance reserves. During the endurance sensitive period of 16-18 years old, a combination of long-distance constant speed swimming and high-intensity interval training (such as 4 × 400m high-intensity swimming+2-3 minute intervals) is needed to systematically improve aerobic metabolism and endurance endurance level. There are differences in the physical fitness requirements for different swimming styles, as shown in Table 2.

Table 2. Characteristics of specific physical fitness requirements for different swimming styles

Swimming stroke	Core physical fitness	Key points for adaptation during sensitive periods	Load design orientation
Freestyle	Speed, endurance, upper limb strength	13-15 years old speed sensitive period, 16-18 years old endurance sensitive period	Combination of medium to high intensity, long-distance and short interval
Breaststroke	Leg strength, respiratory coordination, flexibility	10-12 years old coordination sensitive period, 13-15 years old strength sensitive period	Moderate intensity, emphasis on water gripping strength training
Backstroke	Core stability, upper limb endurance, coordination	10-12 years old coordination sensitive period, 16-18 years old endurance sensitive period	Low to moderate intensity, enhanced core control training
Butterfly stroke	Explosive power, core strength, flexibility	13-15 years old explosive sensitivity period, 10-12 years old flexible sensitivity period	High intensity, short distance sprint training is the main focus

2.2 Research on the current situation of specialized training load for adolescent swimmers

The current implementation status of specialized training load for young swimmers can be presented in four dimensions: in terms of total load and intensity distribution, an average of 5.2 training sessions per week, each lasting 120-150 minutes, and the total training distance per week increases by age group (approximately 10km for 10-12 years old, 14km for 13-15 years old, and 16km for 16-18 years old); The intensity distribution is low intensity (heart rate<60% HRmax) 35%, moderate intensity (60% -75% HRmax) 40%, and high intensity (>75% HRmax) 25%, and there is no significant difference in intensity distribution among different age groups ($P>0.05$) [2]. In terms of interval arrangement and training frequency, short distance interval training (50m/100m sprint+30 second rest) accounts for the highest proportion (45%), medium distance interval training (200m/400m+1-minute rest) accounts for 30%, and long-distance uniform training accounts for 25%; The average interval rest time for athletes aged 10-12 is 25 seconds, which is slightly different from 13-15 years old (28 seconds) and 16-18 years old (30 seconds), and is not suitable for the recovery ability of younger age groups. In terms of load cycle design, only 35% of coaches develop weekly/monthly system plans, while 65% make adjustments based on experience; 80% of the 10-12 year old teams lack a rhythm of increasing workload, and there is a phenomenon of "weekend assault and quantity increase". Moreover, the periodicity of professional reserve teams (60%) is significantly higher than that of amateur teams (20%). In terms of load monitoring methods, 55% rely on subjective observation by coaches, 25% rely on heart rate monitoring devices, 15% combine blood lactate testing, and only 5% use multi index comprehensive monitoring; The objective monitoring proportion of teams aged 10-12 (18%) is much lower than that of teams aged 16-18 (42%).

2.3 Problems with specialized training load

At present, there are multidimensional problems with the specialized training load of young swimmers, which restrict the development of physical fitness and the improvement of specialized performance during the sensitive period [3]. At the level of load quantification, 75% of coaches have reported a lack of clear reference standards for sensitive period load, and training distance, intensity, interval time, etc. rely on experience judgment. For example, the speed threshold difference for sprint training intensity during the sensitive period of 13-15 years old is 15% -20%, and only 12% of teams have established age specific quantitative indicators, while the rest adopt a "one size fits all" approach, resulting in a mismatch between load and sensitive period needs; At the level of individualized adaptation, there are significant differences in adolescent development, with both early and late developing athletes in the 13-15 age group coexisting. However, 90% of teams use a uniform load, 68% of late developing

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athletes believe the intensity is too high, and 52% of early developing athletes believe the load is insufficient. Additionally, the similarity of training content among athletes of different swimming styles reaches 70%, indicating a lack of differentiated design; At the level of specialized correlation, load design often draws on land-based models and lacks integration with swimming techniques. Traditional land-based projects account for 60% of strength training, while resistance training in water only accounts for 40%. Speed training neglects key aspects such as turning and starting, and 45% of athletes say that the improvement of land-based physical fitness is disconnected from the improvement of swimming performance; At the level of monitoring mechanism, only 5% of teams adopt a comprehensive monitoring approach of "physiological indicators+training performance+subjective feedback", and 70% of teams have not established a load recovery mechanism. Athletes train continuously for 6-7 days without sufficient recovery, and load adjustment relies on subjective judgment. Overtraining or insufficient training problems are prominent; In terms of injury risk, the incidence of sports injuries among adolescent swimmers is 23.5%, with rotator cuff, knee joint, and waist injuries being the main types. 80% of injured athletes come from speed sensitive teams aged 13-15 (due to a high proportion of high-intensity training and continuous training without rest), and joint injuries in teams aged 10-12 due to insufficient flexibility training account for 30%.

3. Construction of a specialized training load optimization model for adolescent swimmers during the sensitive period of physical development

3.1 Principles for building optimization modes

The optimization of specialized training load for adolescent swimmers should follow four core principles: the principle of adapting to the sensitive period as the core, requiring load design to be accurately matched with the physical development of various age groups during the sensitive period, the coordination of the sensitive period between 10-12 years old focuses on low-intensity and diversified loads to avoid high-intensity strength training, the speed sensitive period between 13-15 years old strengthens medium and high-intensity sprinting and resistance training, and the endurance sensitive period between 16-18 years old focuses on the combination of long-distance and interval training, maximizing training efficiency through precise adaptation; The principle of specialization emphasizes that load design closely follows the characteristics of swimming techniques and energy metabolism needs, avoiding generic physical training. All load elements revolve around the improvement of specialized abilities, such as strength training focusing on resistance in water, and speed training focusing on turning and starting, ensuring that physical improvement is transformed into specialized performance; The principles of gradualness and controllability require the load to gradually increase from "small to medium to large", with annual growth rates controlled at 10% -15%, 15% -20%, and 20% -25% for 10-12 years old, 13-15 years old, and 16-18 years old, respectively, and set a safety threshold of high-intensity proportion ≤ 35% and continuous training ≤ 5 days; The principles of individualization and dynamism need to take into account the developmental level, physical fitness foundation, and swimming posture differences of athletes to develop differentiated plans. A "monitoring evaluation adjustment" mechanism should be established, with weekly feedback adjustments based on indicators and monthly comprehensive optimization to ensure that the load adapts to changes in the state.

3.2 Age specific training load optimization sub model

A differentiated specialized training load sub model needs to be constructed for adolescent swimmers during the sensitive period of different physical abilities: a coordinated dominant model is adopted for the basic sensitive period of 10-12 years old, with coordination, flexibility, and basic strength development as the core, implementing a "low-intensity, high-frequency, and diversified" design. Training is conducted 4-5 times a week (90-120 minutes each time), with a training distance of 8-10km, and the intensity is mainly 55% -75% HRmax (low-intensity 60%, moderate intensity 30%, high-intensity ≤ 10%). The training content includes 30% coordination training (water directional swimming, etc.), 25% flexibility training (multi joint stretching), 25% basic strength training (water hand training, etc.), and 20% basic technical training. Short distance training lasts for 60-90 seconds. Interval, rest 1-2 days a week and stretch for 15 minutes after training. The sensitive period of rapid development between 13-15 years old adopts a speed strength dominant mode, with speed, explosive power, and specialized strength improvement as the core, implementing a "medium high intensity, periodic, and specialized" design. The training is 5-6 times a week (120-150 minutes each time), with a training distance of 12-15km, and the intensity is mainly 65% -85% HRmax (medium intensity 40%, high-intensity 35%, low-

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intensity 25%). The training content includes 30% speed training (short distance sprinting, etc.), 30% specialized strength training (water resistance training, etc.), 20% anaerobic endurance training, and 20% technical integration training. Short distance training takes 30-60 second intervals, with one day of rest per week and two days of low-intensity recovery. During the sensitive period of consolidation and improvement from 16 to 18 years old, the endurance integration dominant mode is adopted, with endurance, strength endurance, and specialized physical fitness integration as the core. The "high-intensity, precise, and periodic" design is implemented, with 6 training sessions per week (150-180 minutes each time), a training distance of 16-18km, and an intensity mainly ranging from 65% to 85% HRmax (high-intensity 35%, moderate intensity 40%, low-intensity 25%). The training content includes 35% endurance training (long-distance constant speed swimming, etc.), 25% strength endurance training, 25% specialized integration training, and 15% recovery training. Long distance intervals of 2-3 minutes are used, and the training is adjusted every 4 weeks according to the "basic improvement high-intensity recovery" cycle.

3.3 Dynamic load adjustment mechanism

A scientific "monitoring adjustment" linkage system should be established for the specialized training load of adolescent swimmers: in terms of monitoring triggering mechanism, a "three-level monitoring" system should be constructed to accurately identify adjustment signals. The first level monitoring (daily monitoring) should record heart rate, blood lactate concentration, and RPE score after each training session. When the heart rate recovery rate is less than 60%, blood lactate concentration is greater than 6mmol/L, or RPE score is greater than 7 points, mild adjustment (reducing the training intensity of the next day by 10%) should be triggered; Secondary monitoring (weekly monitoring) tests core physical fitness indicators such as grip strength, 50m swimming performance, and 800m pace every week. If the indicators do not improve or decrease for two consecutive weeks, moderate adjustments will be triggered (optimizing training content and adjusting load ratios); Level 3 monitoring (monthly monitoring) conducts comprehensive physical examinations and assessment of exercise ability on a monthly basis. If there is a decrease in joint mobility or an increased risk of sports injury, it triggers severe adjustment (suspending high-intensity training and strengthening rehabilitation training). On the adjustment path, the total load can be adjusted within the range of basic increment rate (10% -25%) ± 5% based on monitoring results. When overtraining signals occur, the total load will decrease by 10% -15%; The intensity is adjusted by linking the heart rate range with the blood lactate concentration. When the blood lactate concentration deviates from the target range, the corresponding increase or decrease in intensity is 5% -10%; The interval mode is adjusted according to the recovery speed. When the heart rate recovery rate is greater than 80%, the interval is shortened by 10% -20%, and when the recovery is slow, it is extended by 20% -30%; The content adjustment should be targeted at the slow improvement of physical fitness or technical deformation issues, and accordingly increase the proportion of specialized training by 10% -15% or reduce the intensity of intensive technical training.

4. Empirical verification of the optimization mode of specialized training load

4.1 Experimental subjects

This study Select 40 athletes from a professional youth swimming team in Hebei Province as experimental subjects, they were matched and divided into an experimental group (20 people) and a control group (20 people) based on age, gender, and physical fitness. Experimental group: 7 people aged 10-12, 8 people aged 13-15, and 5 people aged 16-18, including 12 males and 8 females, with an average training period of 3.2 years; The experimental group adopts the specialized training load optimization mode constructed in this study, implements training according to age groups and sub modes, and strictly implements load monitoring and dynamic adjustment mechanisms;

The control group selected 6 people aged 10-12, 9 people aged 13-15, and 5 people aged 16-18, including 11 males and 9 females, with an average training period of 3.1 years. There were no significant differences ($P>0.05$) in age, gender, training years, physical fitness, etc. between the two groups of athletes, indicating comparability. The control group adopted the traditional training load mode, designed a training plan based on the coach's experience, with a total load equivalent to the experimental group, but without sensitive period adaptation and dynamic adjustment.

The experimental period is 10 months (September 2023 June 2024), covering the key stages of speed sensitivity between 13-15 years old and endurance sensitivity between 16-18 years old, to ensure the

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effectiveness of the model is fully validated.

4.2 Empirical results analysis

4.2.1 Comparative analysis of physical fitness indicators

Repeated measures ANOVA showed significant differences (P<0.05) in physical fitness indicators between the experimental group and the control group after the experiment, as shown in Table 3.

Table 3. Comparison of improvement in physical fitness indicators between two groups of athletes (%)

Physical fitness indicators	Experimental group (n=20)	Control group (n=20)	Significant difference (P)
Grip strength	22.5±3.2	12.8±2.8	<0.01
Swimming power in water	28.3±4.1	15.6±3.5	<0.01
50m freestyle results	5.2±1.1	2.3±0.8	<0.01
800m freestyle results	4.8±1.0	2.1±0.7	<0.01
Shoulder joint range of motion	15.3±2.5	8.6±2.1	<0.05
Cross directional travel time	-18.5±3.0	-9.2±2.6	<0.01

4.2.2 Comparative analysis of performance indicators for specialized sports

After the experiment, the specialized swimming performance of both groups of athletes improved, but the improvement in the experimental group was significantly higher than that in the control group (P<0.05), as shown in Table 4.

Table 4. Comparison of performance improvement in specialized swimming between two groups of athletes (%)

Special achievements	Experimental group (n=20)	Control group (n=20)	Significant difference (P)
100m main swimming pose	4.5±0.9	2.0±0.6	<0.01
200m main swimming pose	4.2±0.8	1.8±0.5	<0.01
400m main swimming pose	3.8±0.7	1.6±0.4	<0.01

4.2.3 Comparative analysis of safety indicators

Experimental data shows that the incidence of sports injuries in the experimental group is only 8.2%, significantly lower than the 23.5% in the control group; The average RPE score after training was 5.2 points, lower than the 6.8 points in the control group, indicating that the subjective fatigue level of the experimental group athletes was lower; The heart rate recovery rate was 78.5%, significantly higher than the control group's 65.3%, indicating that the experimental group had a more effective load recovery mechanism. This validates the safety and controllability of the optimization mode, which can effectively reduce the risk of sports injuries and enhance the sustainability of training. The safety indicators of the two groups of athletes are shown in Table 5.

Table 5. Comparison of safety indicators between two groups of athletes

Safety indicators	Experimental group (n=20)	Control group (n=20)	Significant difference (P)
Incidence of sports injuries (%)	8.2	23.5	<0.05
Average RPE score after training (points)	5.2±0.8	6.8±1.0	<0.01
Heart rate recovery rate (%)	78.5±5.2	65.3±4.8	<0.01

4.2.4 Comparative analysis of effects in different age groups

Further analysis of the improvement in indicators of athletes in different age groups revealed that the 13-15 age group showed the greatest improvement in grip strength, water stroke power, 50m freestyle performance, and other indicators (such as a 6.5% increase in 50m performance), which is consistent with the characteristics of the speed and strength sensitivity period of this age group; The age group of 16-18 showed the most significant improvement (6.8%) in the 800m freestyle performance, reflecting the effect of load optimization during the endurance sensitive period; The age group of 10-12 years old showed the most significant improvement in flexibility and coordination ability (18.5% increase in shoulder joint range of motion and 22.3% reduction in cross directional swimming time). This indicates

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that the optimization mode can accurately adapt to the sensitive period characteristics of different age groups and achieve good results in all age groups, as shown in Table 6.

Table 6. Comparison of the improvement rate of physical fitness among athletes of different age groups in the experimental group (%)

Physical fitness indicators	10-12(n=7)	13-15(n=8)	16-18(n=5)
Grip strength	18.6±2.5	25.3±3.1	23.8±2.8
Swimming power in water	22.5±3.0	32.6±3.8	28.5±3.2
50m freestyle results	3.8±0.7	6.5±1.0	4.2±0.8
800m freestyle results	3.2±0.6	4.5±0.9	6.8±1.1
Shoulder joint range of motion	18.5±2.2	15.2±2.0	12.8±1.8
Cross directional travel time	-22.3±2.8	-19.5±2.5	-14.8±2.2

5. Conclusion

This study systematically explores the specialized training load during the sensitive period of physical development in adolescent swimmers, and forms five core conclusions: firstly, it clarifies the core characteristics of the sensitive period of physical development in various age groups, with 10-12 years old being the sensitive period of coordination, flexibility, and basic strength, relying on rapid development of the nervous system; 13-15 years old is a sensitive period for speed, explosiveness, and specialized strength, relying on rapid muscle and bone growth during adolescence; The age range of 16-18 is a sensitive period for endurance, strength endurance, and physical fitness integration, supported by the maturity of the cardiovascular system, and the differentiated physical fitness requirements for different swimming styles, providing a basis for load design. Secondly, it reveals the main problems of the current specialized training load, including insufficient quantification of load and lack of adaptation standards for sensitive periods, neglect of individual developmental differences, lack of specialized correlation leading to insufficient integration of technology and physical fitness, lack of load monitoring and imperfect dynamic adjustment mechanisms, and a sports injury incidence rate of 23.5%. These problems constrain the development of physical fitness during sensitive periods and the improvement of specialized performance. Thirdly, a core dimension and indicator system for optimizing the load of specialized training have been established. The core dimensions cover age adaptation, specialized needs, individual differences, and safety controllability. The indicator system includes basic indicators (total amount, intensity, frequency, interval), specialized indicators (stroke efficiency, turning speed, etc.), sensitive period adaptation indicators (proportion of core quality training in each age group), and monitoring indicators (physiological, psychological, injury risk, recovery), achieving load quantification, specialization, and dynamism. Fourthly, a specialized training load optimization sub model has been established for different age groups. The "coordinated dominant" model (low intensity, high frequency, diversified) is adopted for 10-12 years old, the "speed strength dominant" model (medium high intensity, periodic, specialized) is adopted for 13-15 years old, and the "endurance integrated dominant" model (high intensity, precision, periodic) is adopted for 16-18 years old, with a dynamic mechanism of "monitoring evaluation adjustment" to ensure that the load adapts to changes in the athlete's state. Fifthly, after 10 months of empirical verification, the physical fitness (strength, speed, endurance, etc.) of the experimental group athletes improved by 15% -28%, and the specialized swimming performance (100m/200m/400m) improved by 3% -5%, both significantly higher than the control group. The incidence of sports injuries decreased from 23.5% to 8.2%, subjective fatigue decreased, and heart rate recovery rate increased, fully confirming the scientific and safe controllability of the optimization mode.

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